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Landfill gas monitoring, assessment of potential health risks and the development of a zero-waste conceptual framework for rural landfills in South Africa

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Declaration

I, NJOKU PRINCE OBINNA, hereby declare that this thesis titled - **LANDFILL GAS MONITORING, ASSESSMENT OF POTENTIAL HEALTH RISKS AND THE DEVELOPMENT OF A ZERO-WASTE CONCEPTUAL FRAMEWORK FOR RURAL LANDFILLS IN SOUTH AFRICA -** for the degree of Doctor of Philosophy (PhD) in the Department of Geography and Environmental Sciences at the University of Venda, hereby submitted by me, has not been previously submitted for a degree at this or any other institution. This is my work in design and execution; all reference materials contained herein have been duly acknowledged**.**

Signature ________ ___________ Date: _22/08/2024_______________

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Abstract

A landfill is a piece of land where waste (hazardous and non-hazardous) is taken to and buried under the ground; this is oldest and cheapest form of waste management technique. In South Africa, approximately 90% of MSW (Municipal Solid Waste) generated is deposited in a landfill, once it is deposited in the landfill, it undergoes decomposition which generates harmful gases like - methane (CH_4), carbon dioxide (CO_2) - and trace gases like - hydrogen sulphide (H_2S), benzene (C_6H_6), carbon monoxide (CO), nitric oxide (NO), ammonia (NH_4) and toluene ($C_6H_5CH_3$). These landfill gases (LFG) generated can migrate beneath the sub-surface of the waste into the surrounding landfill area and further extend outside of the boundaries of the landfill. Furthermore, LFG generated can be emitted into the surrounding atmosphere, thereby, contributing to an increase in air pollutants, in the environment. As a result, in South Africa, monitoring the subsurface flow of gases is a mandatory requirement for landfill operators. The objective of this study was to conduct a comprehensive analysis of LFGs from a selected Thohoyandou landfill and develop a zero-waste conceptual framework, based on the Swedish Boras model.

To monitor the sub-surface flow of the LFGs, eighteen gas sample probes were constructed with PVC pipes and placed approximately 3 meters below the landfill; these were placed approximately 100 meters apart on the boundaries of the site. A GA 2000 landfill gas analyser was used to monitor the CH_4 and CO_2 generated from the sub-surface of the landfill. The monitoring of the LFGs was conducted over a period of two years, taking into consideration the wet and dry seasons of the year. Furthermore, to measure the surface emission (near-ground emissions) of the LFG, a flux chamber was constructed from a strong ceramic PVC material with a sharpen based to conceal the flow of LFGs. The LFG samples were collected from the flux chamber using a tedler bag, in the early hours of the day and late hours in the evenings. These LFG samples were immediately taken to the laboratory and a gas chromatography (GC) was used to analyse them. The results from the GC were compared to results generated from the LandGEM model. To monitor the ambient air quality of the surrounding landfill, American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) was used to simulate the LFG emissions in the ambient air. From this process, it was possible to compare these results with real time measurements from the TROPOspheric Monitoring Instrument (TROPOMI) satellite imagery. In addition, the cancer risk of the residents living close to the landfill was assessed.

The results of the study revealed that CO_2 concentrations were most abundant and surpassed the CH_4 concentrations; this is a result of the oxidation process in the landfill. The results indicate that in 2020, CH_4 emissions ranged from 0.54 % vol/vol to 2.22 % vol/vol and for the year 2021, the CH_4 concentration ranged from 0.24% vol/vol to 2.33% vol/vol, which were found in the months of March and November, respectively. Similarly, the CO_2 concentrations for the year 2020 ranged from 4.66% vol/vol to 6.37% vol/vol and in 2021, the CO_2 concentration ranged from 3.55% vol/vol to 6.56% vol/vol, which were found in the months of June and September, respectively.

The results from the flux chamber show that most of the LFG (near ground) fluxes were from areas close to where there were landfill activities. The study showed that during the wet seasons, CH_4 emission in the capped area, had a high concentration of 360819.80 mg/m^3, with an average emission rate of 433.00 $g/m^2/day$, resulting in 6363.43 Mg/year. The active sample areas had the highest values, with a concentration of 419863 mg/m^3, an average emission rate of 503.86 $g/m^2/day$, and annual emissions of 7031.57 Mg/year. The virgin areas had the lowest values, with a concentration of 45922.52 mg/m^3, an average emission rate of 55.11 $g/m^2/day$, resulting in 605.72 Mg/year. Similar results were obtained during the dry season, as the concentrations and emission rates in all areas of the landfill were lower, compared to the wet season. The active and capped sample area had the highest values in comparison to the leachate and virgin sample areas, as experienced during the dry season.

The study concluded with the development of a strategic framework for an appropriate MSW management technique, especially, for rural landfills. The designed framework incorporated strategies to - reduce waste, promote recycling, and maximise resource recovery. Thulamela Municipality can encourage waste sorting, recycling infrastructure, and explore innovative technologies in landfill operations, so as to reduce the generation of harmful gases. This study should enhance the understanding of stakeholders in Thohoyandou, around LFG emissions in by providing actionable measures for improving waste management practices, safeguarding community health, and advancing sustainable solutions for environmental challenges.

Keywords: Ambient air quality, Health risks, Landfill gases, Rural landfills, Zero-waste conceptual framework

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First and foremost, I want to acknowledge my late Professor John Ogony Odiyo. He was a guiding light on my academic journey, and even though he could not witness the completion of this thesis, his profound influence and steadfast support have left an indelible mark on me. Professor Odiyo was not just a supervisor, he was a mentor, a source of inspiration, and a true academic visionary. His passion for research, commitment to excellence, and boundless curiosity continue to resonate within the fabric of this thesis. I am immensely grateful for the time we shared, the discussions we had, and the insights he imparted. His guidance played a pivotal role in shaping the direction of my research, and his memory will forever inspire me to strive for excellence in his honour.

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In conclusion, this thesis is the result of the collective efforts of many, hence, it would not have been possible without the support and encouragement of the individuals and entities mentioned above. I am honoured to have been part of this collaborative and enriching academic community.

Dedication

With profound reverence and gratitude, I dedicate this PhD thesis to the source of all knowledge, guidance, and inspiration on the intricate tapestry of life's journey, the Almighty God. To You my heart turns with deep recognition of Your steadfast presence, benevolence, and influence. Amidst the challenges and triumphs that have defined this endeavor, I acknowledge your divine grace, which has illuminated my path. Your boundless wisdom has served as my beacon, and your infinite love has been my source of strength. Every step taken, every milestone achieved, and every obstacle overcome, stand as a testament to Your abundant blessings.

May this work stand as a testament to the profound connection between human inquiry and the infinite wisdom You bestow. With every discovery made, every lesson learned, and every contribution offered, I recognise Your guiding hand, thus, as I humbly present this contribution to the world of knowledge, I do so with heartfelt gratitude and humility.

Table of Contents

List of Figures

List of Tables

Scholarly Outputs during the course of the study

TOPIC	ARTICLE	STATUS
Monitoring of Subsurface Emissions and the Influence of Meteorological Factors on Landfill Gas Emissions: A Case Study of a South African Landfill.	Njoku, P. O., Piketh, S., Makungo, R., & Edokpayi, J. N. (2023). Monitoring of Subsurface Emissions and the Influence of Meteorological Factors on Landfill Gas Emissions: A Case Study of a South African Landfill. *Sustainability*, 15(7), 5989.	Published
Estimation of landfill gas production and potential utilisation in a South Africa landfill.	Njoku, P. O., & Edokpayi, J. N. (2023). Estimation of landfill gas production and potential utilisation in a South Africa landfill. *Journal of the Air & Waste Management Association*, 73(1), 1-14.	Published
Quantification and modelling of methane and carbon dioxide surface emissions from a South African landfill.	Njoku, P. O., Piketh, S., Makungo, R., & Edokpayi, J. N. *Quantification and modelling of methane and carbon dioxide surface emissions from a South African landfill.*	In draft stage
Modeling and monitoring ambient air quality and assessing the health impacts of landfill gases.	Njoku, P. O., Piketh, S., Makungo, R., & Edokpayi, J. N. *Modeling and monitoring ambient air quality and assessing the health impacts of landfill gases.*	In draft stage
Developing a conceptual framework for an Integrated Solid Waste Management System (ISWMS)	Njoku, P. O., Makungo, R., & Edokpayi, J. N. *Developing a conceptual framework for an Integrated Solid Waste Management System* (ISWMS).	In draft stage to be sent to Waste Management Journal

Conferences attended during the course of the study

- Annual Conference of the National Association for Clean Air (NACA) 5 - 7 October 2022 **(Presented at the conference the paper - *'The influence of meteorology on landfill gas emissions: A case study of a rural landfill in South Africa'*) (Grants awarded by SACNASP)**

- Global Methane, Climate and Clean Air Forum 26-30 September 2022, Washington, D.C. **(Participated virtually: a joint event sponsored by GMI and CCAC)**

- Annual Conference of the National Association for Clean (NACA) Air, 6 - 8 October 2021 (**Participated virtually, reading the paper:** ***'Estimation of landfill gases and potential utilisation in South Africa'*****) (Grants awarded by SACNASP)**

- Seventh Student Workshop at Eskom Power Plant Engineering Institute (EPPIE) 12 – 13 November 2020

CHAPTER ONE: Introduction

1.1 Background of the Study

The world, currently, generates approximately 2 billion tonnes of Municipal Solid Waste (MSW) annually, and by 2050, it is projected that MSW generation will increase to approximately 3.4 billion tonnes, corresponding to a significant rise in MSW generation from 0.74 to 1.42 kilograms per person, per day (Nanda and Berruti, 2021; Adenuga et al., 2020). This increase can be attributed to factors, such as urbanisation, economic development, and population growth. According to Shi et al. (2021) Africa's poor waste management practices, lack of expertise, fiscal irresponsibility, and system maintenance inadequacies, have resulted in a shortage of MSW collection and reuse. South Africa generates approximately 108 million tonnes of general solid waste annually, with the average person in South Africa producing about 0.76 kilograms (7.6×10^{-4} tonnes) of waste per day. Low-income households, however, produce a lesser amount of waste per person, approximately 3×10^{-4} tonnes, whereas high-income households generate 13×10^{-3} tonnes (Njoku et al., 2020), with the latter comparable to the average waste, per person, in developed countries. This situation has raised concerns for the South African waste management sector (Njoku et al., 2020).

MSW refers to the solid waste collected from homes, businesses, institutions, and commercial enterprises. This waste includes both biodegradable and non-biodegradable fractions and comprising of organic and inorganic materials, however, the composition and classification of the MSW can vary significantly among different sites, worldwide. The efficient management of MSW involves all processes and resources necessary for the proper handling of waste, ranging from the maintenance of waste-transport vehicles to disposal facilities in compliance with health codes and environmental regulations (Zorpas, 2020). In South Africa, approximately 70% of the total MSW collected by municipalities is disposed of in landfills and dumpsites, while 19% is recycled, and 11% is utilised for energy recovery (Nanda and Berruti, 2021). With the current global population of 7.6 billion, waste management practices reflect the need for more sustainable solutions.

A landfill is a designated site where MSW is deposited and then buried underground, representing one of the oldest and most cost-effective waste management methods. When MSW is placed in a landfill, it undergoes decomposition, leading to the generation of harmful gases like, methane

(CH_4), carbon dioxide (CO_2), and other trace gases, such as hydrogen sulfide (H_2S), benzene (C_6H_6), carbon monoxide (CO), nitric oxide (NO), ammonia (NH_4), toluene ($C_6H_5CH_3$), among others (Njoku et al., 2020).

Research has shown that the continuous release of Landfill Gas (LFG) into the atmosphere has a significant negative impact on the environment and these emissions can persist for up to 200 years after a landfill is closed (Njoku et al., 2018; Shammas et al., 2020). Of particular concern are CH_4 and CO_2, which are potent greenhouse gases (GHGs) known to contribute significantly to global warming and climate change. Their effects include - increased flooding, rising sea levels, changes in rainfall patterns, more intense and unpredictable hurricanes, extreme heatwaves, and the melting of glaciers (AghaKouchak et al., 2020).

In South Africa, there has been a worrying increase in heatwaves, with temperatures exceeding the monthly average by up to 5°C in 2015, as reported by the South African Weather Service in 2018 (Ndlovu and Demlie, 2020). Additionally, the country faced a severe drought in 2015, similar in magnitude to the significant drought of 1991-1992 (Ndlovu and Demlie, 2020). These issues have profound impact on rural areas, particularly, affecting rural livestock farming in South Africa (Maluleke and Mokwena, 2017). CH_4 is a combustible gas with a relatively low heating power of 37.784 MJ/m^3 in dry volume, however, when its concentration in the air falls within the range of 5% - 15%, it becomes highly explosive (Franzidis et al., 2008). This explosion risk primarily emerges from the sub-surface lateral movement of LFG through soils and pores, leading to its infiltration into buildings, sub-terranean structures, or nearby sinkholes. Several factors, including - barometric pressure, temperature, soil moisture content, soil type, nutrient availability, and oxygen concentration - influence the surface and sub-surface lateral migration of LFG. Notably, the continuous emissions of LFGs have been shown to be linked to various disease outbreaks in places, including Thohoyandou and its surroundings (Kar and Basunia, 2020; Made et al., 2020, and Njoku et al., 2019). These ill-effects are further associated with complaints of odors and dust emissions, emphasising the critical need for prioritisation by the South African government and relevant stakeholders on environment-friendly manner in operating landfills.

In light of these challenges, to address the issues associated with the Thohoyandou landfill, it is crucial to undertake a comprehensive LFG analysis which would involve several key procedures. Firstly, extensive monitoring of the sub-surface migration of LFG within the landfill area is essential to understand the pathways and potential risks of gas movement below the surface. Secondly, monitoring the surface emissions fluxes of LFGs is critical to assess the quantity and composition of gases released into the atmosphere, this step aids in identifying potential sources of pollution and evaluating the effectiveness of existing control measures. Additionally, monitoring the ambient air quality, of the surrounding area and its dispersion patterns, is paramount to assessing the broader impact of landfill gas emissions on the local environment and public health.

This study, therefore, aimed to evaluate sub-surface emissions from the Thohoyandou landfill, while considering meteorological factors and to quantitatively measure surface emissions of CH_4 and CO_2 from the landfill. Additionally, it aims to assess the concentration of ambient air quality in the Thohoyandou landfill area, in order to offer insights into public health and environmental well-being from the operations of the site. Finally, it is hoped to develop a comprehensive conceptual framework for an Integrated Solid Waste Management System (ISWMS) tailored towards a zero-waste in the South African context, drawing from successful practices based on the Boras Model, developed in Sweden.

1.2 Statement of Problem

Most rural landfills in South Africa, however, do not have LFG collection or utilisation systems for proper management of LFG emissions, although, as mentioned earlier, landfills are the widely used MSW disposal technique in the country. Deposition of MSW, over the years, from the inception of landfills, poses a great threat to humans and the environment (Abualqumboz et al., 2016).

These MSW deposits, buried in the landfills, decompose and generate harmful gases, especially greenhouse gases (CH_4 and CO_2) and other trace gases. Some of these LFGs emitted into the atmosphere contribute to the formation of tropospheric ozone which aid significantly in climate change, global warming, and ultimately harmful effects on human health (Pin et al., 2018). MSW transport trucks, bulldozers, waste unloading and sorting, all generate particulate matter emissions during operations in the landfill. Various studies have shown that different illnesses are associated with pollutants from landfill (Vrijheid, 2000; Adeola, 2000; Brender, 2011; Njoku et al., 2019), however, despite extensive information on the composition of LFG and its effects on health and environment, comprehensive data is still needed on these airborne particles, their dispersion and their impact on the ambient air quality.

One of the established ways for proper management of LFGs is by the collection and utilisation of these gases. Due to the prevailing global warming, climate change is rapidly escalating in South Africa, with temperatures projected to rise by over 4 °C in the inland areas of Southern Africa and over 6 °C in the western, central, and northern parts of South Africa, by 2100 (Chersich and Wright, 2019). Global warming has led to noticeable extreme weather events, such as droughts and wildfires, as well as an increase in vector and waterborne diseases (Chersich and Wright, 2019). As landfills continue to emit LFGs into the atmosphere and contribute considerably to Southern Africa and global GHG emissions, it is imperative to address the issue. This process should focus on the continuous emission of LFGs by quantifying and monitoring their emissions, producing a LFG emission inventory which will help to understand the emissions and proffer better policies and possible mitigation strategies like the implementation of LFGs' utilisation through an effective LFG collection system.

The compaction of MSW daily in many landfills has been done with clay soil, or whatever rubbles are available to reduce the production of bad odour, atmospheric gaseous emissions, and leachate in the landfill. This covering encourages vertical barriers for LFG within the landfill leading to lateral LFG movement in the landfill. These LFGs migrate and accumulate in sinkholes, surrounding buildings, cracks in the landfill, and wells, thereby, posing elevated risks to fire and explosion in the landfill. Several landfill fires have been recorded in different areas of South Africa (Kunene 2019; Ntseku, 2021).

A fire outbreak was reported by Kunene (2019) on October 7, 2019, at the New England Road landfill site, in Msunduzi Municipality in South Africa. The incident was claimed to have been initiated by waste pickers within the landfill, according to the firefighters in charge; this led to the shutting down of about 5 schools. Also, the spokesperson for the Msunduzi Municipality reported that there had been other fire outbreaks in the same landfill about a month before following the dumping of toxic waste in the landfill (Kunene, 2019). Nivashni Nair on 29 July 2020, in the Sowetan, reported a week-long fire incident that occurred in Pietermaritzburg's landfill with more than 70 fire fighters deployed to the scene. The firefighters battled the fire, day and night, as a heavy cloud of smoke lingered over KwaZulu Natal's capital city (Ntseku, 2021). The cause of the fire was attributed to waste pickers who had started their collection activities at the landfill’s boundaries. Also, in Cape Town, some residents near the Coastal Park landfill in Muizenberg complained about the poor air quality. One of the residents claimed her family and other neighbors have been waking up with sore throats and headaches, as well as respiratory problems and insomnia. According to a resident, the authorities indicated that putting out the fire would be difficult; she complained - “*which I find horrible - that we're being exposed to poisons like this, and nothing has been done for weeks, all during a pandemic*" (Ntseku, 2021). In Johannesburg, on the 17th of September 2021, there was a fire outbreak in the Robinson landfill site, Pikitup and the Johannesburg emergency services unit had to run 24-hour operations to extinguish the raging fire which was ongoing for two weeks.

Following the Polokwane National Waste Summit held in 2001, South Africa made a commitment to reduce waste generation by 50% and waste disposal by 25% by the year 2012. Additionally, the nation pledged to work toward achieving the goal of zero-waste by 2022. The zero-waste processes will maximise recycling, minimise waste, reduce consumption and ensure that products are made to be reused, repaired, or recycled back into nature or the marketplace (Annexure, 2005). This zero-waste agreement seems to be far-fetched as no proper model has been put in place, hence, waste generation and disposal reduction agreements, did not seem feasible, any time soon. Also, lack of policies, regulations and implementation on already existing policies was evidence of the challenges encountered. This inability to control LFG emissions and reduce other associated problems from landfills, demonstrated that the zero-waste approach was a more viable and feasible way in managing MSW.

The Thohoyandou landfill has recently garnered significant governmental concern due to its adverse impact on the surrounding environment and nearby communities, as highlighted in a report by the South African Human Rights Commission (Schenck, et al., 2021). The landfill is likely to be in violation of residents’ constitutional rights to a healthy environment, as it poses environmental hazards, such as air and water pollution, which adversely affect both the well-being of neighbouring communities and the environment. In response to these concerns, efforts have been initiated to enhance the landfill's environmental management. The Thulamela Municipality, however, is laudably taking steps to address waste management issues by implementing a waste management plan and a waste minimisation program (Mabadahanye, 2017). These measures are aimed at reducing the volume of waste destined for the landfill and promoting recycling and reuse, however, despite these efforts, challenges persist in achieving sustainable landfill management. Key challenges identified in South Africa, include - inadequate waste collection, lack of source sorting, and insufficient funding - these contribute to waste accumulation at landfills and heighten the risk of environmental hazards. Unfortunately, the Thohoyandou landfill has no form of LFG collection and monitoring operations, thereby placing the landfill at a high risk of fire outbreak and the potential accumulation of harmful gases. It is very urgent government requirement for landfill operators to constantly monitor movement and accumulations of LFG in the surrounding areas.

1.3 Motivation

The surface and sub-surface migration of LFGs results in their continuous movement in landfills. The constant monitoring of LFG emission is essential with regards to specific requirements of certain legislations and regulations of landfill management, around the world. In Europe, the European landfill Directive 1999/31/EC (Preamble 16 and Annexes I, III) requires that LFG emissions should be measures during landfill operations and after-care phase of the landfill. The Italian Legislation - D.Lgs. No. 36/2003 - requires that landfill operators fulfil these requirements by - (a) the monitoring of ‘‘collected” but also ‘‘uncontrolled” LFG emissions, including possible external gas migrations; (b) the qualitative and quantitative characterisation as well as identification of LFGs’ migration in soil and sub-soil; (c) the periodical monitoring of environmental media and emissions (Capaccioni et al., 2011). The South African government has made it mandatory for landfill operators to constantly monitor the gaseous emissions from landfills, however, different operators, especially, in rural areas of South Africa have failed to comply with these regulations. This could be because of lack of adequate technical knowledge and negligence on the part of landfill operators or financial constraints in monitoring these gases. The introduction of legislation and regulations on LFG monitoring and emissions stems from the recognition that the collection and extraction systems for LFG, in both sanitary and unsanitary landfills, are not entirely efficient. The appropriate and continuous monitoring of LFGs will help in understanding their migration into the surrounding areas. Due to the inability of landfill operators to monitor LFGs, their accumulation in certain areas of the landfill cannot be detected, thereby, increasing the potential risk of fire and airborne diseases' outbreak in these areas. Also, because of lack of constant monitoring of LFGs there is limited data on the type of gases emitted from the landfill. This in turn, could lead to difficulties for landfill operators, stakeholders, and government in providing basic appropriate landfill policies that will help in improving its operations and management. It is, therefore, essential for this study to be conducted, as the results will help fill the gap in existing literature on rural landfills in South Africa. Furthermore, the results from this study will serve as a benchmark for other rural landfills in South Africa, hence, will assist in the detection and avoidance of potential fire outbreaks and various pollutants from landfills.

Quantifying CH_4 and CO_2 emissions from the Thohoyandou landfill involves measuring the actual fluxes of these gases emitted from the site. CH_4 emitted from landfills possesses a lower heating value of 37.784 MJ/Nm and is commonly utilised as a fuel source for electricity generation and vehicular power (Franzidis et al., 2008). Unfortunately, many landfills in South Africa, including the Thohoyandou landfill, lack information about the quantities of CH_4 and CO_2 emitted from their sites, leading to a deficiency in LFG utilisation facilities and an inability to consider or implement LFG management policies. These gaps in knowledge have resulted in increased CH_4 and CO_2 emissions into the atmosphere, contributing to the overall escalation of GHGs and exacerbating climate change and global warming, however, in understanding the volume of CH_4 emitted from the landfill, stakeholders can strategically plan for potential LFGs utilisation in the future. The study's findings, therefore, will aid these various stakeholders in devising potential regulations to mitigate and reduce LFG emissions from the landfill into the surrounding atmosphere.

In recognising the critical nature of air quality for our well-being, it becomes evident that deteriorating air quality over the years can be attributed to various human and natural activities in our environment. Scholars have identified landfill activities as significant contributors to air pollution, emitting pollutants like SO_2, PM, H_2S, and others into the atmosphere (Liu et al., 2016; Abualqumboz et al., 2016). Air pollution originates from various sources, making it crucial to identify these exact sources. Identifying pollutants' exact sources will facilitate mitigation efforts which will enable stakeholders, and landfill operators to develop policies aimed at reducing emissions from landfills. This study, therefore, will measure and monitor ambient air quality, assessing its potential impacts in the vicinity of the Thohoyandou landfill. The collected data will assist landfill operators and relevant stakeholders in addressing the primary pollutants emitted from the landfill and proposing potential solutions to reduce these emissions.

1.4 Objectives

1.4.1 Main Objective

The aim of this study is to conduct a comprehensive analysis of the LFGs from Thohoyandou landfill and develop a zero-waste waste management strategy for Thulamela Municipality.

To conduct a thorough analysis of LFG emissions, it is essential to implement sub-surface, surface, and ambient air monitoring systems at the landfill site. Additionally, it is crucial to assess the potential health effects of LFG exposure on individuals residing or working near the landfill.

1.4.2 Specific Objectives

i. To monitor the sub-surface migration of gases from the Thohoyandou landfill site and the influence of meteorological parameters.

ii. To quantify the amount of CH_4 and CO_2 fluxes from the Thohoyandou landfill site.

iii. To quantify and model the ambient air quality of the surrounding landfill and assess the health impacts from the LFGs generated.

iv. To develop a conceptual framework for a zero-waste management strategy for Thulamela Municipality.

1.5 Research Hypothesis

i. LFGs migrate from the sub-surface of Thohoyandou landfill and flow into the surrounding environment.

ii. LFGs are emitted from the surface of the Thohoyandou landfill and can be quantified.

iii. The ambient air quality around the Thohoyandou landfill area, significantly affects the health of the residents residing close to the landfill.

iv. A conceptual framework for zero-waste management strategy for Thulamela waste management can be developed.

1.6 Study Areas

The Thohoyandou landfill (Figure 1.1), situated within the Thulamela Municipality in the Limpopo Province of South Africa, is the primary waste management facility for the area. The Thohoyandou landfill is geographically situated at 22°57'50.3" S and 30°27'30.3" E and is strategically positioned within proximity to Thohoyandou town. Thohoyandou is the central urban center of Thulamela Municipality which serves as the administrative, economic, and cultural nucleus. This landfill's strategic location and its significant role in managing MSW makes it a central fixture in the region's waste disposal infrastructure. The Municipality is located approximately 180 km from Polokwane, and it serves as a gateway to the renowned Kruger National Park. Thulamela Municipality, with a population of approximately 584,257 people, is characterised by predominantly rural settlements (Ngobeni, 2019).

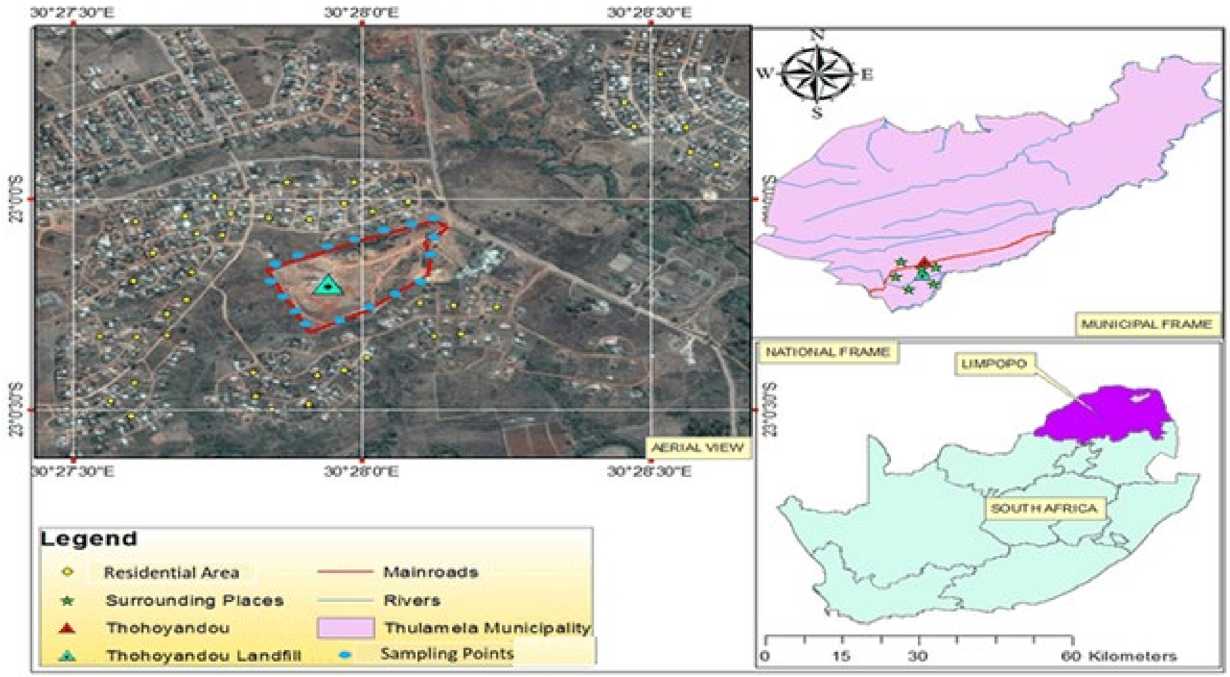

Figure 1.1: Study area map for Thohoyandou Landfill

The Thohoyandou landfill obtained its operational permit in 2004, granted by the then Minister of Water Affairs and Forestry. This permit authorised the landfill to exclusively receive general waste, excluding materials categorised as ‘hazardous waste’ according to the definition provided by the United Nations Development Programme (UNDP). Hazardous waste - any substance possessing physical, chemical, and toxic attributes capable of causing acute or chronic adverse effects on both human health and the environment - was strictly prohibited from deposition at the site. Presently, the Thohoyandou landfill functions as the primary disposal facility for a majority of the MSW generated within the Thulamela Municipality area. The landfill which comprises of approximately four distinct cells, with three closed and one currently operational, continues to receive waste.

Thohoyandou receives an annual rainfall of approximately 752 mm, with most of this precipitation occurring during mid-summer, from November to March. The Municipality's average annual temperature is 22.64ºC, representing a 1.42% increase as compared to the national averages in South Africa (Saexplorer, 2017). This information is significant for this study, as climate affects various aspects of landfill management and environmental matters. In the pursuit of continual landfill-management enhancements, there are plans to establish a weighing bridge to enable a precise measurement of the waste being deposited. Another crucial step in improving the landfill's environmental performance is the proposed installation of a LFG monitoring station. This station will serve the vital function of continuously monitoring both - sub-surface and surface - ambient air emissions of LFG. This comprehensive monitoring system will be instrumental in gauging the environmental impact of the landfill, particularly, in terms of gas emissions, as it presently lacks any LFG collection or flaring system. The introduction of a monitoring station will be a crucial initial step towards better understanding and managing LFG emissions, which have implications for both environmental quality and public health.

1.7 Research Design

To monitor the sub-surface LFG emissions, the study employed the government-approved GA 2000 landfill gas analyser. For the procedure, LFG samples were collected using a closed flux chamber methodology and subsequently transported to a laboratory for analysis through Gas Chromatography. The AERMOD model was utilised to access the ambient air quality surrounding the Thohoyandou landfill and TROPOMI satellite data was used to validate the results derived from the ARMOD model.

To develop an appropriate zero-waste model for the Thulamela Municipality, the Boras Model was employed, hence, this served as a benchmark for the of the framework. To gain insights into waste management of MSW in Thulamela Municipality, this study employed a qualitative approach, interviews were conducted with landfill personnel, landfill users, waste experts and researchers. After a comprehensive analysis of the collected data, a conceptual framework for zero-waste in Thulamela Municipality was developed. The methodological processes are visually represented in Figure 1.2 providing the flow in the conducting of the study.

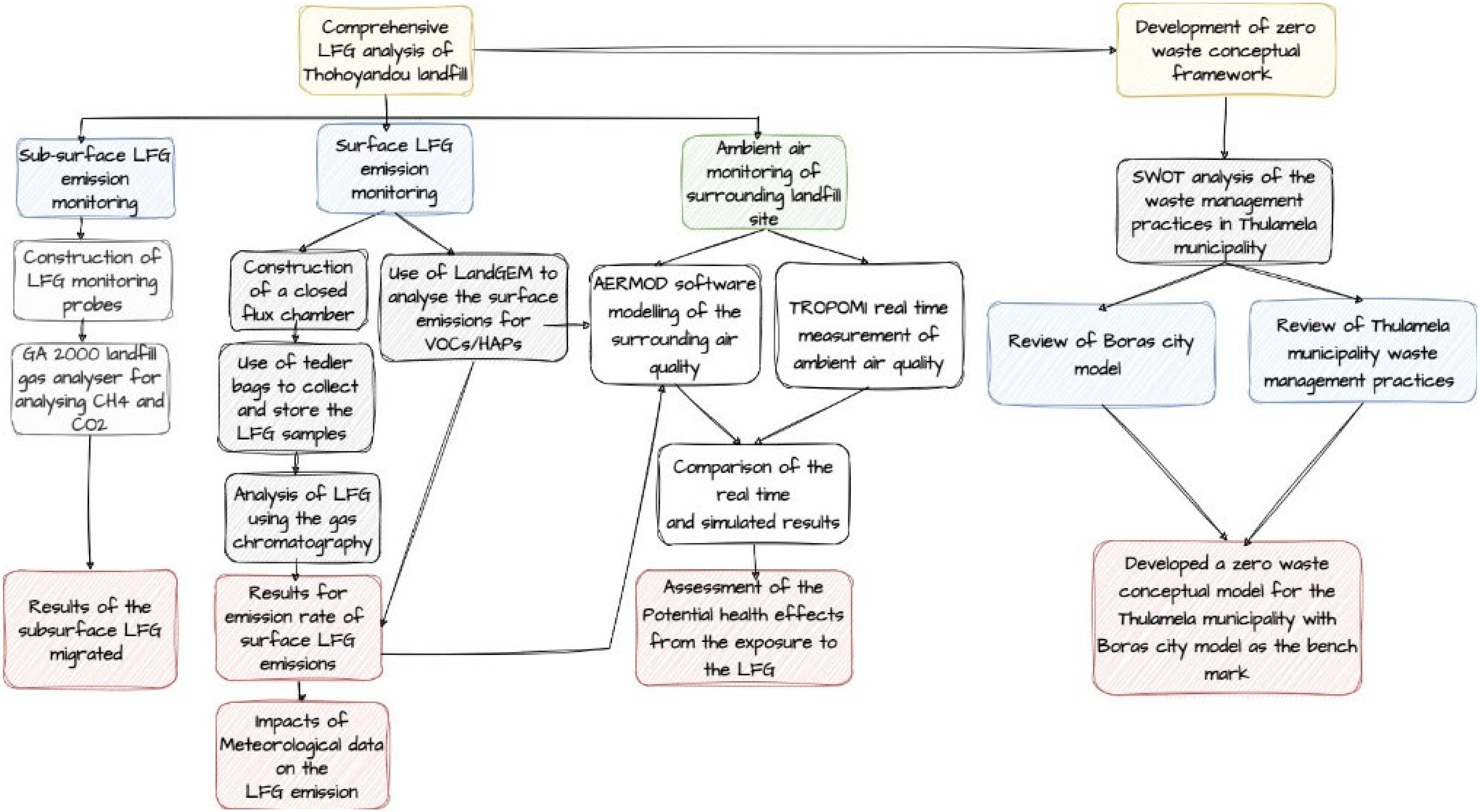

Figure 1.2: A design of the research process

1.8 Structure of the Thesis

This thesis is structured into eight chapters, each focusing on distinct but interrelated aspects of LFG emissions, management practices, and the development of a zero-waste management framework for Thulamela Municipality. The thesis was written in papers/articles format. The sequential flow of the research report is designed to provide a comprehensive understanding of the current state of landfill management in South Africa and propose a framework for sustainable waste management. The following chapters outline the thesis structure:

CHAPTER Two: Literature Review

This chapter presents a comprehensive review of relevant literature and previous research in the field of landfill gas emissions, waste management practices, and zero-waste initiatives. It lays the foundation for the subsequent chapters by identifying gaps in the existing literature and setting the context for the research.

Chapter Three: Monitoring of subsurface emissions and the influence of meteorological factors on LFG emissions: A case study of a South African landfill

This chapter focuses on the monitoring of sub-surface LFG emissions at a Thohoyandou landfill. It explores the impact of meteorological factors on LFG emissions, providing valuable insights into the dynamics of gas migration.

Chapter Four: Quantification of CH_4 and CO_2 surface emissions from a South African landfill

Building on the monitoring results from Chapter Three, this chapter quantifies methane and carbon dioxide surface emissions from a South African landfill. It offers a detailed analysis of the gases released and their environmental implications.

CHAPTER FIVE: Modelling and monitoring ambient air quality and assessing the health impacts of LFGs

Chapter Five employs modelling techniques, specifically the AERMOD approach, to assess the ambient air quality impacts of the landfill. This analytical chapter provides a comprehensive understanding of potential health effects from exposure to LFG emissions.

Chapter Six: SWOT analysis as a tool to analyse landfill management practices in South Africa

The SWOT analysis framework was used in Chapter Six to critically evaluate current waste landfill management practices in South Africa. It identifies the - strengths, weaknesses, opportunities, and threats - offering an in-depth assessment of the existing management landscape.

Chapter Seven: Developing a Conceptual Framework for an Integrated Solid Waste Management System (ISWMS)

This pivotal chapter takes the research a step further by proposing a conceptual framework for an Integrated Solid Waste Management System (ISWMS). It draws on the findings from previous chapters to present a blueprint for sustainable waste management.

Chapter Eight: Conclusion

In this concluding chapter, the research culminates by providing - a summary of the key findings, contributions to the literature in the field, and makes recommendations for future research. It connects the research back to the overarching goal of moving towards a zero-waste approach in landfill management.

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CHAPTER TWO: Literature Review

2.1 Solid Waste Management

Waste was once considered as any substance which has no value and must be discarded (Bhagwandin, 2013), however, this is no longer the case, especially in this time of numerous environmental challenges, which have evolved from waste generation. The understanding of waste in recent time, thus, has shown that waste substances have tremendous number of benefits and can be reused or recycled back into the environment. Currently, the generation of waste is a natural process, although an epidemic that plagues man and affects both health and environmental stability. The South African National Environmental Management Waste Act, defines waste as "any substance, whether or not that substance can be reduced, reused, recycled and recovered, that is surplus, unwanted, rejected, discarded, abandoned or disposed; where the generator has no further use of for the purposes of production, reprocessing or consumption; it must be treated or disposed of (Mammburu, 2020). Waste is a growing concern in the world and its management differ between developing and developed countries. Generally, developed nations manage their waste generated despite generating large amount of waste, however, in developing nations, like in cities of South Africa, although, lesser waste is produced, there is poor waste management. Several studies have shown that the increase in factors like, urbanisation, industrialisation and population growth, have been major contributors to waste generation over the past decades, yet these factors are also essential for the economic growth of a nation (Serge and Simatele, 2020; Rodseth, et al., 2020). If a nation desires to develop, incorporating environmental management systems into development plans, can, therefore, lead to sustainable growth with minimised waste generation.

The continuous generation of waste, urbanisation, industrialisation, decreasing landfill capacity, limited vacant land space, negative environmental and health impacts from waste and more, have led to government authorities and other relevant stakeholders to promote waste management (Bhagwandin, 2013). Efficient waste management practices entail its proper handling from the manufacturer to final consumers. It also involves the proper management of - waste trucks, waste bins, carrier bags and disposal facilities - in compliance with health codes and environmental regulations. There are eight dominant types of waste management techniques around the world. They include - incineration, usage of landfills, recycling, composting, fermentation, source reduction, reuse, and land application (Singh et al., 2014). Waste is categorised in different forms, however, this study focuses on general MSW that are deposited in landfills. These MSW in general includes - household waste, commercial waste, industrial waste, institutional waste, construction sites, agricultural activities, and waste from markets. These wastes are collected and disposed by the local municipality or authority. Waste hierarchy is a means used in the evaluation of processes that protect the environment, resources, health, and energy consumption, from waste generation outcomes (Figure 2.1).

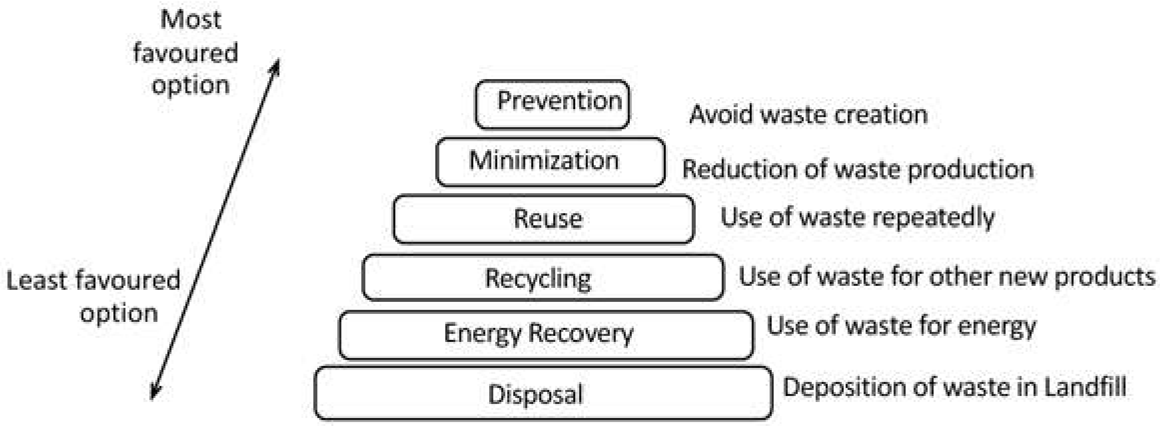


Figure 2.1: Waste management hierarchy (Njoku et al., 2018)

From Figure 2.1, waste prevention involves the avoidance, either by government regulations or laws, of the different types of waste generated. It also involves the sensitization of the public, on the advantages of low waste generation, for example, in schools and households; promoting the use of cleaner technology in the industrial sector, also prevents the production of gaseous emissions into the atmosphere. Waste prevention has the highest priority because, if waste is reduced to its barest minimum or no waste is generated, then there is no need for waste management and the mitigation of problems associated with waste. Nonetheless, in navigating the complexities of global industrialisation and the surge in population, it is crucial to acknowledge the inherent challenges associated with waste generation, hence, the conceptual framework that was developed in this study, envisions a path towards zero-waste, which maybe, ambitious yet a very necessary strategic roadmap.

Waste minimisation is the systematic method for reduction of sources of waste production; for instance, the reduction of volume of waste during manufacturing process such as reduction of materials during packaging of goods (Makgae, 2011). Reuse is the secondary use of waste material, for instance, using of water bottles for storage of other liquids in the home or the use of plastic grocery bags for storage purposes (Rakib et al., 2014). To recycle is the breaking down of used waste product, as raw materials for production of new product. Some types of recyclable materials include, paper, glass, food, and construction materials (Makgae, 2011). Waste-to-energy recovery is a typical example of recycling because it consists of the degradation of MSW to generate energy, in the form of electricity, heat, biofertilizer and transport fuels (Willumsen, 2001).

Figure 2.1 indicates disposal as the least-preferred option for waste management. This is associated with the end-product having an adverse effect on the environment and health of people. This process comprises of the dumping of MSW, for example, in landfills (Makgae, 2011).

The 3 Rs from the waste hierarchy - reduce, reuse and recover - have been strongly adhered to initiatives in the developed world. These processes have contributed enormously to the progress made in managing their waste (Yano and Sakai, 2016). Countries in Asia, like Japan, South Korea, Taiwan, and Singapore are fast-growing economies, and are also progressing in their solid waste management system, with the objective of finally eliminating landfills (Bhagwandin, 2013). These countries have initiated several strategies - legal support, effective solid waste monitoring, establishing facilities and technical training, carrying out various solid waste research projects and public sensitisation and awareness - in their attempts to address this challenge. These initiatives have been shown to be quite effective in sustainable solid waste management, over the years. In June 2001, Germany adopted an Act that prohibits the disposal of untreated organic-rich waste and adopted the 1986 Waste Avoidance and Management Act – where recycling was given preference over waste disposal. This Act and other organised strategies significantly reduced the number of landfill sites from 50,000 in 1970 to 160 in 2013 (Zhang et al., 2010). Sweden, in its combat with waste generation, implemented several key strategies and environmental policies which included - extended producers' responsibility, landfill bans, taxes, recycling targets, policies on waste packaging and minimisation by manufacturers as well as a ban on organic-waste landfill (Swedish E.P.A, 2005). With the effective implementation of these management strategies, some successes have been achieved by Sweden. In Sweden, for instance, less than 1% of household waste is deposited in landfills, demonstrating a highly effective waste management system (Miliute-Plepiene et al., 2018). The country had also exceeded its recycling targets for 2020, as evidenced by the recycling rates in 2016 - 93% of glass was recycled compared to the government's target of 70%; 47% of plastic was recycled against a target of 30%, and 82% of paper was recycled, surpassing the target of 65% (Swedish Waste Management, 2018). Additionally, Sweden has made significant progress in recovering materials and energy from household waste. As of 2004, approximately 1.3 million tonnes of materials and 5.7 TWh of energy in heat and electricity were recovered, and these figures have continued to increase (Swedish E.P.A, 2005). Notably, emissions from waste incineration have decreased despite a sharp rise in the quantity of waste being incinerated (Swedish Waste Management, 2018).

2.2 Laws governing South African solid waste management

South Africa's developmental gap presents an opportunity to learn from developed nations that have successfully managed their MSW. These countries have addressed challenges and used waste as a stable energy source. By learning from their experiences, South Africa can enhance its waste management practices and explore the benefits of converting MSW into sustainable energy and resource solutions. Godfrey and Oelofse (2017) in their study - *'Historical review of waste management and recycling in South Africa'* - identified various regulations and policies that have been proposed by the South African government on solid waste management, although, stakeholders have not been diligent in implementing these policies.

Godfrey and Oelofse (2017) narrate the evolution of the South African waste management sector over the past 30 years in four stages. The first stage is termed 'the age of landfilling', this was a period between 1989 to the 2000s when landfilling was predominant, worldwide, although, , it is still the predominant solid waste management technique in South Africa. The second stage, marked by a rise in recycling, began in 2001 with the initiation of the Polokwane Declaration, culminating in the prohibition of single-use plastic bags. Drafted by the Government of South Africa's Department of Environmental Affairs and Tourism, the Polokwane Declaration resulted from collaborative efforts between the government, civil society, and the business community during the National Waste Summit held in Polokwane from 26th to 28th September 2001. The meeting concluded on set targets for the reduction of waste generation and disposal by 50% and 25%, respectively, by 2012 and the development of a plan for zero-waste by 2022 (Langa, 2021). South

Africa has made strides in its recycling activities, however, there are still substantial potential for improvement. According to Department Environment, Forestry and Fishery (DEFF) in 2021, organic waste contributed to more than 50% of the total of general waste disposed of in landfills and has a relative recycling rate of 49%. South Africa recycles amounts of paper, plastic, glass, metal, and tyres, however, when compared to many other developed nations, the percentage is exceptionally low (Gumbi, 2015). In recent years, many developed countries are striving towards the goal of achieving zero-waste, although, some countries like Sweden have been able to make extremely high strides, towards the zero-waste phenomenon (Burlakovs et al., 2018).

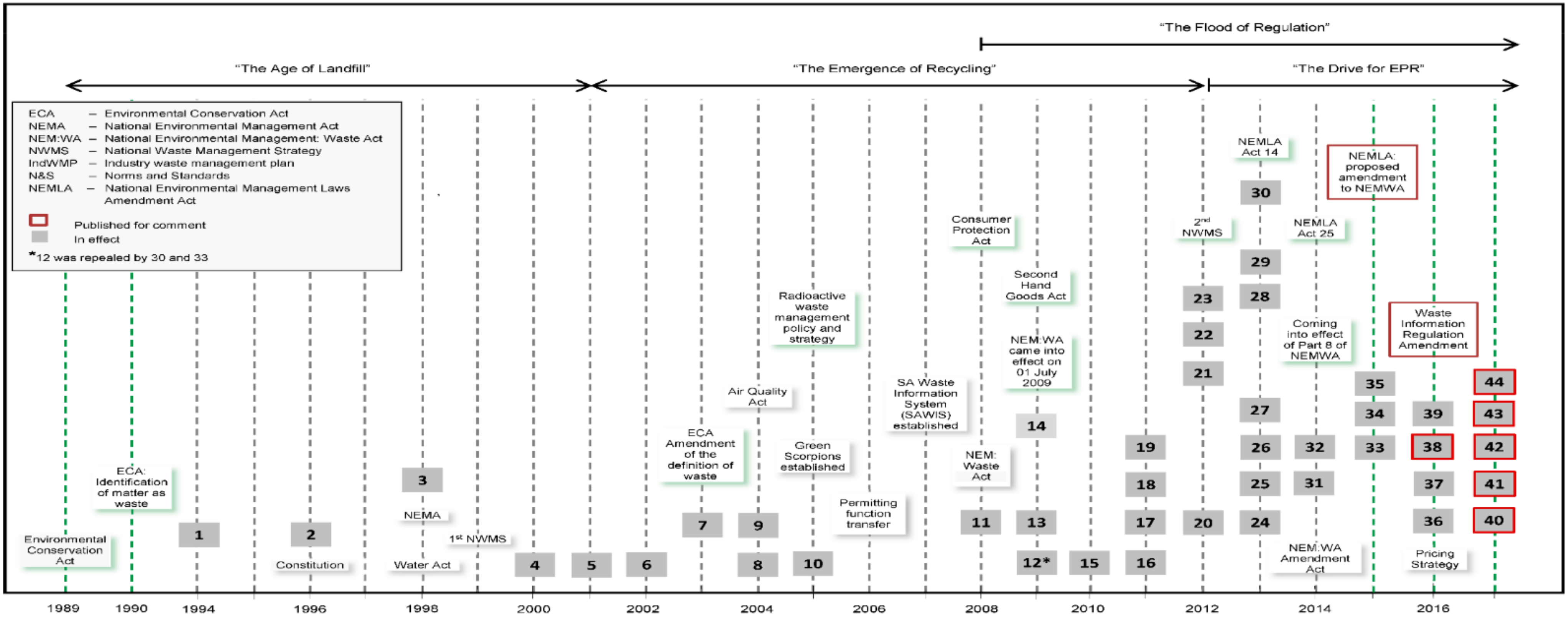
Zero-waste is a philosophy that necessitates a recoceptualisation of resources' life cycles so that all products are recycled, resulting in no waste being deposited in landfills and incinerators (Ayeleru et al., 2018); this process is similar to the way resources are reused in nature. In zero-waste, a material is used repeatedly, until the optimum level of consumption is reached, It strives towards the concept of a circular system so that no material is underused in the system. This is due to the fact, that the products are recycled, reused, sold, or dispersed again within the system until they reach the end of their useful lives. If reuse or repairs of materials is no longer possible, the material can be recycled, thereby, replacing the demand for the extraction of more natural resources. Several developed countries, like Sweden, Germany, and France, have opted for the ideology of zero-waste as their waste management strategy (Bolton and Rousta, 2019). For this study, the integrated waste management approach of Sweden is examined, so as to obtain a picture of the dynamics of the nation's success in implementing a zero-waste policy with less than 1% of their waste ending up in landfills. This Swedish model will be incorporated in the South Africa context to help develop a relevant model that will help municipalities achieve zero-waste, in years to come.

The process of separation at source involves dividing waste into groups or streams of waste that are comparable enough to be collected separately. This can be accomplished by using distinct bin services, curb-side collections, or by delivering wastes directly to drop-off locations. Any type of waste, including MSW, commercial and industrial waste, and waste from building and demolition, can be separated (Moh, 2017). The advantages of source separation include, providing waste streams that are - more homogeneous, have a higher value, enable improved resource recovery, minimise the contamination of waste streams, as well as supporting efforts to keep waste out of landfills.

Solid waste management is a critical issue that requires effective planning and implementation strategies to address its environmental and social impacts. In South Africa, like many other developing countries, the management of solid waste poses significant challenges due to rapid urbanisation, population growth, and inadequate infrastructure. As the population increases and urban areas expand, the generation of solid waste continues to rise, placing additional pressure on existing waste management systems (Nzediegwu and Chang, 2020). The management of solid waste in South Africa is governed by various policies, legislation, and regulations aimed at promoting sustainable waste management practices. The National Environmental Management: Waste Act (2008) provides the legal framework for waste management in the country, emphasising the principles of waste minimisation, recycling, and responsible disposal. Additionally, the National Waste Management Strategy of 2019 outlines the strategic objectives and targets for waste management in South Africa (Godfrey and Oelofse, 2017).

South Africa still faces numerous challenges in effectively managing solid waste, despite the existence of these policies and regulations. One of the key challenges is the inadequate collection and disposal infrastructure, particularly in rural and peri-urban areas. Many municipalities struggle to provide regular waste collection services, resulting in the accumulation of waste in unauthorised dumping sites or the burning of waste, which contributes to environmental pollution and health risks. Another challenge is the limited capacity for waste recycling and resource recovery. While there are efforts to promote recycling and the establishment of recycling facilities, the overall recycling rate in South Africa remains low, at about 10%. This is partly due to the lack of infrastructure, technology, and public awareness about the importance of recycling (Jessa and Uys, 2019). Furthermore, the issue of landfill management poses significant environmental and health risks. Improper landfill practices, such as inadequate lining and leachate management, can lead to the contamination of soil, groundwater, and surface water bodies. Methane emissions from landfills also contribute to climate change, highlighting the need for better waste management practices to reduce greenhouse gas emissions (Mbazima et al., 2022). To address these challenges, there is a growing recognition of the need for an integrated and sustainable approach to solid waste management in South Africa.

In the area of ISWMS, numerous waste reduction techniques have been tried in most cities and nations and the secret to the effectiveness of such management strategy is, typically source separation, which simply means separating the waste from the source or where it was generated. Source separation has been discovered to be a successful method of lowering waste, improving recycling, and ultimately improving waste management (Moh, 2017). A summary of the waste management policies is shown in Figure 2.2 (Godfrey and Oelofse, 2017).



1	Minimum Requirements Edition 1	10	Glass Memorandum of Agreement	19	Domestic Waste Collection Standards	28	Norms & Standards: Assessment of waste for landfill Disposal	37	Notice: Intention to require waste transporters to register on SAWIS
2	Green Paper Environmental Policy	11	Asbestos Regulation	20	Municipal Solid Waste Tariff Strategy	29	Amendment to Plastic Bag Levy	38	Dangerous Goods Standards
3	Minimum Requirements Edition 2	12	List of Waste Management Activities, 2009	21	Redisa Tyre IndWMP	30	List of Waste Management Activities Regulation, 2013	39	Notice: Intention to call for P&P, WEEE and Lighting IndWMPs
4	White Paper Integrated Pollution and Waste Management	13	Waste Tyre Regulations	22	Waste Information Regulations	31	Norms & Standards: Remediation of Contaminated Land	40	Amendment list of waste management activities
5	Polokwane Declaration	14	Policy Thermal Treatment	23	Municipal Waste Sector Plan	32	Fee Structure for Consideration and Processing of Applications for Waste Management Licenses	41	Norms & Standards: Sorting shredding, grinding, crushing, screening or bailing of general waste
6	Plastic Memorandum of Agreement and regulation	15	Policy Economic Instruments	24	Norms & Standards: Extraction and Flaring of Landfill Gas	33	List of Waste Management Activities Regulation, 2015	42	Notice: Tyre industry to prepare and submit IndWMP
7	Plastic Carrier bags and flat bag regulations	16	Amendment to Plastic Bag Levy	25	Norms & Standards: Scrapping of motor vehicles	34	Admission Of Guilt Fine Regulations, 2015	43	Consultation on intention to consider withdrawal of REDISA Tyre Plan
8	Gauteng Waste Regulations	17	Model Waste By-Law	26	Norms & Standards: Storage of waste	35	Residue Stockpiles And Residue Deposits Regulations	44	Proposed regulations to exclude waste streams from definition
9	National Waste Management Strategy Implementation	18	Refuse Removal Services: Indigent Households	27	Waste Classification and Management Regulations	36	Waste Tyre Regulations Amendment		

Figure 2.2: Waste policy and regulation in South African context from the year 1989 to 2017 (Godfrey and Oelofse, 2017)

2.3 Solid waste management system/framework for zero-waste

The concept of achieving zero-waste to landfills has gathered considerable attention in recent years as a strategy for minimising the environmental consequences of poor waste management practices. This approach of zero-waste to landfill entails redirecting all waste away from landfills through a combination of waste reduction, reuse, recycling, and material recovery (Nizar et al., 2018). Developing a conceptual framework for achieving zero-waste to landfill necessitates a comprehensive understanding of waste management, encompassing its environmental, social, and economic impacts, as well as the policies and practices essential for attaining zero-waste. Numerous studies have put forth conceptual frameworks for zero-waste to landfill (Kaza et al., 2018; Ahmed et al., 2023; Sundana et al., 2021; Borgaonkar et al., 2022). Kaza et al. (2018), for instance, devised a framework for implementing zero-waste in cities, encompassing strategies for waste reduction, collection, and processing, along with stakeholder engagement and policy development. Their framework explains the imperative need for collaboration among various stakeholders, including government entities, industries, and community members, to realise zero-waste goals. Other studies have concentrated on specific policies and practices that contribute to achieving zero-waste to landfill (Zaman, 2015; Zotos et al., 2009). In contrast, this current study is distinct in its focus on developing a comprehensive zero-waste framework specifically tailored to rural areas in South Africa. This focus acknowledges the unique challenges and dynamics of waste management in rural settings, which may differ, significantly from urban environments.

Over the years, South Africa's solid waste management system was all about waste collection and disposal, however, due to the overwhelming impacts of waste disposal and landfilling, the country is shifting its focus and considering other solid waste management options, like recycling and waste minimisation (Bhagwandin, 2013). South Africa's municipalities have put in place several policies to improve solid waste management, but - the lack of finances, increase in population, urbanisation, industrialisation, insufficient waste collection systems in urban informal and rural areas, lack of recycling facilities which promotes separation at source, illegal dumping and unlicensed disposal facilities, poor skills' development, limited MSW policies and poor enforcement of already existing policies - have been shown to have hindered any progress in solid waste management (Bhailall, 2015; Guerrero et al., 2013). Due to the reforms of the solid waste sector in South Africa, the Department of Environmental Affairs (DEA) developed the South

African Waste Information System (SAWIS). This contains data about the different amounts of tonnage of waste disposed in South African landfill sites. A study conducted by DEA (2012) showed that South Africa generated 59 million tonnes of general solid waste in 2011; the results showed that, 55% of this waste comprised of general waste (metal waste 13%, organic waste 13%, non-recyclable municipal waste 35%, (tyres 1%, construction and demolition waste 20%, paper 5%, plastic 6% and glass 4%); in addition, 44% was unclassified waste and 1% was of hazardous waste. Figure 2.3 shows the result obtained from the study (Bhailall, 2015).

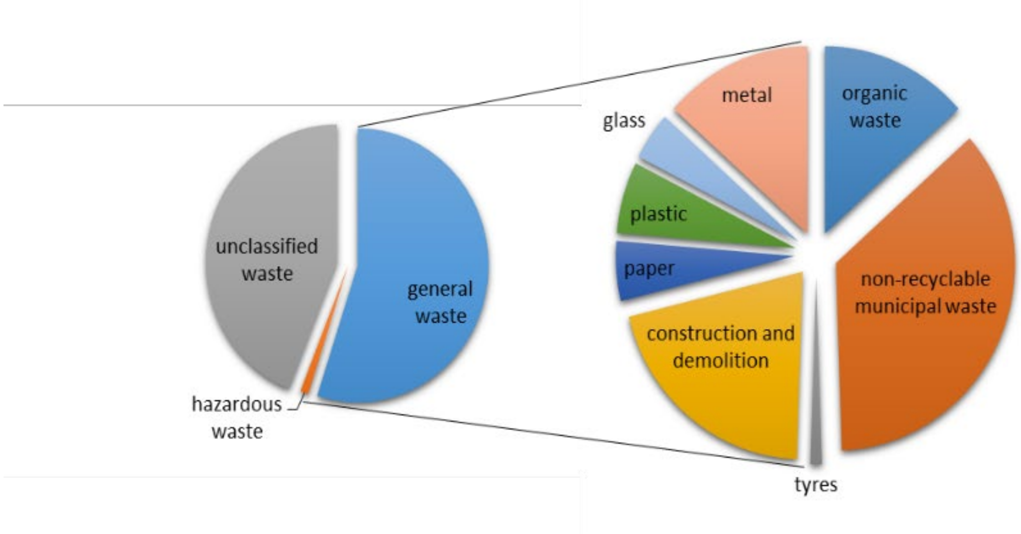


Figure 2.3: Waste profile for South Africa in 2011 (Bhailall, 2015).

2.3.1 The Swedish Boras Model

The Swedish city of Boras stands out as one of the pioneering urban centers to adopt a sustainable waste management system. In the period leading up to 1980, over 90% of the city's waste found its way to landfills. Recognising the environmental concerns, a pivotal moment occurred in 1986, triggering an investigation into the development of an integrated waste management system, which was later implemented. The city took a substantial step by formulating its inaugural waste management plan in 1987, with a central objective of diminishing the volume of waste sent to landfills. This strategic approach involved enhancements in biological and thermal waste treatment facilities, as well as introducing waste separation at the source (Rajendran et al., 2013).

At present, household waste in Boras City undergoes segregation into 30 distinct categories, each of which is either recycled or utilised for energy, fuel, or heat generation. The result is a very significant reduction in waste, with virtually zero-waste ending up in landfills, a remarkable achievement attributed significantly to the active participation of the citizens. Education played a pivotal role, with children learning waste management and sorting techniques in schools, and Furthermore, regular sports and social events were organised to raise awareness among the adult population. The success of Boras' waste management system can be attributed to several key factors, including - active citizen involvement, informed decision-makers, ongoing research and development, and the inclusion of children through educational initiatives. An illustrative example of waste management policy, in Boras, was the implementation of a rate system, where citizens were encouraged, through taxes to increase their rate of waste sorting and face higher taxes when they decrease it. The University of Boras contributes to this initiative through an extensive research program aimed at transforming waste into new, valuable products (Bolton and Rousta, 2019).

In Boras, to facilitate proper waste management, the Municipality provides household with informative pamphlets offering guidance on handling several types of waste. These pamphlets list approximately 130 dissimilar materials, helping residents understand the appropriate disposal methods for each. For instance, coloured and white glass bottles are clearly distinguished in the sorting process, as are fluorescent, halogen, LED bulbs, and other energy-saving lamps. Walking paths in the city are equipped with recycling bins placed at convenient distances from every home, making it easy and convenient for residents to separate and dispose of different materials. These separated materials are then delivered to factories for further processing. In addition to this, each family receives both white and black bags from the Municipality. Black bags are designated for compostable garbage, while white bags are used for other non-compostable waste (Rajendran et al., 2013). The biological treatment procedures generate biogas from the black bags and other organic materials, amounting to over 3,000,000 m^3 of biogas annually. This biogas serves as a sufficient energy source to fuel buses, garbage trucks, and around 300 CNG cars in the city, as well as producing 960 MWh and electricity daily. Two combustion plants, each with a 20 MW capacity, handle industrial waste, including white bags. The comprehensive waste management system in Boras is a model of efficiency and sustainability, driven by a combination of informed citizens, innovative policies, and advanced technologies (Rousta, 2008).

2.3.2 Summary of the Boras model for solid waste management

The different phases of the Boras model and how these were achieved the are shown in Figure 2.4.

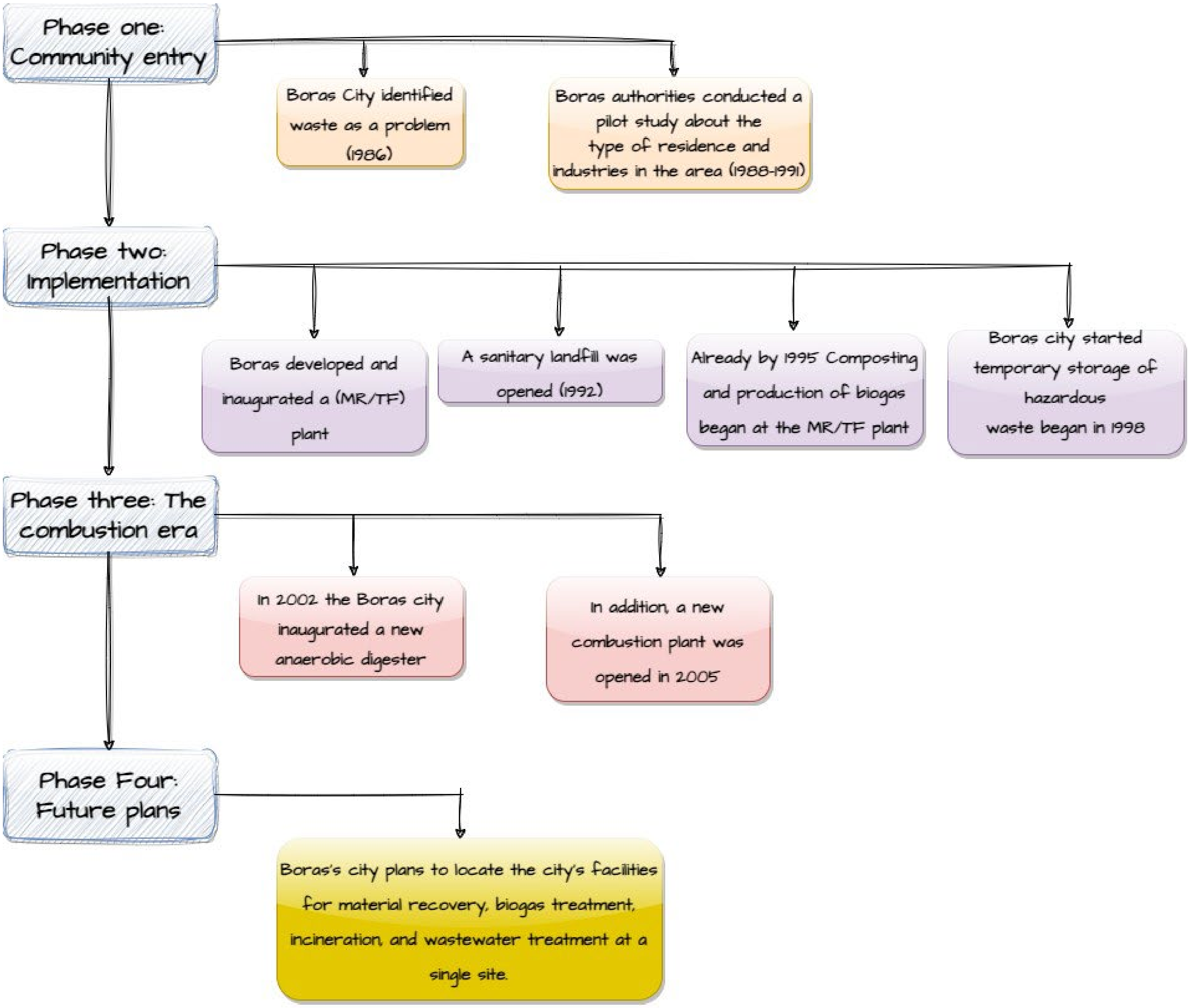


Figure 2.4: Self-made framework of the Boras model for solid waste management from 1975 - 2016

Phase One: Community Entry

- Boras City identified waste as a major challenge

The city of Boras was the pioneer in the implementation of a sustainable waste management system in Sweden. This medium-sized Swedish city has approximately 110,000 residents. By 1980, more than 90% of the city's MSW was managed through landfills and this was acknowledged as a problem by various Swedish stakeholders and the government. In the same year an investigation into the implementation of an Integrated Waste Management System was started (IWMS) and in 1987, the city created its first waste management strategy, with the minimisation of waste been deposited in landfills as its main objective. The strategy involved adding or improving biological and thermal waste treatment facilities, as well as waste separation at the source.

- The Boras authorities conducted a pilot study about the type of residences and industries in the area (1988-1991)

In the bid to develop a solid waste management plan, the city's second waste management plan was established for the period 1991- 2000. To understand the practical details of issues surrounding waste separation fractions at source, the Boras city conducted research involving households among other relevant stakeholders in the city. In 1988, a 3000-household pilot study was launched and over the next three years, face-to-face communication was employed to explain the waste sorting strategy to these households.

Phase two: Implementation stage

- Boras city developed and inaugurated a MR/TF plant

In 1991, the MR/TF launched its first project dubbed "Sobacken," which was later turned into a full-scale optical sorting system, within 4 years. With Sobacken, all waste management processes, including - sorting, separation, composting, biogas production, and landfilling - were all conducted to treat the wastes, which were mostly generated by residential activities and light industrial operations.

- A sanitary landfill was opened (1992)

A sanitary landfill was then established in 1992 as this was thought to be unavoidable.

- In 1995, composting and production of biogas began at the MR/TF plant

At the plant, composting and the manufacture of biogas started, and temporal storage of hazardous waste started in 1998.

- Boras city started a temporal storage of hazardous waste

Phase three: The combustion era

- In 2002 Boras city inaugurated an anaerobic digester

At this phase, there was a strong emphasis on the necessity of reducing waste generation and landfill waste. An anaerobic digester was launched in 2002 which made it possible to convert biogas into automobile gasoline.

- In addition, a new combustion plant was opened in 2005.

A new combustion facility was also inaugurated in 2005, enabling the city to receive both heat and electricity from the combined heat and power plant (CHP).

Phase four: Future plans

- Boras's city plans to locate the city's facilities for material recovery, biogas treatment, incineration, and wastewater treatment at a single site.

The phase four waste management strategy for the city was from 2012 - 2020 and the goal was to improve on the city's waste management system. At that time, the city's motto was - "A city free from fossil fuels," and currently all municipal buses are powered by biogas made from waste. The plan's next stage was to consolidate the city's facilities for wastewater treatment, incineration, biogas treatment, and material recovery at one location, with the goal of increasing the integrated waste management system's effectiveness.

The amount of MSW that is dumped in landfills in Boras has decreased from 100,000 tons in 1990 to less than 200 tons in 2010. This was achieved even though the total waste increased during this period as Sweden also buys and collects waste from other neighbouring countries (Figure 2.5).

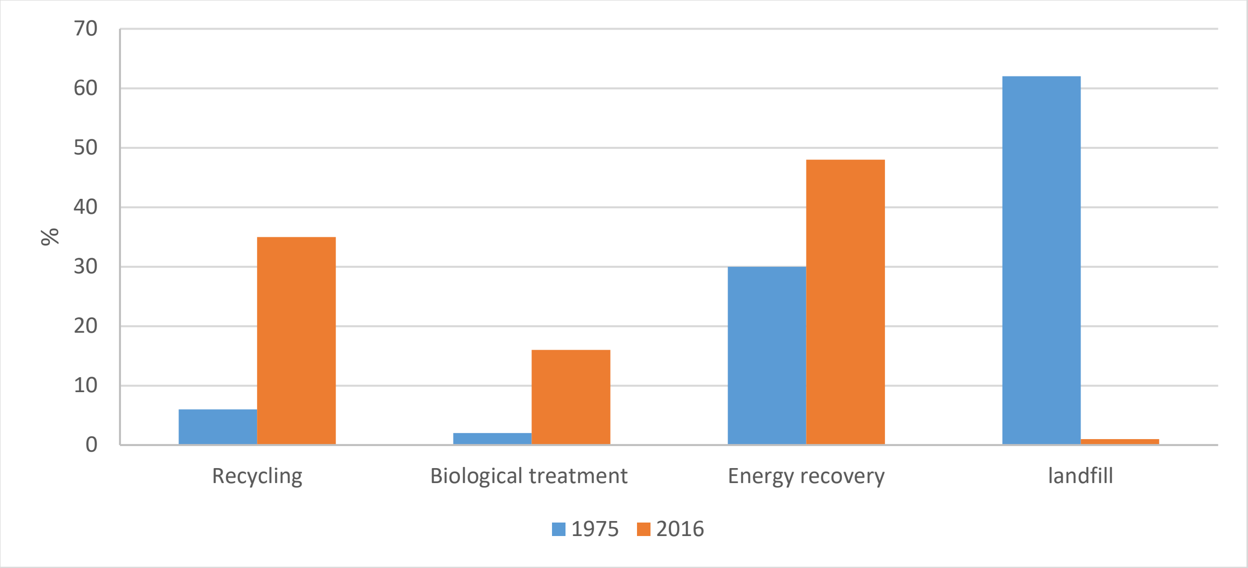


Figure 2.5: Amount of municipal waste that was treated using different methods in 1975 and 2016.

2.4 Landfill

Landfill is the most used waste management technique in the world, especially, in South Africa as stated earlier; landfilling is the continuous burial of waste on land. The world has evolved from just the burial of waste in ground to a controlled method of waste disposal, called 'sanitary landfills'. Sanitary landfill was first engineered in the United Kingdom in 1912 and since then the technology has spread around the world; it is an engineered method of disposing of waste (Ghosh and Hasan, 2010).

The classification of landfills is based on their sizes, water capacity and ability to produce leachate. The size of a landfill depends on the amount of waste deposited in it, which in turn, is dependent on the population size and the area the landfill will serve. The maximum rate of deposition (MRD) of waste in a landfill is calculated using Equation 2.1.

$$MRD = IRD\ (1 + D)^t \qquad \text{Equation 2.1}$$

where MRD = maximum rate of deposition (tonnes day^{-1}); IRD = initial rate of deposition (tonnes day^{-1}); D = expected annual development rate of landfill, which is dependent on the population increase rate with respect to the time / opening year of the landfill. Landfill sizes are further classified into four distinct categories as shown in Table 2.1.

Table 2.1: the classification of landfill site

Landfill size category	MRD (tonnes day^{-1})
Commercial (C)	< 25
Small (S)	25 – 150
Medium (M)	150 – 500
Large (L)	> 500

2.4.1 Landfill Management Practices

Early landfills in South Africa started out as unlicensed dump sites, which were not carefully nor appropriately designed. These sites had no provision for factors like landfill liners, gas collection and recovery systems. These shortcomings made landfills, over the past an unhealthy hole, home to various pollutants. As scholars continued doing more research on landfills, it was realised that landfills must be designed structurally within engineered systems (Godfrey and Oelofse, 2017). The new waste classification and management regulations which came into effect in 2013, made it compulsory for landfill operators to adhere strictly to these regulations. This was to ensure that the structural design of landfill sites improved their performance, in line with recognized authorities. Most registered landfills in South Africa are managed by the local municipalities and in the case of Thohoyandou landfill, the Thulamela Municipality handles and manages its affairs and operations.

The daily operation of a landfill in Thulamela Municipality entails, the MSW is collected by the municipal trucks from households and institutions to the landfill. On reaching the landfill site, the municipal trucks are expected to be weighed, however, due to non-availability of a weighing bridge, the amount of waste from each truck is estimated. The landfill operator inspects the solid waste to check for any inappropriate waste according to the codes governing landfills, and any inappropriate waste is separated from the rest. The landfill trucks then offload the remaining solid waste into the appropriate landfill and immediately a bulldozer compacts and spreads the waste to prevent the wind scattering the waste about and odour (Carey et al., 2000). Meanwhile, the landfill truck is reweighed (if a weighing bridge is available) to estimate the amount of waste carried by the truck; landfill operators record and keep this data. At the end of the day, a landfill bulldozer compacts and spreads soil or other cover materials over the solid waste to about 6 inches thick.

This process helps to prevent any further MSW's contact with the ambient air, thus reducing incidences of rodent infestation, birds, flies, and odour emitting from the landfill; water trucks spray water into the atmosphere to reduce dust. In the meantime, authorised scavengers or recycling companies come and search for recyclable materials. Finally, a landfill supervisor inspects the day's operations and certifies them. This final stage often helps in identifying any loopholes that might have occurred during the day (Carey et al., 2000).

When a MSW is deposited in a landfill, its physical, chemical, and biological compositions are transformed during the degradation of the waste. These changes occur simultaneously to form an MSW decomposition pattern. The physical change during the decomposition of MSW involves changes in weight, porosity, and compatibility. The chemical change entails the dissolution of materials from the waste to leachate, involving changes in the energy potential and nutrient availability in the landfill, while the biological change involves changes in the sugar, fats, and protein properties of the MSW deposited. The changes from the biological process are more significant in relation to LFG production than the physical and chemical changes (Slezak, et al., 2015). In the degradation of MSW, the production of LFG undergoes five phases; Figure 2.6 shows the summary of these five stages. Every stage has an impact on the quality and rate of LFG production; Table 2.2 shows in percentages the different LFG components from a typical landfill.

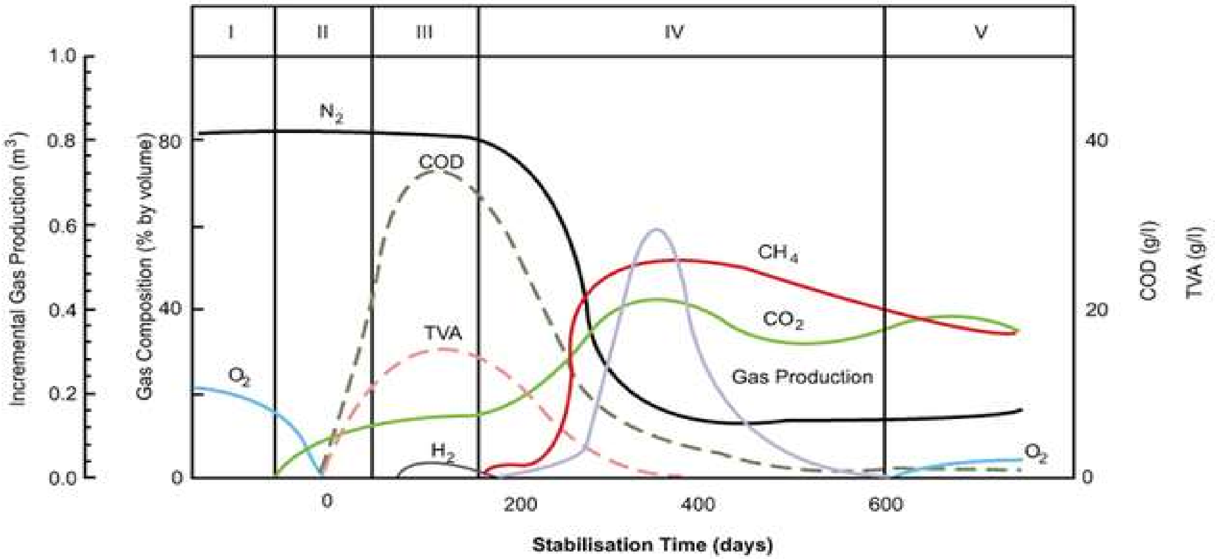


Figure 2.6: Summary of LFG generation over time (ATSDR, 2001)

Table 2.2 Typical LFG components

Component	**Percent (%) by Volume**	**Characteristics**	**Effects**
Methane	45–60	Methane is a naturally occurring gas. It is colourless and odourless. Largest LFG emitted from landfill, it is GHG, highly flammable.	Global warming, major cause of landfill fire
Carbon dioxide	40–60	Carbon dioxide is colourless, odourless, and slightly acidic. It exists in the earth's atmosphere at a concentration of 0.04 (400ppm) percent by volume It is a GHG.	Global warming, major source of ocean acidity
Nitrogen	2–5	Nitrogen comprises approximately 79% of the atmosphere. It is odourless, tasteless, and colourless.	Oxides of Nitrogen (NO_x) are toxic gases, source of smog and acid rain, respiratory problems, lung damage. Nitrites and nitrates can cause cancer and thyroid problems.
Oxygen	0.1–1	Oxygen comprises approximately 21% of the atmosphere. It is odourless, tasteless, and colourless.	Iron rusting supports combustion in landfill fires, excess oxygen at partial pressure can lead to severe health problem like cells damage, brain damage.
Ammonia	0.1–1	Ammonia is a colourless gas with a pungent odour. It is a corrosive gas, and highly irritating	Burning in the nose, throat and respiratory tract, coughing, skin and eye irritation. Pungent and suffocating odour. Eutrophication, and soil acidification.
NMOCs (non-methane organic compounds)	0.01–0.6	NMOCs are organic compounds (i.e., compounds that contain carbon). (Methane is an organic compound but is not considered a NMOC.) NMOCs may occur naturally or be formed by synthetic chemical processes. NMOCs most found in landfills include acrylonitrile, benzene, 1,1-dichloroethane, 1,2-cis trichloroethylene, dichloromethane, carbonyl sulfide, ethylbenzene, hexane, methyl ethyl ketone, tetrachloroethylene, toluene, trichloroethylene, vinyl chloride, and xylenes.	Carcinogenic, leukemia, headaches, nausea. Some of the gases are highly flammable, and have pungent odour
Sulfides	0–1	Sulfides (e.g., hydrogen sulfide, dimethyl sulfide, mercaptans) are naturally occurring gases that give the landfill gas mixture its rotten-egg smell. Sulfides can cause unpleasant odour even at very low concentrations.	Irritation to the eye, nose, and throat, causing breathing difficulty, poor memory, tiredness. It has a pungent odour,
Hydrogen	0–0.2	Hydrogen is an odourless, colourless, tasteless, highly combustible, light gas.	Supports burning in landfill fires.
Carbon monoxide	0–0.2	Carbon monoxide is an odourless, colourless gas.	Reduces oxygen circulation in the body, causes vision problems, reduced manual dexterity and even death; also formation of smog

Source: USEPA, (2022)

2.4.2 LFG generation and migration

The production of LFG is influenced by distinct factors such as - waste composition, moisture content, temperature, oxygen, and the age of the refuse (ATSDR, 2001).

Composition and type of organic waste – MSW composition is dependent on the type generated from the community. The composition and total amount of MSW deposited in a landfill is a critical characteristic in the determination of LFG generation. The DOC or carbon content in the MSW is very essential because carbon is a major element needed to achieve optimum microbial activities. The higher the composition of organic waste present in the landfill, the more LFG is generated. According to the IPCC model, the composition of waste in a MSW includes food, garden waste, paper, wood, textile, nappies, domestic and plastic wastes. A study has shown that domestic waste, contains lower amount of halogenated hydrocarbon concentration than industrial or company disposal waste (Parker et al., 2002). Organic waste contains certain nutrients, like sodium, potassium, calcium, magnesium, which serve as enhancers for bacterial activities and help in the degradation process, hence, an increase in organic waste, in a landfill contributes to faster degradation of the waste and LFG emission. Some wastes, however, are composed of compounds that impede bacterial growth and are harmful to the bacteria, such as compounds with high salts concentrations which impede methane – producing bacterial activities (ATSDR, 2001).

Moisture content – Rainfall, ground and surface water infiltration and degradation of MSW help maintain a level of moisture content in the site. The increase in moisture provide nutrients for microbial growth and supports the reproduction of bacteria, which will increase the production rate of LFG (Global Methane Initiative, 2012). The amount of moisture content in the landfill is especially, important since the entire process of LFG generation is done in an aqueous state, although, there is a limit to the required amount of moisture content in a landfill. Trace LFGs, like ammonia in the landfill, are highly soluble, however, if the moisture content increases it dissolves ammonia in the waste and reduces the amount of ammonia gas generated (Parker et al., 2002). Lays et al. (1997) found that reduced moisture content reduces methanogenic activities (methane formation) in organic waste. They also discovered that the reduction of moisture content from 96% - 90% saw a reduction in methanogenic activity from 100% to 53% at a neutral pH. A study conducted on a tropical landfill in Thailand (Chiemchaisri et al., 2007), on solid wastes' physical and chemical characteristics and CH_4 emission rates, used a static gas chamber to measure the CH_4 emission rates from the landfills. The study showed that the solid waste comprised of mostly plastic and foam waste (24.05 %), food waste (16.8 %), paper waste (13.3 %) and other components that makes up the remaining percentage. The landfill experienced a rise in density as the depth of landfill increased. Due to the reduced volatile solid content in the waste, most biodegradable processes in landfills take place at the bottom of the landfill. This study in Thailand showed that the average emission rate of CH_4 was approximately 23.95 $g^{-2}day^{-1}$ in the dry season and 1.17 $g^{-2}day^{-1}$ during the wet season (Chiemchaisri et al., 2007). These results, however, disagree with those of Yao et al. (2006), that showed that its experimental site experienced higher CH_4 emission rate during wet season when compared to the dry season. Chiemchaisri et al. (2007), however, identified issues of cracks in the landfill which enhanced CH_4 emission rate during the dry season. Scholars have identified higher CH_4 emission rate during the wet season as compared to the dry season (Lays et al., 1997; Park and Shin, 2001), as moisture enhances methanogenic activities in a landfill. Chiemchaisri et al. (2007) further ascertained the level of moisture content in the landfill, for if it exceeds 15 % - 20 % this may impede LFG generation in the landfill, because of the high amount of rainfall received in tropical regions of the world.

Oxygen in the landfill – the presence of oxygen in landfills aids aerobic bacteria in waste decomposition. It increases the degradation process, rate of waste decomposition and settlement, but decreases the production of CH_4 and supports CO_2 formation. When a landfill is closed, there is blockage of oxygen into the landfill, therefore, this brings about a reduction of oxygen and increases the amount of moisture content. The presence of anaerobic bacteria also emerges in the landfill, which helps in CH_4 production, a process which is dependent on the lack of oxygen in the landfill (ATSDR, 2001). Anaerobic process, due to absence of oxygen, in landfill, - promotes slow stabilisation of waste; stimulates the formation CH_4; and enhances the formation of Non-Metallic Organic Compounds (NMOC), through chemical or volatilisation reaction (Themelis and Ulloa, 2007). The capping of landfill, however, reduces LFG production due to the decrease in oxygen diffusion, thereby, reducing composting rates, although, the absence of oxygen and low redox potentials are used in the formation of methanogenic bacterial and CH_4 formation.

Landfill Temperature and Density – Change in temperature has great effects on LFG generation. Warm temperatures (15°C - 45°C) encourage bacterial activity which increases LFG generation.

A stable temperature is experienced when the landfill is capped for about 25°C and 45°C which are temperatures commonly found in deep landfills, however, shallow landfills easily affect the LFG generation by seasonal temperature variations. An increase in temperature improves volatilisation and chemical reactions (ATSDR, 2001). Lanini et al. (2001), conducted research to investigate the role and effects of temperature rise in a landfill. The laboratory experiment showed that high thermal temperature at 70°C could be reached if there is a free flow of oxygen in the landfill, therefore, a landfill should be closed properly after dumping of waste to avoid high temperature. Temperature, however, should not exceed certain limits to avoid landfill fire; a temperature range of 15°C - 45°C in the landfill is most conducive for LFG production (Lanini et al., 2001). Increase in density of MSW increases the generation of LFG per unit volume of void space. The high density of MSW reduces its permeability which results in an increase in LFG pressure.

Age of waste deposited – Newly-deposited MSW will generate more LFG than older ones, because the former is still fresh in organic content and the degradation process of the MSW is just beginning. Landfill emissions reach their peak at the closure of a landfill because of the non-continuous deposition of solid waste in the landfill, however, as much as 20 years down the line, the landfill will continue to experience LFG emission; some landfills experience emission of LFG for 50 years or more after closure (ATSDR, 2001). Also, high waste-input rates will enable more rapid progress of the anaerobic process, where most LFG is produced.

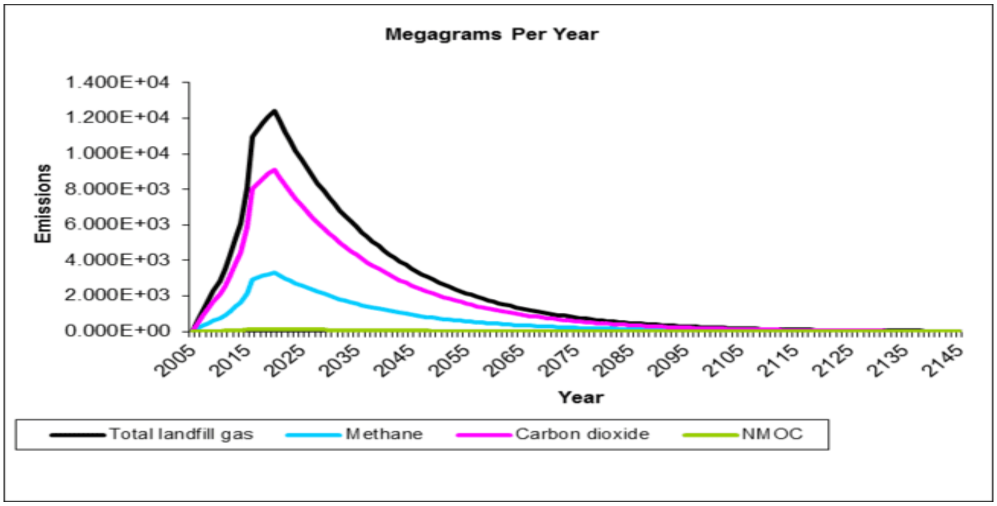


Figure 2.7: LFG generation from a landfill over time (Njoku et al., 2018).

The development and increase in - pressure, concentration and temperature gradient - within a landfill will result in the emission of gases into the atmosphere and in lateral migration through the surrounding soil. The pressure and composition of the LFG varies from time to time within the landfill. The CH_4 and CO_2 emissions lead to an increase in pressure and corresponding partial pressures. These changes then develop pressure gradients, thereby, leading to gas advection and concentration gradients which lead to gas diffusion. The production of heat within the landfill also affects the migration of gas because of its effects on the thermodynamics on fluids (Franzidis et al., 2008). LFG migrates either vertically to the atmosphere or laterally through the soil and extents across the boundaries of the landfill into the surrounding geological formations (Kim et al., 2010). There are different strategies which exist for the prevention of LFG migration, such as, the installation of gas recovery wells and trenches around the landfill, with a network of monitoring wells. The flow rates or pressures at these recovery wells are selected to inhibit LFG migration to the atmosphere and beyond the lateral landfill boundaries. Also, the gas extraction system should be used to minimise the introduction of atmospheric oxygen into the landfill, which is harmful to the anaerobic bacteria responsible for producing CH_4 and ensuring anaerobic stabilisation of organic waste. During the completion of a landfill, the waste is commonly covered with low permeable capping system; this inhibits the amount of infiltration of water and minimise leachate production. Also, the landfill cover hinders LFG emissions into the atmosphere, however, the lateral migration of LFG beyond the boundaries of the landfill will be enhanced if not monitored and treated properly.

2.5 LFG Monitoring

Landfill gas monitoring, that is the process of tracking gases emitted from landfill sites, gained prominence following a pivotal event in March 1986 near Loscoe, Derbyshire, UK. A residential property was destroyed by an explosion caused by accumulated methane gas from a landfill site, prompting a re-evaluation of waste sector regulations. The incident highlighted the urgency of LFG monitoring to prevent potential dangers associated with uncontrolled gas migration (Fearon and Jowsey, 2014). In the aftermath of the Loscoe disaster, investigations revealed the need for enhanced monitoring practices as regulatory authorities recognised the hazards of vast CH_4 production from landfills' organic matter. Subsequent regulatory updates mandated venting and flaring of landfill sites capable of producing methane, along with the implementation of liners to prevent hazardous material seepage. Landfill waste, as observed in later studies, can produce significant volumes of gas.

While incidents like the Loscoe explosion highlighted how imperative it is for LFG monitoring, however, it is also crucial to note that monitoring data alone may not fully reflect individual exposure to contamination. A comprehensive understanding of the outcomes of monitoring practices and their effectiveness in mitigating potential risks, therefore, should be a focus in future research.

Available data provide valuable insights into general air quality, landfill gas (LFG) migration, and potential health risks. Monitoring the gases emitted by landfills is typically divided into five categories: soil gas monitoring (subsurface gas monitoring), near surface gas monitoring, ambient air monitoring, and indoor air monitoring. Each category plays a crucial role in assessing and managing the environmental impact of landfill emissions and ensuring the safety and health of surrounding communities.

As mentioned earlier, decomposing waste in landfills produces gases containing a variety of chemicals. These gases travel through soils and may finally reach the surface and are commonly referred to as "soil gas", hence, its monitoring is the measuring of gas concentrations in the subsurface.

2.5.1 Soil gas monitoring

This entails the measurements of the concentration of gases in the pore spaces of soils. Measurements of soil gas levels are taken at depth of the landfill with the use of probes or wells. Probes or wells remove the flammable CH_4 component of landfill gases as they are generated, allowing it to be flared or used as a fuel, if its composition is greater than 50%. The CH_4 limit that has been established is as follows - the migration rate is 1.0 percent v/v, while the CO_2 limit is 1.5 % v/v. The measured data can be used to assess the risk of an explosion and to determine whether LFGs are moving through the soils to off-site places. Landfill operators are obliged by federal law to monitor CH_4 levels outside the boundary of the landfill; the presence of oxygen, CO_2, and nitrogen is commonly monitored as well. If federal or state officials perceive a serious problem, H_2S and other specific NMOCs, such as vinyl chloride, will also be measured. Monitoring of the perimeter-drilled-hole wells from the landfill must be done once a month, according to the existing monitoring method described in each site's waste license permit issued by EPA, South Africa, and these measurements must be submitted to the appropriate department. An incident report must be filed with the Department if the measured values surpass specific criteria, of 1.0 % v/v for CH_4 and 1.5 % v/v for CO_2. The GA 2000 hand-held gas analyser is the required measurement equipment currently employed by several government organisations and this has provided good result in several studies, although, other studies have used other measuring instrument to monitoring soil gas (Beirne et al., 2010; Collins et al., 2011; Kiernan et al., 2010).

In a study by Beirne et al. (2010), they developed and validated an autonomous gas-sensing platform for monitoring methane and carbon dioxide in landfills. The system, enclosed in a rugged casing, suitable for outdoor deployment, uses a custom micro-controller board to regulate sampling processes. Powered by a 12V 7Ah lead-acid battery, the platform operates continuously for seven weeks, sampling twice a day. Gases from ambient air and landfill spaces are introduced and removed through the solenoid valves, while an SKC Grabair pump draws samples at a flow rate of 0.6 L/min. Four sensors, including CO_2 and CH_4 IR gas sensors, a humidity sensor, and a temperature sensor, were employed in a modified sampling chamber. Beirne et al. (2010) found that monthly monitoring was insufficient to capture LFG dynamics accurately, rather, conclusive evidence suggested that twice-daily measurements provided reliable insights, optimising technology performance for enhanced monitoring and control of greenhouse gas emissions.

Similarly, Kiernan et al. (2010) designed an Infra-Red, energy-efficient sensor module for greenhouse gases with the purpose of offering an autonomous landfill gas monitoring platform. This was due to the sensor's light sensitivity and linear range for this application, as well as, its higher accuracy, although, they consume more energy and cost more than electrochemical sensors. In a study, the final prototype was successfully deployed for over 4 months, extracting samples from the designated perimeter-drilled-hole well headspace, measuring them, and sending the results to a database over a global system for mobile (GSM) communications network. The sampling was done twice a day, which is a 60-fold increase over current monitoring protocols (GA 2000 gas analyser), which only tests gas concentrations once a month. Kiernan et al. (2010) suggest that due to the dynamics, the LFG management system cannot be captured by collecting measurements once a month, it is recommended that sampling be done at least once a day. Also, drilled-hole well samples should not be taken from the top of the well, but rather from a depth of 0.5 – 1.0 m within the headspace. To achieve a steady-state measurement from the headspace and to take a representative sample, the sampling duration should be raised to 3 minutes. The extracted sample should be recycled back into the drilled hole well for continuous monitoring on-site. The sample should not, however, be returned to the drilling well for compliance monitoring.

2.5.2 Near-surface monitoring

Near-surface monitoring entails the measurement of gas concentrations within a few inches of the surface of the landfill. The monitoring of LFG close to the surface is executed to determine the need for, and the design of, a LFG control system. Near-surface monitoring is also used to determine if a LFG control system is adequately preventing CH_4 and other LFGs from escaping in high quantities through the landfill cover. Government authorities, especially in South Africa, under the Clean Air Act, require large landfills' management to install LFG collection and control systems; this involves a near-surface methane monitoring, quarterly, to ascertain whether the system will operate properly. Some studies on near-surface monitoring are highlighted below.

Wang-Yao et al. (2006) conducted a study on the seasonal variation of the emission of LFG from seven landfills in Thailand. The study employed the use of a static chamber technique to measure the LFG fluxes from September – November 2005 (dry season) and January – February 2006 (wet season). The authors identified that the use of a static gas chamber which is low in cost, and simple in operation, however, requires extreme labour and is time consuming. The conclusion of this study was that the spatial variability of LFG emissions in the wet season was higher (ranging from 0 – 825.79 $g/m^2/d$), however, the spatial variability of the dry season was lower than the wet season and ranged from 0 – 686.93 $g/m^2/d$. This was because of the higher moisture content present in the landfill.

Scheutz et al. (2011) carried out a study on the quantification of multiple methane emission sources at Fakse landfill, using a double tracer technique. The study identified that the double tracer technique was able to quantify CH_4 effectively, based on the characteristics of the Fakse landfill site. The study was carried out in two different sections (I and II); section I was a closed landfill, while section II was a landfill that was still operational. The study identified various onsite sources of LFG emissions, including the compost area, sludge pit, a pump station and a leachate collection well. The study concluded that emissions of CH_4 and N_2O (0.5 ± 0.25 and 0.06 ± 0.03 kg/h respectively) were relatively small from the compost area, however, a strong CO_2 emission (332 ± 166 kgCO_2/h) was found in the compost area. From the results in section II, the CH_4 and N_2O measured from the sludge pit area were 2.4 ± 0.63 kg/h and 0.03 ± 0.01 kg/h respectively, however, CO_2 was not measured due to interference from the composting area. The overall conclusion of the study was that CH_4 emissions from the compost area did not contribute significantly to the overall CH_4 emission from the landfill and that the sludge storage and leachate collection area were significant sources of CH_4 emission.

Kjeldsen et al. (1997) conducted an investigation into the degradation of LFG in LFG-affected soil and the importance of the degradation process. In the measurement of the LFG emissions, the static chamber was used and the samples collected were analysed immediately, using a transportable gas chromatograph. The samples were analysed for CH_4, CO_2 and O_2 fluxes present in the landfill. The study showed that high CH_4 emissions were observed, far away from the boundaries of the landfill; this was because of the clay covering of the landfill, which enhanced the lateral movement of the LFG. The results also showed a linear progression within 30 – 60 minutes of sample collection, which indicated that the factors influencing the LFG emissions were constant at that period. Due to the clay coverings of the landfill, most of the LFG migrated laterally and were emitted at the boundaries of the landfill.

Park and Shin (2001) measured the surface emission of LFG efflux rate from Sudokwon landfill in Korea using an air flux chamber. LFG efflux rate involves the summation of CH_4 and CO_2 gas flow rate. The air flux chamber system consisted of a mixing chamber, a compressed air tank, a flow meter, a circulation fan and a Gillian personal sampling pump. The highlights of the measurements were the time of the day and the seasonal variations. The study concluded that at minimum temperatures during the day, lower LFG efflux was experienced, however, at the highest temperature of the day, maximum LFG efflux was observed. It was also observed that there were changes in LFG efflux with seasonal variation, with rates being higher during summer than the winter season. The daily efflux rates for winter, spring and summer were, 0.27, 0.51 and 5.81 $m^3m^{-2}d^{-1}$, respectively.

Di bella et al. (2011) conducted a field measurement of CH_4 emissions from Palermo Municipal landfill and compare the results with modelled CH_4 emission flux. The static flux chamber was used to obtain field measurements, while the LandGEM and Ehrig models were used to model CH_4 emission flux. The results showed that the two measurements were in agreement, however, the models gave slightly higher results for CH_4 emission flux than the results from the field measurements; also, the flux chamber was found to be more reliable and easier to use. The use of statistical and geostatistical methods to produce contoured flux maps was suitable and was able to identify areas with abnormal CH_4 emissions. This can help in optimising designs for LFG recovering facilities, monitoring and scheduling maintenance for landfill-cover systems. The results from the field measurement were tools to validate the results obtained from the models.

Fredenslund et al. (2010) conducted a study on the use of trace methods to measure LFG emissions from leachate collection systems in Fakse and AV Miljo landfills in Denmark. The study showed that atmospheric pressure variations had significant impacts on the emissions of LFG. A decrease in atmospheric pressure resulted in a steady rise in CH_4 emissions and vice versa. The total LFG emissions from the landfill were measured and it was observed that the leachate collection system emitted approximately 27% of total CH_4 emissions at the AV Miljo landfill, however, the landfill was still operational. Meanwhile, 44% of the total CH_4 emissions from the landfill were observed to be emitted from the leachate collection well, because, of a more impermeable soil cover at the Fakse site than at the AV Miljo site. In conclusion, the study observed that for both landfills, the leachate collection system was a significant pathway for LFG emissions.

These abovementioned studies have shown different ways for conducting field measurements of LFG, although, the main and most-used method is the flux chamber method. The flux chamber can either be static/non-stationary or dynamic. The chamber system is normally used to measure LFG emissions from small areas of the landfill, typically less than or equal to 1 m^2. This technology has been proven effective by scholars and has been implemented in other fields of study (Kim et al., 2007). The static flux chamber is the most-widely used among the two techniques; it can also measure the net emissions of the whole landfill area. The data retrieved can be statistically evaluated to measure the whole landfill emissions by establishing statistically-based sampling schemes, such as the geo-statistical method. The flux chamber technology is usually labour-intensive and the process can take several days to collect enough samples to represent the entire landfill, however, the implementation of a geo-statistical method and identification of a main emitting crack zones have helped to improve the accuracy of samples collected (Di Bella et al., 2011).

The tracer method depends on an existing concentration measurement of gases in an inert tracer gas which is released at a known rate, therefore, the concentration ratio of the two gases can be related to the ratio of their fluxes. Some examples of inert gases used in different studies include CO and SF_6 (hexafluoride); these gases are released from one source or different sources and are measured downwind within the gas of interest. Assuming a well mixture among the gases, then CH_4 emission can be calculated directly by the ratio method as shown in Equation 2.1 (Czepiel et al., 1996).

$$Q_m = Q_t (C_m/C_t) \qquad \text{Equation 2.1}$$

where Q_m is the CH_4flux rate; Q_t is the tracer release rate (SF_6); C_m and C_t are the CH_4 and SF_6 mixing ratio respectively to form a plume.

A landfill with an area of 20 – 100 hectares needs about 3 to 4 evenly-spaced sources of release points to ensure proper simulation of the emissions. The plume can be located by using a continuous analyser for either CH_4 or SF_6 to derive the ratio values to calculate the CH_4 flow (Czepiel et al., 1996). The tracer method is used whereby the gas of interest is not mixed with any other gases, from other sources; his method requires a significant high amount of gas of interest in air to ensure there is adequate mixing of these tracer gases. The meteorological activities at that time can highly influence the results. The advantage with this method is that - it is appropriate for measuring emissions for a whole landfill area by integrating all the emission from the landfill. This technique, however, is relatively very expensive and depends on meteorological conditions such as wind velocity, rainfall, potential interference of gases from other sources; these trace gases are potential greenhouse gases, therefore, negates the reason for the experiment. Also, sampling needs to be done at great distances which could be about 100 meters, depending on landfill size to ensure the tracer gas mixes thoroughly with the plume of interest (Czepiel et al., 1996).

Other methods to measure LFG near-surface emissions include, micrometeorological methods and isotope measurements. The use of an organic vapor analyser-flame ionisation detector (OVA/FID) is a typical way of near-surface gas monitoring. The equipment is usually calibrated for CH_4, although it can also be calibrated for other gases prevalent in landfills. A funnel can be placed over the monitoring probe inlet on the OVA. The probe inlet and funnel are then held 2 to 3 inches above the ground surface, and a sample technician then records the gas measurement. LFG samples can also be taken with a sampling gear that includes, a Tedlar bag or a polished SUMMA canister; the samples are then taken to a laboratory for analysis in both circumstances. When compared to the use of portable devices, laboratory analysis may produce data for many more specifically-characterised elements of LFG. To offer a full examination of gases emitted through the landfill cover, a combination of a portable instrument and a Tedlar bag sample is occasionally employed. The portable equipment is used to find "hot spots" in the landfill surface where significantly high methane concentrations have been discovered. The Tedlar bag is then used to collect a sample, which is subsequently delivered to a laboratory for qualitative and quantitative tests for numerous pollutants found in LFG.

2.5.3 Ambient Air Monitoring

Ambient air monitoring assesses the amount of contamination in the air that is breathed by individuals or in the open air. The pollution levels found in an ambient air are a result of a variety of activities being conducted around the vicinity and even far away from the vicinity. Monitoring of the ambient air at or near landfills is primarily done to assess the worker and community exposure risks related to airborne discharges of harmful substances (Raza et al., 2021). The South African government does not currently enforce laws on compulsory monitoring of the ambient air monitoring around MSW landfills, hence, there are many landfills from which there are no data available. Ambient air monitoring is essential for several reasons. Firstly, it is a legal requirement under the National Environmental Management: Air Quality Act No. 39 of 2004 for provincial authorities to monitor ambient air quality. The data obtained from this monitoring is crucial for determining the extent and impact of air pollution on health and the environment. The process also aids the government and other stakeholders in making informed decisions regarding environmental issues, leading to the implementation of effective air quality management systems. Secondly, ambient air monitoring provides timely air quality data to the public and communities, enhancing transparency and awareness. It also allows for the evaluation of the effectiveness of current and future air emissions control strategies. Over time, the data collected reveals air quality trends, supporting research on ambient air quality and its impacts. Additionally, this data is used to evaluate air quality models, further enhancing our understanding and management of air pollution.

The atmosphere is a gaseous envelope that comprises the whole mass of ambient air surrounding the earth. It is also the earth's largest shared natural resource that supports and protects all life from the absorption of harmful ultraviolet rays from the sun, thereby, warming and regulating the earth's surface temperature. This very critical role, however is under threat because of anthropogenic activities including landfilling, environmental conditions and natural activities which result in the introduction of pollutants into the atmosphere (Weli and Adekunle, 2014). These activities generally generate gaseous emissions, mainly through degradation processes that release gaseous emissions into the atmosphere which in turn, contribute to the instability of environmental media and health. Ambient air is normally a mixture of 78% nitrogen, 21% oxygen, 0.03% CO_2, and a small amount of argon and other gases. The pollution of the ambient air is normally attributed to urbanisation and industrialisation, however, the polluted air can easily disperse across semi-urban and rural areas. Pollutants in the atmosphere have the potential to remain toxic for long periods of time, which can cause adverse effects on the environment and human health. One of the reasons air pollutions is a great threat to human health is because humans have no choice over the air they breathe. Inhaling polluted air is the major route of entry of toxic pollutants into our bodies, which could lead to the impairment of our health and even premature death (Tshehla and Wright, 2019). The World Health Organisation (WHO) and the Department of Environmental Affairs (DEA) have set permissible ambient air quality standards according to which pollutants are not meant to exceed during a specific time (usually for 24 hours or annual averages). These standards are essential to efficiently manage the air quality of an area because they determine safe permissible exposure levels for humans, thereby leading to safer health and environment of an area (Bhailall, 2015). Some air quality standards from the WHO and DEA against pollutants relevant to this study are shown in Table 2.3.

Table 2.3: Air quality standards from the WHO and DEA

Pollutants	**Time in average**	**Concentration**	
		ppb	**µg/m^3**
Hydrogen Sulfide**	24 hours	1005	150
	Annual	-	-
Benzene**	Annual	1.6	5.0
Particulate Matter*	24 hours	-	75
	Annual	-	40
Total Suspended particles	24 hours	-	300
	Annual	-	100

Source: Bhailall, (2015)
Note: South African Air Quality Standards* and World Health Organisation guideline**

The ambient air can be polluted by several factors from the landfill, including the anaerobic and aerobic degradation of waste in the landfill which then emits gaseous pollutants into the atmosphere. Factors include, dust particles in the landfill which are stirred up by the movement of municipal trucks and bulldozers. The hauling and continuous movement of trucks, bulldozers, private vehicles all tend to emit several pollutants from their exhausts. LFG collection and utilisation plants also emit several pollutants from their engines. All these and more from the landfill daily operations, contribute significantly to the emissions from landfills. Examples of the several pollutants which result from daily landfill operations are - Particulate Matter ($PM_{2.5}$), Volatile Organic Compounds (VOCs), including sulfur dioxide (SO_2), hydrogen sulfide (H_2S), NO_2, benzene, toluene, ethylbenzene, and xylenes (BTEX) and non-methane hydrocarbons (NMHC). Several studies done around the world have shown that the long-term exposure to certain fine atmospheric particles with a medium aerodynamic diameter equal to or less than 2.5 microns ($PM_{2.5}$), SO_2, NO, NO_2 and other pollutants are associated positively and significantly with high rate of disease and even early death (Bhailall, 2015; Raza, 2021). The current research, therefore, monitored and modelled the emissions of LFGs into the surrounding ambient air of the Thohoyandou landfill to assess its potential effects on the environment and the health of nearby residents.

2.6 Modelling Air Dispersion

There are several models developed over the years for modelling air dispersion. These models were developed based on different scenarios and operates at different functionality levels. Some of these models are - AERMOD, CALPUFF, CALINE4, ADM3, AERSCREEN models (Gibson et al., 2013; Holnicki et al., 2016; Dehghani et al., 2018).

The California Department of Transportation (Caltrans) initiated the development of line source dispersion models in the early 1970s, starting with the introduction of the initial model in 1972 to predict carbon monoxide (CO) concentrations. CALINE2, introduced in 1975, brought enhancements to compute concentrations in various conditions, yet faced challenges, particularly over predictions for stable, parallel wind conditions (Benson, 1988). In response, CALINE3, introduced in 1979, addressed these issues by incorporating modified dispersion curves and multiple link capabilities. CALINE3's performance was validated and authorised by the Environmental Protection Agency (EPA) in 1980 for estimating concentrations of non-reactive pollutants near highways. CALINE4, the latest version, builds upon CALINE3, refining and extending its capabilities, allowing predictions of CO, nitrogen dioxide (NO_2), and aerosol concentrations (Madiraju and Kumar, 2022).

In parallel, CALPUFF, an advanced long-range atmospheric dispersion modeling system, simulates air pollutant transportation and dispersion over regional and urban scales. Recognised for handling complex terrain and meteorological conditions, CALPUFF is useful for assessing air quality impacts from diverse sources, such as industrial facilities and power plants (Bezyk et al., 2021).

AERSCREEN, a screening model developed by the U.S. EPA, is designed for preliminary analysis of air quality impacts, related to the dispersion of pollutants from industrial sources. It focuses on estimating concentrations of air pollutants near emission sources in the permitting process (Nimmatoori and Kumar, 2013).

AERMOD, developed from an evolution of a seven-step process, was proposed by the EPA to replace the ISC3 model. It incorporates meteorological preprocessors (AERMET and AERMIC Terrain pre-processor, AERMAP) and adopts a modified Gaussian plume approach. AERMOD includes algorithms for dispersion in - both convective and stable boundary layers, plume rise, buoyancy, plume penetration into elevated inversions, vertical profiles of wind, turbulence and temperature, treatment of receptors on various terrains, building wake effects, as well as plume meander. Several studies have applied AERMOD for simulating air dispersion in different contexts, including the assessment of pollutants from point and line sources in various cities and the quantification of landfill methane gas (Matacchiera et al., 2016; Gibson et al., 2013).

Choosing the appropriate dispersion model is crucial for accurate and reliable results in air quality assessments. AERMOD stands out for its comprehensive approach, considering various atmospheric conditions and incorporating advanced algorithms for pollutant dispersion. The model provides detailed and refined predictions, particularly in complex scenarios. Its extensive capabilities, including - treatment of diverse terrains, consideration of building aftermath effects, and incorporation of detailed meteorological data - make AERMOD a robust choice for a wide range of air quality modeling applications. Additionally, its widespread adoption in various studies and regulatory applications attests to its reliability and effectiveness in providing valuable insights into air pollutant dispersion patterns (Gibson et al., 2013).

The AERMOD modelling system is comprised of two pre-preprocessors and a dispersion model - the AERMIC meteorological preprocessors (AERMET) and the AERMIC Terrain pre-processor (AERMAP). The AERMET provides the AERMOD with meteorological data and surface characteristics to calculate boundary layer parameters, for example, mixing height, friction and velocity which are needed by the AERMOD. Also, AERMET's major aim is to calculate the boundary layer parameters for use by AERMOD. The meteorological INTERFACE, internal to AERMOD, uses these parameters to generate profiles of the needed meteorological variables, AERMET then passes all meteorological observations to AERMOD. Surface characteristics in the form of - albedo, surface roughness and Bowen ratio, plus standard meteorological observations (wind speed, wind direction, temperature, and cloud cover) - are input data into AERMET. AERMET then calculates the PBL parameters like - the friction velocity, Monin-Obukhov length, convective velocity scale, temperature scale, mixing height, and surface heat flux. These parameters are then passed to the INTERFACE (which is within AERMOD) where similarity expressions (in conjunction with measurements) are used to calculate vertical profiles of wind speed, lateral and vertical turbulent fluctuations, potential temperature gradient, and potential temperature (Gibson et al., 2013).

The AERMAP, however, uses gridded terrain data for the modelling area to calculate a representative terrain height scale associated with each receptor's location. The terrain height scale, which is uniquely defined for each receptor location, is used to calculate the dividing streamline height. The gridded data, formatted as Digital Elevation Model (DEM) data, is utilised in AERMAP to create a representative terrain height scale associated with each receptor location. The gridded DEM data, selected for application in AERMAP, provides essential information for accurately determining terrain characteristics and ensuring precise modeling of the dispersion of air pollutants. AERMAP is also used to create receptor grids, for the elevation for each specified receptor is automatically assigned through AERMAP. For each receptor, AERMAP passes the following information to AERMOD - the receptor's location, its height above mean sea level, and the receptor-specific terrain height scale (Zade and Ingole, 2015).

The AERMOD model incorporates new or improved algorithms to enhance its functionality and accuracy. It features advanced dispersion modeling for both convective and stable boundary layers, and more precise calculations for plume rise and buoyancy. The model also addresses plume penetration into elevated inversions and computes vertical profiles of wind, turbulence, and temperature. Additionally, AERMOD includes improvements for the urban nighttime boundary layer and the treatment of receptors on all types of terrain, from the surface up to and above the plume height. It effectively handles building wake effects and offers an improved approach for characterizing fundamental boundary layer parameters. Furthermore, the model incorporates a refined treatment of plume meander, enhancing its overall performance and reliability.

Gibson et al. (2013) used the AERMOD to model the air dispersion of point and major line emissions of $PM_{2.5}$, NO_x, and SO_2 in several cities in Canada. The results of the study showed that the AERMOD model had similar results when compared with the observed SO_2 concentration, however, the authors realised some discrepancies between the results modeled by AERMOD and the observed $PM_{2.5}$ and NO_x concentrations in some cities. The authors still concluded that AERMOD is very useful in understanding the surface impact of $PM_{2.5}$, NO_x, and SO_2 from point and major line sources at annual, monthly, and hourly averaging periods in the model's domain. Also, Matacchiera et al. (2016) used the AERMOD model, on a UK landfill, to simulate landfill methane gas quantification and to understand the gas mixing, especially when using the Tracer Dispersion Method (TDM). Several other studies have incorporated the AERMOD model to simulate the LFG concentrations and dispersion (Bhailall et al., 2015; Asadollahfardi et al., 2019; Elmi et al., 2021)

2.7 Importance of Landfill Gas

LFG is a viable renewable energy source due to its substantial methane content. LFG utilisation is the process of collecting, processing and treating the LFG collected during aerobic and anaerobic decomposition of MSW deposited in the landfill to produce electricity, heat, fuels, and various chemical compounds. There are more than 1000 LFG utilisation technologies that are operational around the world with more LFG being utilised every year (Terraza and Willumsen, 2010).

Before commencing the construction of a LFG utilisation technology, several factors must be considered. These include the type of waste deposited in the landfill and ensuring a continuous flow of municipal solid waste. It is crucial to select the best type of LFG utilization engine to achieve maximum results for a proposed landfill. The availability of potential end-users of the technology and the quality and duration of the potential LFG generation are also important considerations. Additionally, the capital expenditure and operating costs for the utilisation of technology must be evaluated, along with the availability of expertise for the proper operation of this heavy machinery.

LFG is extracted from landfills using a series of wells and a blower/flare (or vacuum) system which are connected to the ground of the landfill. Then the system channels the collected LFG to a central system where it is processed and treated depending on the required use for the gas. From this point, the gas can be flared or beneficially used in a LFG utilisation plant. LFG can be used in several ways, such as direct use in the form of electricity, boiler system, fuels for vehicle, natural gas network, various chemical compounds and leachate evaporation. Table 2.4 shows the summary of the different uses of LFG, currently.

Table 2.4: Summary of LFG utilisation

LFG utilisation	Uses	Characteristics
As a source of natural gas	Can be used domestically for cooking and industries. Can be used in generation of revenue for the government, when sold.	The technique for conversion of raw LFG to natural gas is relatively expensive.
Boiler system	Can be used in landfill sites, schools, hospitals for heating the system. Can make use of maximum amount of LFG generated from the landfill.	For accessibility reasons, end-users must be close by. The cost is tied to length of pipelines.

		Relatively not expensive Does not require large amount of LFG when processing.
Furnace, dryers and kilns	The raw LFG can be used directly from the kilns in some manufacturing companies. Can be coupled with other energy products.	Constraint of LFG utilisation, if used seasonally. Inexpensive and easy to install.
Use as vehicle fuel	Use as source of fuel to landfill vehicles and trucks. Can also be sold as a source of income by the government.	Can be expensive due to the processing of the raw LFG collected, into vehicle fuels
Use as a source of electricity	Can be a source of electricity. Can be used as a source of revenue for the government due to the sale of electricity. Maximum use of LFG, when LFG is collected from the landfill site.	Relatively high cost of operations. Requires a high level of expertise and technology. Cost may be negligible for countries with low electricity costs.

Source: Terraza and Willumsen (2010); Global Methane Initiative (2012)

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CHAPTER THREE: Monitoring of Subsurface Emissions and the Influence of Meteorological Factors on Landfill Gas Emissions: A Case Study of a South African Landfill

Preamble

This chapter, titled "Monitoring of Subsurface Emissions and the Influence of Meteorological Factors on Landfill Gas Emissions: A Case Study of a South African Landfill," has been published as a manuscript in the journal "Sustainability." It presents a detailed examination of subsurface emissions of LFGs from Thohoyandou landfill site, considering the impact of meteorological factors on the emissions.

Njoku, P. O., Piketh, S., Makungo, R., & Edokpayi, J. N. (2023). Monitoring of Subsurface Emissions and the Influence of Meteorological Factors on Landfill Gas Emissions: A Case Study of a South African Landfill. *Sustainability,* 15(7), 5989.

Abstract

This chapter focused on the sub-surface migration of LFG from Thohoyandou landfill and the influence of meteorological factors. The government-accredited GA 2000 landfill gas analyser was used to monitor the LFGs (CH_4 and CO_2) generated from the sub-surface of a landfill. Eighteen gas sample probes were constructed and placed approximately 100 m apart on the boundaries of the landfill site. The monitoring of the gases was conducted over a period of two years, taking into consideration the different seasons of the year. Results from the study show that as the LFG migrates toward the boundaries of the landfill in the sub-surface, higher CO_2 levels were recorded when compared to CH_4. This could be mainly because of the oxidation process and the anaerobic conditions within the buried waste. CH_4 emissions ranged from 0.54 - 2.22% *v*/*v* and 0.24% - 2.33% *v*/*v,* in 2020 and 2021, respectively. Similarly, CO_2 concentration ranged from 4.66 - 6.37% *v*/*v* and 3.5- 6.56% *v*/*v* in 2020 and 2021, respectively. Furthermore, higher emissions of CH_4 and CO_2 were found in the surrounding active cells, where there is currently disposal of MSW, however, the monitoring probes situated in areas far away from the active area recorded lower gaseous levels. This study recommends that there should be continuous monitoring of LFG

emission from the Thohoyandou landfill to prevent the potential risk of fire hazards, environmental degradation and health effects.

Keywords: GA 2000 landfill gas analyser; landfill gas; meteorological data; subsurface emissions

3.1 Introduction

Landfills are one of the main contributors to the world's anthropogenic greenhouse gas (GHG) emissions because massive amounts of CH_4 and CO_2 are emitted from the degradation process of deposited waste in them (Manheim et al., 2021). In landfills, LFG is produced in three stages: bacterial degradation, chemical reactions, and volatilisation. Due to complex physical, chemical, and microbiological processes, persistent organic pollutants (such as dioxins and polycyclic aromatic hydrocarbons), CH_4, CO_2, heavy metals, NMOCs, PM, and some trace elements are regularly generated in landfills (Sibeko et al., 2020 and Sekhohola-Dlamini and Tekere, 2019).

Other concerns associated with waste deposition in landfills, include litter, dust, rodents, and unexpected landfill fires. Wastes deposited in landfills are usually compacted in horizontal strata, creating low-permeability barriers and poor vertical LFG flow (Nanada and Berruti, 2020). Landfills are compacted daily with high-permeability top layers to prevent water intrusion, odour, and gaseous emissions. As a result, rather than the LFGs escaping vertically through the landfill's surface, LFG will frequently travel horizontally toward the landfill's boundaries, where it will be discharged into the surroundings areas through sinkholes and cracks, posing a threat of fire explosion (Flores-Orozco et al., 2020). LFG migration, in unsaturated soils around the landfill is mostly influenced by soil physical characteristics, such as water content and soil permeability particularly in the deeper layers of the soil strata. Microbial activity, air pressure, wind speed, temperature, nutrient availability, and oxygen content at the soil surface, also influence gas movement and composition (Sharma et al., 2020 and Bian et al., 2020). In addition, meteorological parameters, such as barometric pressure, wind speed, rainfall, and temperature do influence the emissions of LFG. To understand the flow rate and migration of LFGs, it is crucial to understand how these parameters affect LFG emissions (Braker et al., 2020 and Czepiel et al., 2003). Studies have shown that changes in barometric pressure have a major influence on LFG migration. Furthermore, the effects of wind turbulence-induced pressure variations on soil-gas migration cause a significant fluctuation in gas movement, in the upper layer of the soil (Aghdam et al., 2019 and Shu et al., 2021). Likewise, it has been observed that soil water content enhances microbial activities, thereby increasing microbial CH_4 oxidation rates and having a significant impact on LFG migration in the soil (Aghdam et al., 2019 and Vaverkova, 2019). The main objective of this study is to investigate the sub-surface migration of LFG within the Thohoyandou landfill and its environs. Furthermore, this study investigates the influence of meteorological conditions of Thohoyandou area on LFG generation. This study hypothesises that meteorological factors, around Thohoyandou environs influence LFGs' generation. This study is significant because it addresses critical environmental concerns of landfill operations, pollutant emissions, LFG sub-surface migration, and the influence of meteorological factors on these processes. Its findings can inform strategies for mitigating the environmental impact of landfills and improving waste management practices. Additionally, the research contributes to the broader field of environmental science and helps advance the understanding of landfill-related challenges.

3.2 Methodology

3.2.1 Design and installation of monitoring probes

A reconnaissance survey was conducted before the LFG monitoring probes were installed in the landfill. A proper assessment was conducted to ascertain where the LFG monitoring probes will be located. Critical areas between the landfill and adjacent buildings like groves of trees, utility lines and fracture zones were assessed before installation. After a proper assessment has been conducted, the installation of the LFG monitoring probes was done around the perimeter of the landfill site.

The LFG monitoring probes installed were made from PVC pipes. Bhailall et al. (2010) highlighted the need for monitoring probe to be made from a PVC pipe and not metals to avoid higher risk of vandalisation or theft. These pipes were perforated along the sides to allow the ingress of LFG into the probes. The LFG monitoring probes were designed with expert precise measurements for an easy monitoring of the sub-surface migration of the LFGs according to Bhailall et al. (2010). A meticulously crafted design and construction approach for LFG monitoring probes was implemented to minimise the ingress of ambient air into the system. This design ensures that precise gas samples can be reliably collected from the probes, ensuring the accuracy of the collected data. If air enters the probes, it can dilute the samples making it unrepresentative. A schmatic diagram and actual sampling probes shown in Figure 3.1 and Plate 3.1. The materials used in the construction and installation of monitoring probes include PVC pipes with diameters of 42.1 mm and 48.3 mm, cement, and gravel stones. Additionally, a sampling valve with a stopper is required. The installation process also involves the use of a drilling machine, a tape rule, and an auger to ensure accurate placement and functionality of the probes.

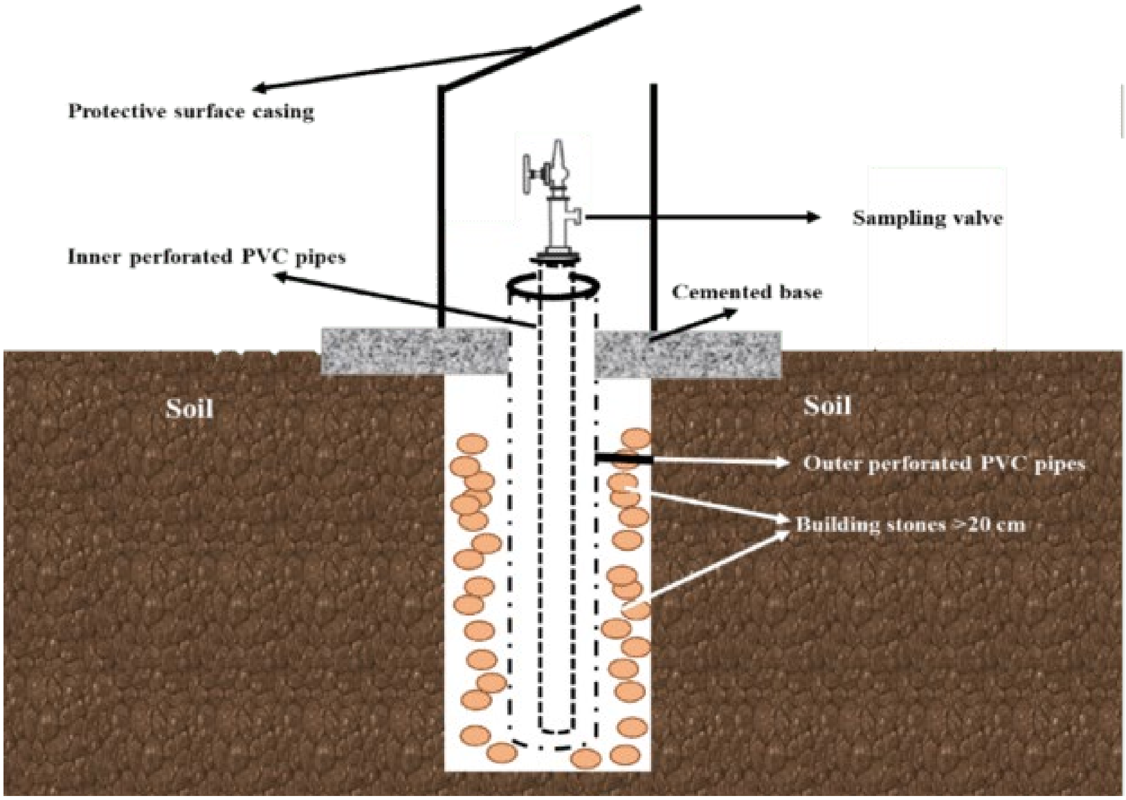

Figure 3.1: Schematic diagram of an installed LFG monitoring probe installed in the landfill

Plate 3.1: Pictorial image of an installed LFG monitoring probe installed in the landfill

The PVC pipes were perforated using a drilling machine on the sides with equal measurement. This is to allow the free flow of the gases from the subsurface soil. The top of the PVC pipes were fixed with sampling valves and a stopper. The sampling valve serves the purpose of facilitating readings from the monitoring probes, while the strategically positioned stopper effectively prevents the LFGs from escaping vertically. To establish an optimal configuration, a drilled hole of about 1.0 to 3.0 m depth was drilled at the landfill boundary. According to Kieman et al. (2010), the experimental procedure for analysing subsurface flow from a landfill involved collecting samples from two drilled holes located at depths of 0.0 m and 1.0 m. This justify the choice of sampling depth of 1.0 m, as it is sufficiently distant from the dilution effects caused by air at the top of the well. While it is possible to choose depths greater than 1.0 m, the authors explain that, for the site used in the validation trial, extraction at a depth of 1.0 m was feasible.

The constructed PVC pipes with drilled holes were installed in the middle of the drilled hole and packed with 20 cm gravel stones at the side of the PVC pipe. These gravel stones have greater pore and allow for the free flow of the gases through the monitoring probe installation area. On top of the drilled hole, cement moulded in form of a protection was applied around the monitoring probes to safe guard the probes from oncoming vehicles, theft, vandalisation and in an unforseen event of landfill fires. The threaded cap was used as a connection in which the gas samples were collected from the probes and measured using the GA 2000 landfill gas analyser (Geotechnical Instrument;

Keison Products, Chelmsford Essex, UK). The protective surface casing was designed with a tight cap which prevented water intrusion into the probes. Water intrusion into the corners of the probes was also averted with the cemented base of the monitoring probe.

The installation of the probes was in November 2019. The number of monitoring probes installed was 18 at the boundaries of the landfill at a depth of approximately 1-3 meters. Figure 3.2 shows the sampling points where the monitoring probes were installed. The installation of the probes was within the range of 60 to 150 meters apart. Plate 3.2 shows the installation of a probe into the ground of the landfill using an auger. The spacing was dependent on the soil permeability (the more permeable the soil the closer the installation of the monitoring probes).

Figure 3.2: Aerial view of the landfill site showing the different points the LFG monitoring probes were installed at the boundary of the landfill. Note: Point A–R shows the points where the monitoring probes were installed in the landfill.

Plate 3.2: Installation process of the monitoring probes in Thohoyandou landfill

3.2.2 Data collection

In this study, a GA 2000 landfill gas analyser which is a portable infrared gas analyser and developed by Geotec (Keison Products, Chelmsford Essex, UK) was used to directly measure the concentrations of the principal components of LFG, specifically CH_4 and CO_2, as well as O_2 (Plate 3.3) (Beirne et al., 2010). To facilitate the collection of gas samples for analysis, the monitoring probes at the landfill were equipped with a system of outer and inner perforated PVC pipes. The outer perforated PVC pipes were instrumental in allowing the flow of LFG from the landfill into the monitoring probes. These perforations enabled the efficient entry of gas into the gas analyser. Conversely, the inner perforated PVC pipes were designed to trap and contain the gases within the monitoring probes (Bhailall et al., 2010). This setup ensured that the gas samples collected for analysis were representative of the LFG present in the landfill.

Plate 3.3: Geotech gas analyser GA 2000 landfill gas analyser

Given the need to maintain precision in the measurements, the monitoring process was divided into different phases. The duration of each phase was set at 3 minutes to allow sufficient settling time. These phases were: baseline, sampling, and purging.

The baseline procedure marked the initiation of the monitoring process. During this phase, the GA 2000 gas analyser was switched on, and the supply valve was opened to the atmosphere to verify the operational status of the sensor. Additionally, this phase allowed ample time for the infrared (IR) sensors within the analyser to warm up and stabilise. It was a critical step to ensure that there was no residual LFG within the analyser's chamber from previous measurement cycles. This, in turn, guaranteed the accuracy of subsequent readings.

Subsequently, during the sampling operations phase, the sampling valve of the GA 2000 landfill gas analyser was connected to the extraction point of the landfill monitoring probe, which then drew gas from the sampling point for approximately 60 seconds. The analyser recorded readings during this period. These measurements were repeated consecutively three times. This process continued until the readings from the GA 2000 gas analyser reached a stable state. The results from these four measurements were then compared and averaged to yield the result.

Following the sampling operations, the purge procedure was conducted to ensure that any remaining LFG in the instrument's chamber was completely removed. This was a crucial step to prepare the gas analyser for subsequent measurements while maintaining the precision and accuracy of the analysis.

For the meteorological data for this study, the data was collected from the South Africa weather Service (SAWS). The duration of the metrological data was for the year 2020 to 2022. The meteorological data considered were the rainfall, ambient temperature, wind speed and barometric pressure,

3.2.3 Data analysis for the influence of meteorological factors on CH_4 and CO_2 emissions

The data were collected and stored in Excel sheet. To determine Pearson’s correlation and statistical difference between the meteorological data and the LFG, a simple *t*-test analysis was conducted using Excel. To investigate if there is a correlation between the meteorological parameters (rainfall, barometric pressure, wind speed, and temperature) and the LFG concentration, Pearson’s correlation and *p* values (0.05 significant level) were calculated. The Pearson’s correlation coefficient (R) close to +1 or -1 indicates a strong correlation, while values closer to 0 suggest a weaker correlation. To understand the causal effects of meteorological factors influencing the CH_4 and CO_2 emissions, a regression analysis was conducted using Excel. The data monitoring period was for two years (2020 to 2022) on a monthly interval.

3.3 Results and discussion

3.3.1 Methane generation from Thohoyandou landfill

In 2020, CH_4 concentration was above the threshold limit (limit at 1% *v/v*) for most months except for July (0.95% *v*/*v*), September (0.54% *v*/*v*), and October (0.65 % *v*/*v*). However, in 2021, CH_4 concentration levels were above threshold limits except for in the months of March (0.26%), April (0.31%), and May (0.24%) (Figure 3.3). There was no monitoring in the months of April and May 2020 due to the SARS-CoV-2 coronavirus pandemic and the national lockdown in South Africa. Monitoring commenced again in the late winter season (June, July, and August) of 2020. There was an increase in CH_4 concentration with values of 1.46% *v*/*v* in the month of June. In July there was a decline in CH_4 concentration, which was pegged at the threshold limits of 1% *v*/*v*; however, an increase in the CH_4 concentration was recorded in the month of August 2020. In the winter of 2020, it was observed that the average CH_4 concentration was lower than the average summer results. This is consistent with the findings of Monster et al. (2019) and Aghdam et al. (2019). Monster et al. (2019) reported that lateral CH_4 movement from old landfills was not detected during summer due to increased oxidation of the soil.

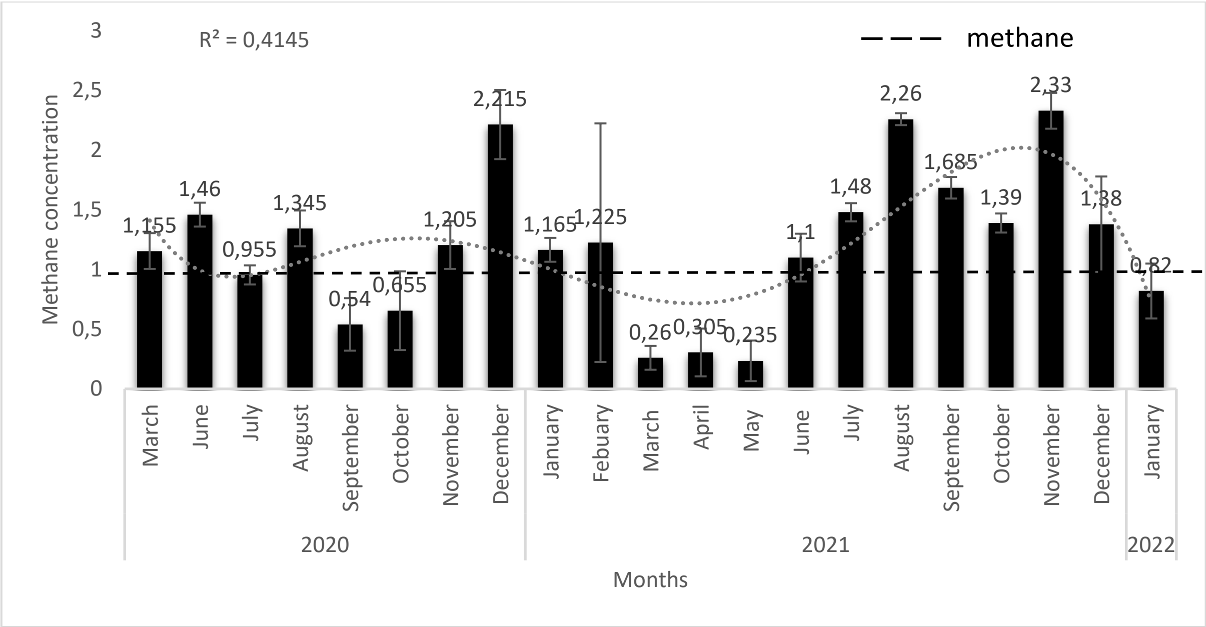

Figure 3.3. Average CH_4 concentration observed during each month (March 2020–January 2022). Note: broken straight line is the methane threshold

In addition, from early September to October of 2020, lower levels of CH_4 was recorded. This coincides with the breakdown of the bulldozer used for compressing and daily covering of wastes. Therefore, there was no form of daily compression and covering of the waste during that period, which resulted in high penetration of oxygen and moisture content into the waste piles, thereby increasing the decomposition process in the landfill. The high presence of moisture encouraged bacterial growth and transported nutrients and bacteria to all areas of the landfill. In addition, the presence of oxygen in the waste piles could have brought about the reduction in CH_4 generation. Monster et al. (2019) suggested that when a very thin layer of cover materials is used during the daily covering, it may not be sufficient to enable the lateral migration of LFG but will increase the vertical movement of the gases into the environment.

It is important that the choice of cover materials does not in itself create an environmental nuisance such as dust, litter, or odour. Notwithstanding, from this study, during the machine breakdown, a decline in CH_4 concentration was observed, and CH_4 concentration was recorded to be below the threshold limit. In November 2020, CH_4 subsurface migration gained momentum following the repairs of the equipment and the improved daily cover of the waste piles. The daily cover of the waste piles enhanced the horizontal flow of the CH_4. Keenan et al. (2021) also suggested that due to sufficient and efficient daily covering of waste piles, there is low infiltration of moisture and oxygen content increasing the methanogenic activities in the landfill as this improves the lateral migration of the gases. As a result, the probes that were installed in the boundaries of the landfill recorded higher CH_4 concentration at that time.

At the beginning of summer (December 2020, January, and February 2021), CH_4 concentrations experienced a rapid spike, exceeding the threshold limit. However, there was a subsequent decline in CH_4 concentrations in March, April, and May of 2021. Landfill activities and different meteorological conditions varied during this period (for example, introduction and siting of new cells, relocation of the leachate ponds, higher rainfall, and increase in temperature). Similarly, Park and Shin (2001) demonstrated that the LFG generation rate decreases from summer to winter, as observed in their study in Inchon city, Korea. The decrease was attributed to the reduction in surface efflux rate caused by low temperatures, which led to decreased surface pores and increased ground compactness during winter. Then during summer, the efflux rate of the LFG rapidly increased due to increased precipitation and high temperature.

In India, Gollapalli and Kota (2018) conducted a study on the CH_4 emission from an Indian landfill for a period of one year and obtained results like those of Park and Shin (2001). This study observed that CH_4 emissions were highest in summer and lowest in winter. This could be due to higher average temperatures in summer (30.5 ˚C) than in winter (19.7 ˚C). In a study conducted in China, three-year monitoring of CH_4 and CO_2 effluxes at a large and well-managed final covered landfill, it was observed that CH_4 efflux in winter (3°C - 12°C) was higher than that in other seasons for most areas of the landfill (Li et al., 2020). Li et al. (2020) attributed the results of the study to the gas permeability and the CH_4 oxidation capacity of the cover layer.

Between the months of March to May 2021, CH_4 concentrations recorded were low and below the threshold limits, following disturbances and increased activities in the landfill. Activities such as the construction of a new cell brought about deep excavations of the topsoil in the landfill. Therefore, this disturbed the flow of the CH_4 gas both laterally and vertically. This brought about the high introduction of oxygen into the waste pile. Oxygen in landfill must be used up first for the methanogenic bacteria to start producing CH_4. When the waste pile is not compacted properly when buried or frequently disturbed, more oxygen is introduced, so the oxygen-dependent bacteria live longer and produce CO_2 and water for longer periods. When the waste piles are very compacted, CH_4 generation will begin earlier as the aerobic bacteria are replaced by methane-producing anaerobic bacteria. CH_4 gas generation begins as the anaerobic bacteria acts on the waste material. This occurs only when the oxygen in the landfill is used up by the aerobic bacteria. Therefore, more oxygen present in the landfill will slow methane production (ATSDR, 2001). In addition, one of the contributing factors is the majority of the gases could escape from the excavated topsoil of the landfill into the ambient air. This brought about the low readings from the monitoring probes.

In the winter (June, July, August) of 2021, the results showed a steady rise in CH_4 concentration from the month of June through August. The average results observed in the winter of 2021 were recorded to be almost the same as the results recorded during the previous summer season. There was no significant variation between the average results of the winter and summer seasons, as recorded in Figure 3.3. The rise in CH_4 concentration from landfills during winter is due to the decrease in temperature. Additionally, the decrease in temperature reduces the rate of CH_4 oxidation, which further contributes to the rise in CH_4 concentration (Aghdam et al., 2019). Following the months of September through December of 2021 there were observed to be varying CH_4 concentrations above the threshold limit. This is a cause of concern to landfill management, and measures must be put in place to reduce methane subsurface migration to avoid unexpected fire explosions at CH_4 concentrations greater than 5% in the air (Pehme et al., 2020).

In summary, for the first year, 2020, during the data collection, it was observed that the CH_4 emission concentrations ranged from 0.54 to 2.22% *v/v*. The results further showed that the lowest concentrations of methane emissions were recorded for the months of September and October 2020, with values of 0.54 and 0.66% *v/v*, respectively. The month of December 2020 exhibited the highest amount of CH_4 emissions with a value of 2.21% *v/v*. Furthermore, for the year 2021, the months of March (0.26% *v/v*), April (0.31 % *v/v*), and May (0.24 *v/v*) showed the lowest amount of methane emission. The months of August (2.26% *v/v*) and November (2.33% *v/v*) recorded the highest methane emission concentrations. It was recorded that the months of March, June, August, November, and December, with average values ranging from 1.16% *v/v* to 2.22% *v/v*, all surpassed the permissible limit (Figure 3.3).

3.3.2. Carbon dioxide generation from Thohoyandou landfill

The CO_2 concentration in March 2020 was 6.37% v/v, which is above the threshold limits of 1.5% v/v (Figure 3.4). However, no measurements were conducted between April and May 2020 due to the national lockdown in response to the SARS-CoV-2. In the winter season, the month of June showed a considerable decline in the CO_2 concentration. Consequently, there was an increase in trends of CO_2 emissions from June to August 2020. The average CO_2 concentration in winter was 14.82% v/v, and that of summer was 15.27 % v/v; there was just a slight difference between the two seasons. Similarly, Li et al. (2020), in a study conducted in a landfill in China, observed that the CO_2 efflux increased in spring (averaging from 13°C - 38°C) and peaked in the summer of that year (averaging from 38°C - 42°C), and then the CO_2 concentration decreased to a minimum in late autumn or early winter (averaging from 15°C to 20°C). This was mainly a result of the seasonal changes in temperature and soil gas permeability. Elmi et al. (2020) showed that CO_2 concentration was greater in winter than in summer. This was a result of higher evaporative losses in summer, which resulted in less waste moisture content; this brought about a limiting factor in the formation of anaerobic conditions.

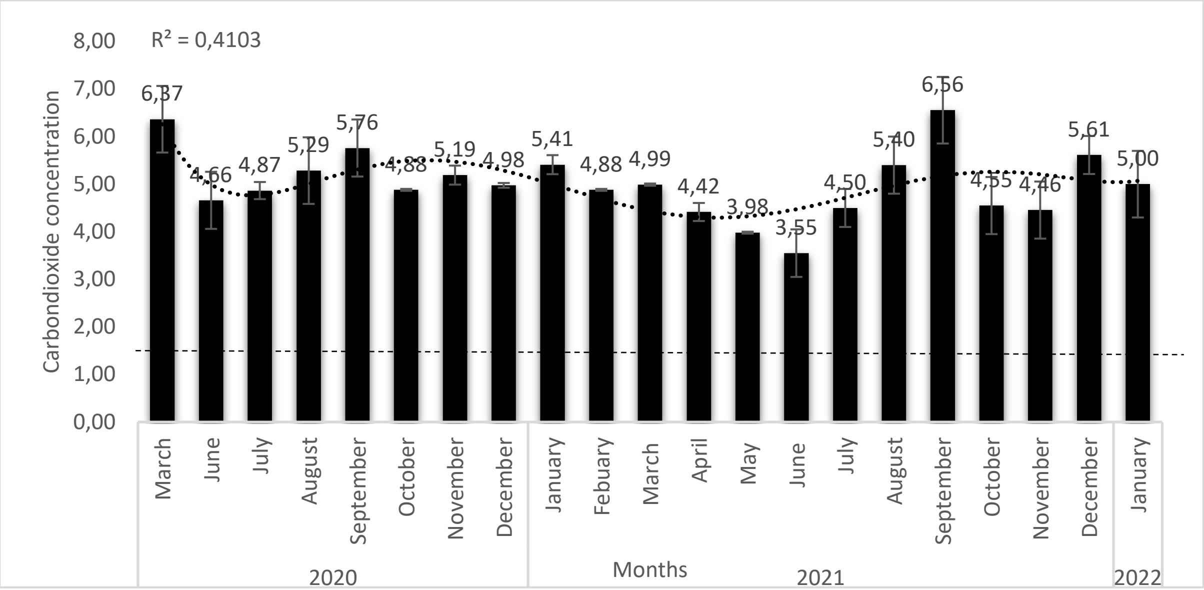

Figure 3.4. Average CO_2 concentration observed during each month (March 2020–January 2022).

There continued to be rapid fluctuations in the CO_2 concentration until the end of the monitoring activity, irrespective of the machinery breakdown that occurred in the month of September 2020. This breakdown affected the daily covering of the waste piles. However, October and November of 2020 showed a decrease in CO_2 concentration. The breakdown of the waste led to the increase in oxygen in the landfill and thus an increase in the oxygen-dependent bacteria decomposing the waste and the byproducts of CO_2 and water. This could have led to the observed increase in CO_2 concentration in the month of September 2020. During the summer season, there was varying CO_2 concentration. At the peak of summer, in the month of January 2021, the highest CO_2 level was recorded when compared to other months. During the winter months of 2021, the month of June experienced the lowest CO_2 concentration of

3.55 % v/v for the duration of the monitoring exercise. During this period, there was increased activity in the landfill, including heavy excavations, relocation of the leachate pond, and the construction of the new cell.

The summary of the concentration data in Figure 3.4 shows that for all the monitoring months of this study, CO_2 emission was above the threshold level of 1.5% v/v for the entire period of the monitoring process. This is a result of the decomposition of the high organic matter content in anaerobic conditions. When organic materials, such as food waste, are buried in landfills, they undergo microbial decomposition in the absence of oxygen, resulting in the production of CO_2 as a byproduct. Furthermore, the transportation of waste to and from landfills, as well as the equipment used to manage and cover the waste, also contributes to the high CO_2 concentration. However, the CO_2 generation varied from time to time during the monitoring process. The minimum and maximum CO_2 concentrations obtained for the monitoring process (March 2020 to January 2022) were 3.55% v/v (June 2021) and 6.56% v/v (September 2021), respectively. These variations were because of landfill disturbances, weather conditions, machine breakdown, soil type, soil permeability, and moisture content. Beirne et al. (2010) showed that a partial blockage of an underground gas extraction pipeline restricted the volume of gas extraction and caused an increase in gas migration toward the sampling point. This blockage disturbed the subsurface flow of the gas component; meanwhile, once the blockage was removed, the CO_2 gas component fell below the threshold limit again.

3.4 Monitoring of CH_4 and CO_2 concentrations from the different probes of the Thohoyandou landfill

Table 3.1 shows the average concentrations of CH_4 and CO_2 emissions for the different monitoring probes. Over the monitoring period, it can be observed that the results obtained from the GA 2000 landfill gas analyser for CH_4 concentration ranged from 0.26 - 2.56% *v/v*.

Table 3.1: Average CH_4 and CO_2 concentrations from the monitoring of the different probes in the landfill

Probes	Average CH_4 ± standard deviation	Average CO_2 ± standard deviation
A	0.56±0.31	5.14±1.30
B	0.30±0.17	4.58±1.31
C	0.48±1.63	3.71±1.79
D	0.26±0.21	4.56±0.50
G	1.58±1.05	3.86±1.14
H	0.69±2.28	3.59±1.78
I	2.30±0.20	6.47±0.81
J	2.33±0.30	6.65±1.10
K	1.60±0.85	6.44±2.35
M	2.56±1.77	5.96±1.37
N	0.55±0.17	5.92±1.19
O	0.55±0.45	6.68±1.44
P	0.40±0.23	6.21±1.38
Q	0.60±0.38	6.08±2.27
R	0.50±0.25	6.74±2.47

Zhang et al. (2019) suggest that the lateral movement of the CH_4 concentration tends to diffuse as it travels below the earth's surface; also, some of the gases tend to escape from the surface of the soil if not covered properly, as is the case of Thohoyandou landfill. This can be applicable to the monitoring probes D and B, which were observed to have the lowest CH_4 concentrations with values of 0.26% *v*/*v* and 0.30% *v*/*v*, respectively. Probes D and B were installed close to the entrance gate of the landfill site. Monitoring probes C and D were located very close to a hotel and had concentrations of 0.48% *v*/*v* and 0.26% *v*/*v*, respectively. These concentrations were below the threshold limit of 1% *v*/*v*; however, it is pertinent to conduct constant monitoring of the hotel buildings because the concentration of CH_4 found in that area fluctuates and could be influenced by several meteorological factors (such as rainfall and high temperature or pressure) and physical activities conducted in the landfill. LFG can migrate from a landfill through the soil into outdoor air as well as the indoor air of nearby buildings. LFG in outdoor air can enter a building through doors, windows, and ventilation systems (Koliopoulos et al., 2019). Scheutz and Kjeldsen (2019) emphasised that one of the main reasons for monitoring LFG emissions is because of their health implications and the risk of off-site gas migration to buildings and structures. Monitoring probes E, F, and L were vandalised; therefore, the research team were not able to collect data from them.

Monitoring probes G and H were installed in one of the first cells constructed in the landfill; this cell had been covered for several years. As shown in Table 1, the average CH_4

concentrations for probes G and H were 1.58% *v*/*v* and 0.69% *v*/*v*. The average concentration sampled from probe G exceeded the threshold limits; however, the levels from probe H were closer to the threshold limit for CH_4 concentration. This shows that the decomposition process of waste continues after many years of burial. Thereby, the LFG continues to be generated; thus, constant monitoring in landfills needs to be carried out even after the closure of the landfills (Njoku et al., 2022). The highest levels of CH_4 were recorded in probes I (2.3% *v*/*v*), J (2.33% *v*/*v*), and M (2.56% *v*/*v*). These monitoring probes were situated closer to the current dumping site in the landfill. However, monitoring probe M was situated closer to an already closed cell in the landfill. Probes G, I, J, K, and M all exceeded the maximum limits for CH_4 emissions. This is approximately 33% of the total monitoring probes installed in the landfill.

The CO_2 emission from the landfill ranged from 3.40 to 6.74% *v*/*v*. The monitoring probe H had the lowest emissions, with a value of 3.59% *v*/*v* However, it was observed the probes I (6.47% *v*/*v*), J (6.65% *v*/*v*), K (6.44% *v*/*v*), O (6.68% *v*/*v*), and R (6.74% *v*/*v*) recorded the highest concentrations from the landfill. Furthermore, it was observed that all the monitoring probes exceeded the emission threshold limits for carbon dioxide. Beirne et al. (2010), in a study on an autonomous greenhouse gas measurement system for analysis of gas migration on an Irish landfill site, showed that CH_4 gas remained below the threshold limit of 1.0% *v*/*v* throughout the experiment period. However, this current study recorded CO_2 concentration level varied over the duration of the data presented and exceeded the threshold limit (1.5% *v*/*v*). Furthermore, Pehme et al. (2020) conducted a study on the spatial distribution of LFG degradation in bio-cover using the GA 2000 landfill gas analyser. It was observed that the highest value of CO_2 recorded was 1.0 % *v*/*v*. The study concluded that CO_2 migration to the atmosphere was low and the gases fluctuated according to the seasons.

3.4.1 Average CH_4 and CO_2 correlation

In this study, a correlation analysis of CH_4 and CO_2 emissions from the landfill was carried out with the purpose of understanding the dynamics governing the LFG emissions. Also, to comprehend patterns and trends in the emission profiles over time.

For the correlation analysis, coefficient close to +1 or -1 indicates a strong correlation, while values closer to 0 suggest a weaker correlation. There was a weak correlation between CH_4 and CO_2 concentrations ($R = 0.18$) ($p < 0.001$). Higher levels of CO_2 were recorded during the study (Table 3; Figure 6). This could be because CO_2 is generated not only from the biodegradation process but also from the oxidation of CH_4 and from soil respiration. CH_4, once generated, can move through the cover soil and become oxidised into CO_2, leading to increased CO_2 emissions. Heavy excavations and diggings in the landfill can disturb the LFG generation and the flow of the gases. This activity will introduce oxygen into the landfill, disrupting the anaerobic process and increasing the aerobic process, resulting in the production of CO_2 and water as by-products. Since the CH_4 generation (anaerobic process) is disturbed by the introduction of oxygen, there will be less CH_4 generation and subsequently lower emissions. This could be what leads to the higher concentration of CO_2 emission from the landfill. Similarly, Popita et al. (2015) showed that CO_2 emissions were observed to be higher than CH_4 emissions in Romania. Pinheiro et al. (2019) explained that the oxidation of CH_4 within the landfill, the poor LFG collection system, and the pressure are the reasons the CO_2 concentration was higher than the CH_4 concentration. Similar results were found by Li et al. (2020). Conversely, Pehme et al. (2020) reported that CH_4 emission was higher than CO_2 emission from the Kudjape Landfill is located in Estonia.

Table 3.2 shows that during the winter season of 2020, CH_4 and CO_2 concentrations observe a strong negative correlation (−0.73), which was statistically significant at $p < 0.001$. The negative correlation between CH_4 and CO_2 emissions can be attributed to the intricate dynamics of their generation and interactions within the landfill environment. When CH_4 is produced through anaerobic degradation of organic matter in the landfill, it is often accompanied by CO_2. However, the relative proportions of CH_4 and CO_2 can be influenced by the availability of oxygen within the landfill. When oxygen is limited (anaerobic conditions), CH_4 production is favoured. Conversely, if oxygen is present (aerobic conditions), CO_2 production is more prominent. As shown in Figure 3.5, the CO_2 concentration showed a constant rise whereas the CH_4 concentration showed a constant decline over the period. The decline in CH_4 is because of reduced oxygen entering into the landfill. During the winter period of 2020, with lower temperatures and lower rainfall, there were expectations of soil respiration and a higher rate of CH_4 oxidation, especially in areas where there is a hotspot area (high LFG concentration detected). A similar result was observed by Xu et al. (2014) where CH_4 and CO_2 emissions had a high linear correlation during the winter season. A different correlation was observed in the winter of 2021. Table 3.2 shows that in the summer of 2020, Pearson's correlation between the CH_4 and CO_2 emissions was −0.07 (a weak negative correlation) and was statistically significant ($p < 0.001$). However, for the summer of 2021, Table 3.2 shows a strong correlation (0.64) between CH_4 and CO_2. As CH_4 emissions increased, CO_2 emissions also increased.

CO_2 respiration and CH_4 oxidation are highly dependent on temperature, and other anthropogenic activities in the landfill. According to Czepiel et al. (2003), the oxidation rate in cover soil was 30% CH_4 generated inside the Nashua, New Hampshire municipal landfill in summer; however, in winter 0% CH_4 emission was reported. The diurnal variation in photosynthetic CO_2 uptake by leaves from vegetation grown on the cover soil or around the landfill might affect the LFG emissions, especially in the summer season, since leaf CO_2 uptake is driven by photosynthetically active radiation. This could also change the ratio of CH_4 and CO_2 emission rates. Table 3.2 shows a Pearson's correlation between CH_4 and CO_2 at 0.6, which was statistically significant at $p < 0.04$. There was a strong relationship between the CH_4 and CO_2 concentrations. This could be because of higher soil CO_2 respiration and higher oxidation rate of CH_4 from the top cover soil. As a result, the CO_2 emission rate was probably higher than the CO_2 production rate associated with CH_4 production, while the CH_4 emission rate was lower than the production rate.

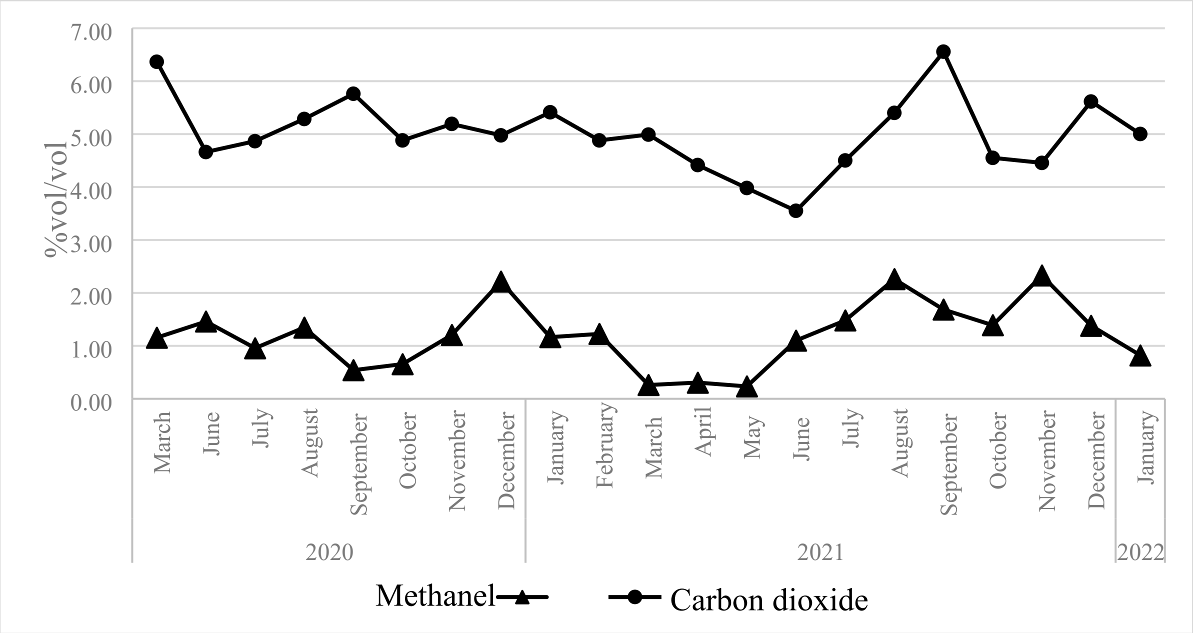

Figure 3.5. Average CO_2 and CH_4 concentrations observed during each month (March 2020–January 2022).

Table 3.2: Pearson's correlation coefficients and p-values between the CH_4 and CO_2 emissions during the different seasons

	Pearson correlation	***p*-value**
Winter 2020	-0.73	$p < 0.001$
Summer 2020	-0.07	$p < 0.001$
Winter 2021	0.64	$p < 0.001$
Summer 2021	0.60	p < 0.04

Table 3.3: Pearson's correlation coefficients and p-values between the selected meteorological parameters and LFG data during the periods studied in 2020 and 2022.

Meteorology	**CH_4**		**CO_2**	
	Pearson correlation	***p*-value**	**Pearson correlation**	***p*-value**
Temperature	0.31	$p < 0.001$	0.39	$p < 0.001$
Rainfall	-0.17	$p < 0.01$	0.10	$p < 0.001$
Wind speed	0.39	$p < 0.001$	0.10	$p < 0.001$
Barometric pressure	-0.10	$p < 0.001$	-0.25	$p < 0.001$
CO_2	0.18	$p < 0.001$		

3.5 Influence of Meteorological Conditions on the CH_4 and CO_2 Levels

LFG generation is dependent on several meteorological factors such as temperature, wind speed, rainfall, barometric pressure, and humidity of the environment. This study investigates the impacts of ambient temperature, rainfall, barometric pressure, and wind speed on the CH_4 and CO_2 emissions from the Thohoyandou landfill. Firstly, Pearson's correlation was determined to understand the relationship between the meteorological data and the LFG emissions. Furthermore, a regression analysis was conducted to determine to what extent the meteorological conditions influence the LFG emissions (Tables 3.3 – 3.5). Table 3.3 shows Pearson's correlation coefficients and the *p*-values between the selected meteorological parameters (ambient temperature, rainfall, barometric pressure, and wind speed) and the CH_4 and CO_2 concentrations. Tables 3.4 and 3.5 show the regression analysis of the meteorological data and the LFG concentrations. The study hypothesises that there is a significant influence of the meteorological data on the LFG concentration.

Table 3.4. Regression analysis of CH_4 and meteorological data.

Meteorology parameters	**R squared**	**Adjusted R squared**	**Mean square**	***F***	***p*-value**
Barometric pressure	0.01	0.051	0.39	2.07	0.17
Ambient temperature	0.03	-0.02	0.10	0.56	0.46
rainfall	0.15	0.11	1.12	3.36	0.08
Wind speed	0.01	-0.04	0.08	0.20	0.66

Table 3.5: Regression analysis of CO_2 and meteorological data

Hypothesis	**R squared**	**Adjusted R squared**	**Mean square**	***F***	***p*-value**
Barometer	0.15	0.11	1.52	3.37	0.82
Ambient temperature	0.01	-0.04	0.10	0.20	0.66
Rainfall	0.09	0.04	0.92	1.90	0.18
Wind speed	0.06	0.01	0.59	1.18	0.29

3.5.1. Ambient Temperature

A weak but positive correlation coefficient of 0.31 was observed between the ambient temperature and CH_4 emission and was statistically significant at $p < 0.001$ (Table 3.4). This means that there is a significant positive relationship between the ambient temperature and the CH_4 emissions from the landfill. High temperature leads to higher microbial activities in the landfill which in turn increase the CH_4 generation rates or CH_4 oxidation rates (Aghdam, 2019). Aghdam (2019) observed that CH_4 emissions were correlated with soil temperature. In 2021, the CH4 concentration was at its lowest in May (0.24% v/v), coinciding with one of the lowest temperatures of the year (17°C). The temperature in June was also relatively low at 16°C. The low temperature at that time influenced the CH_4 concentration in the landfill; low temperature reduces the activities of the bacteria in the landfill, thereby reducing CH_4 generation and emission (Braker et al., 2010). In addition, it was observed that in November of 2021, the highest levels of CH_4 concentration (value at 2.33% *v*/*v*) and highest temperature levels (25.6 ˚C) were recorded (Figure 3.6).

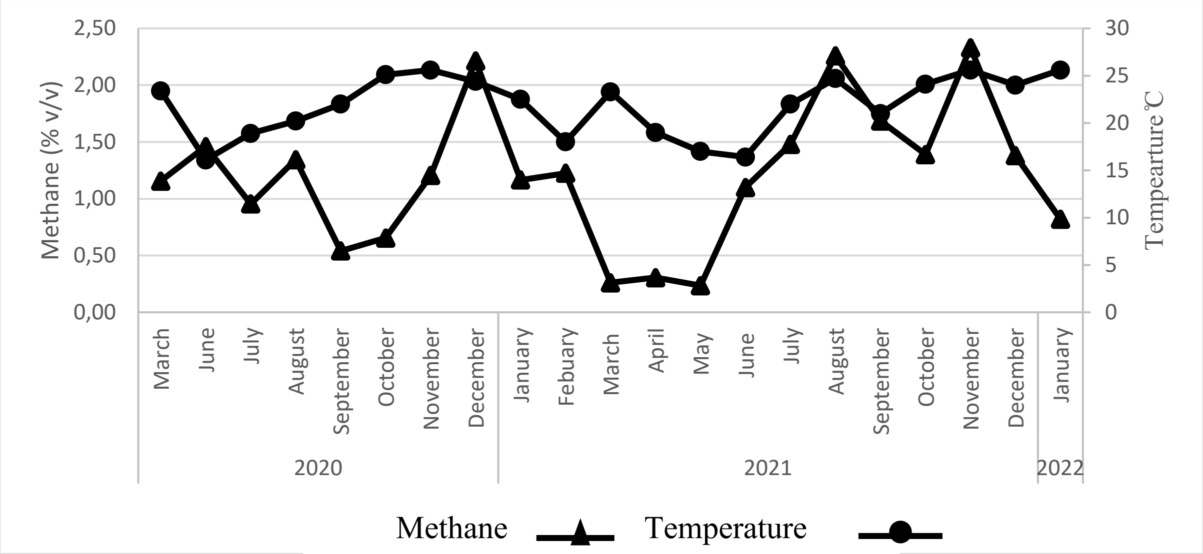

Figure 3.6. Average CH_4 concentration observed during each month (March 2020–January 2022) with ambient temperature.

CH_4 concentration was regressed on predicting variables ambient temperature. The results showed that ambient temperature does not significantly predict the CH_4 emissions at $p = 0.46$. However, there is a 2.9% chance that the changes in ambient temperature may influence the CH_4 emissions ($R^2 = 0.029$). Temperature changes will have a far greater effect on LFG production in shallow landfills than in very deep landfills. This is because the bacteria are not as covered with cover materials as compared with very deep landfills where thick layers of soil cover the waste. Meanwhile, colder temperatures inhibit bacterial activity (Reddy et al., 2019; Schupp et al., 2020). The Thohoyandou landfill is a deep landfill, with some parts of the landfill covered with a thick layer of soil cover and some parts still receiving waste. Variations in landfill cover materials can result in temperature fluctuations within the landfill. Other factors that can contribute to temperature variations include seasonal changes, waste composition, moisture content, gas collection and management practices, landfill design and construction. This can affect the overall LFG generation and emission from the landfill.

Table 3.3 shows a weak but positive correlation between temperature and CO_2 concentration of 0.39 which was statistically significant ($p < 0.001$). This is evident that as the temperature increases so does the CO_2 emission increase. Looking at the Figure 3.7, the lowest CO_2 concentration was recorded in the month of June 2020 (4.66% *v*/*v*), and the lowest temperature reading was observed in the same month of June 2020 (16.1 ˚C) (Figure 3.7). Also, from the Figure 3.7, in 2022, the lowest concentration of CO_2 was recorded in the month of June (3.55% *v*/*v*). Similarly, the lowest temperature was recorded in the month of June (value at 16.4 ˚C).

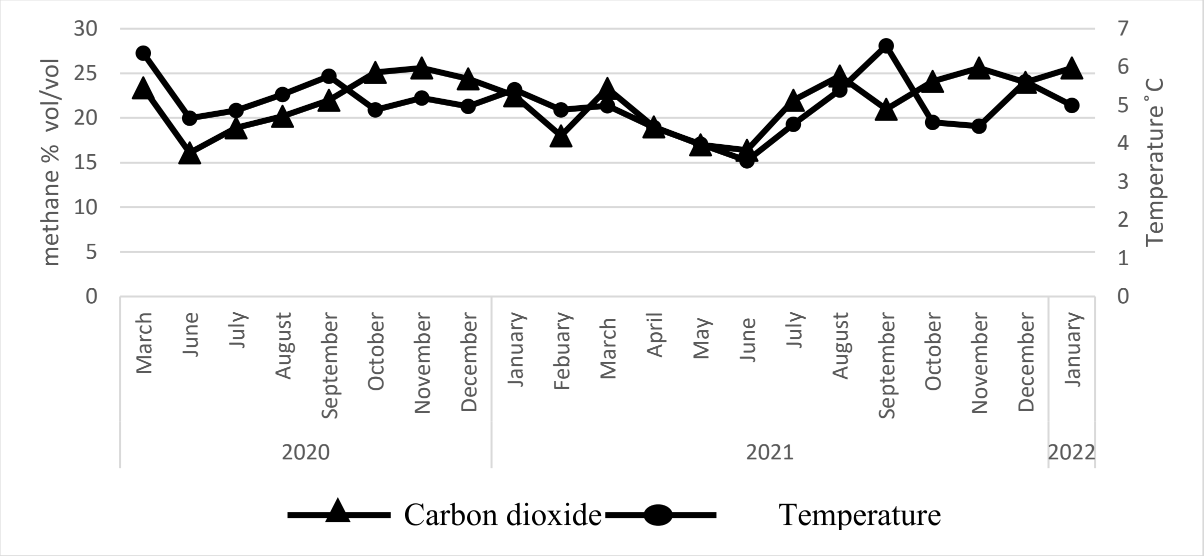

Figure 3.7. Average CO_2 concentration observed during each month (March 2020–January 2022) with ambient temperature.

The dependent variable (CO_2 concentration) was regressed on predicting variables (ambient temperature) to understand to what extent does the temperature influence the CO_2 emissions (Table 3.5). The results show that there is no significant difference between the ambient temperature and CO_2 emissions at $p = 0.66$. However, there is a 1% chance that the changes in ambient temperature influence the CO_2 concentrations at $R^2 = 0.01$.

In a comparison between the results shown in Figures 3.6 and 3.7, it was observed that CH_4 concentration seems to have more variation across the period compared to CO_2. CH_4 exhibited a range spanning approximately 0.2% to 2.2%, representing an elevenfold variation. On the other hand, CO_2 showed a narrower range, fluctuating between approximately 15% and 28%, which translates to a difference of less than twofold. This could be a result of CH_4 oxidation in the cover material of the landfill. Some other factors that could influence the variations could be bacteria, temperature, wind speed, and rainfall. Additionally, the presence of other organic compounds in the landfill, such as volatile organic compounds (VOCs), can also contribute to the high variance in CH_4 over CO_2 (Gong et al., 2018). VOCs can be broken down by bacteria in the landfill, releasing CH_4 and other gases as by-products and reducing CO_2 concentrations.

3.5.2. Barometric Pressure

The barometric pressure showed a weak and negative correlation with CH_4 and CO_2 emission with values of −0.10 and −0.25, respectively, during the duration of the study (Table 3.3). This means there is a slightly inverse relationship between the changes in CH_4 and CO_2 concentrations and barometric pressure. Also, correlations of barometric pressure and the LFG concentration varied significantly at $p < 0.001$. As the Barometric increased the CH_4 and CO_2 emissions decreased. Rachor et al. (2013) showed a similar result, two CH_4 emission hotspots (1 and 20) showed an inverse relationship with pressure in a Pearson's correlation analysis (R = −0.64). The hotspot was distinguished by its unique location near the top of the landfill, where the cover is incredibly thin and exposure to the effects of wind, atmospheric pressure, and temperature is greatest. Similarly, Delgado et al. (2022) showed that a strong inverse correlation emphasises how pressure enhances air access into the landfill surface layers; this prevents CH_4 from escaping into the atmosphere.

Figure 3.8 illustrates the relationship between the barometric pressure and CH_4 concentrations. It was evident that the barometric pressure at its peak or lowest points resulted in decreasing CH_4 concentrations. The barometric pressure continued to decrease throughout the year; however, December 2020 showed the highest CH_4 concentration reading at 2.22% *v*/*v*. Furthermore, in 2021, the lowest CH_4 concentration was identified in the month of May at a value of 0.24% *v*/*v*, and the barometric pressure was observed to be at one of its highest values during that same period at a value of 95.19 kPa.

The dependent variable (CH_4 concentration) was then regressed on barometric pressure (Table 3.4) to know to what extent does the inverse relation occur. Table 3.4 shows that barometric pressure does not significantly predict landfill gas emissions ($p = 0.17$). However, there is a 9.8% chance that the changes in barometric pressure influence the CH_4 concentrations at $R^2 = 0.098$. That is, the changes in the increase in barometric pressure have a 9.8% chance of influencing the CH_4 concentration emitted from the landfill. Higher barometric pressure infuses more air into the landfill, which affects the stability of the LFG generation and overall concentration. When air is introduced into the landfill, the presence of oxygen is increased, thereby increasing the aerobic bacteria activities in the landfill, producing more CO_2 and less CH_4 generation. During the study, there were different landfill activities that disturbed the daily operations of the landfill and eventually disturbed the LFG generation and emission in the landfill. Xu et al. (2014) showed that landfill CH_4 emissions strongly depended on variations in barometric pressure; increasing barometric pressure suppressed the CH_4 emission, while decreasing barometric pressure improved the CH_4 emission, a phenomenon called barometric pumping. Similar results were also observed by Aghdam et al. (2019).

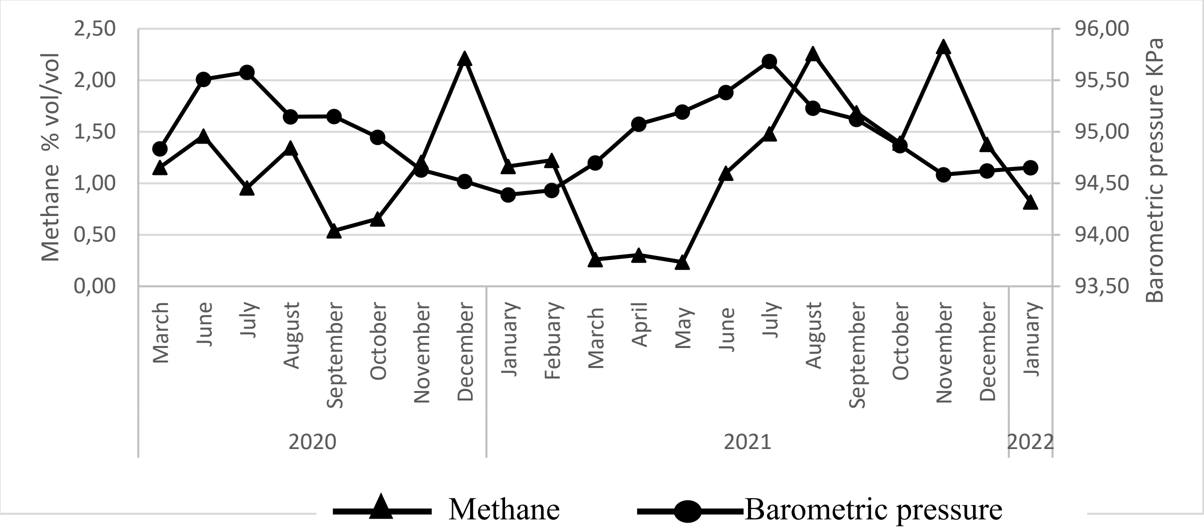

Figure 3.8. Average CH_4 concentration observed during each month (March 2020–January 2022) with barometric pressure.

A strong linear relationship was identified between CO_2 emissions and atmospheric pressure, as evidenced by a high coefficient of determination ($R^2 = 0.95$). Pearson's correlation (−0.25) shows a weak correlation between the barometric pressure and CO_2 concentrations. There is a significant difference between barometric pressure and CO_2 concentration ($p < 0.001$). This means that there is a relationship between barometric pressure and CO_2 emissions. In June 2020, the lowest concentration of CO_2 was recorded, at 4.66% *v*/*v*; however, there was sharp increase in barometric pressure at that time. Throughout the year 2020, there was a consistent decline in barometric pressure. However, the CO_2 concentration fluctuated, ranging from its lowest concentration of 0.5% v/v to its highest concentration of 2.3% v/v. At the beginning of the year 2021, there was a constant increase in barometric pressure, as the increase continued, the records show a constant decline in CO_2 concentration reading (Figure 3.9).

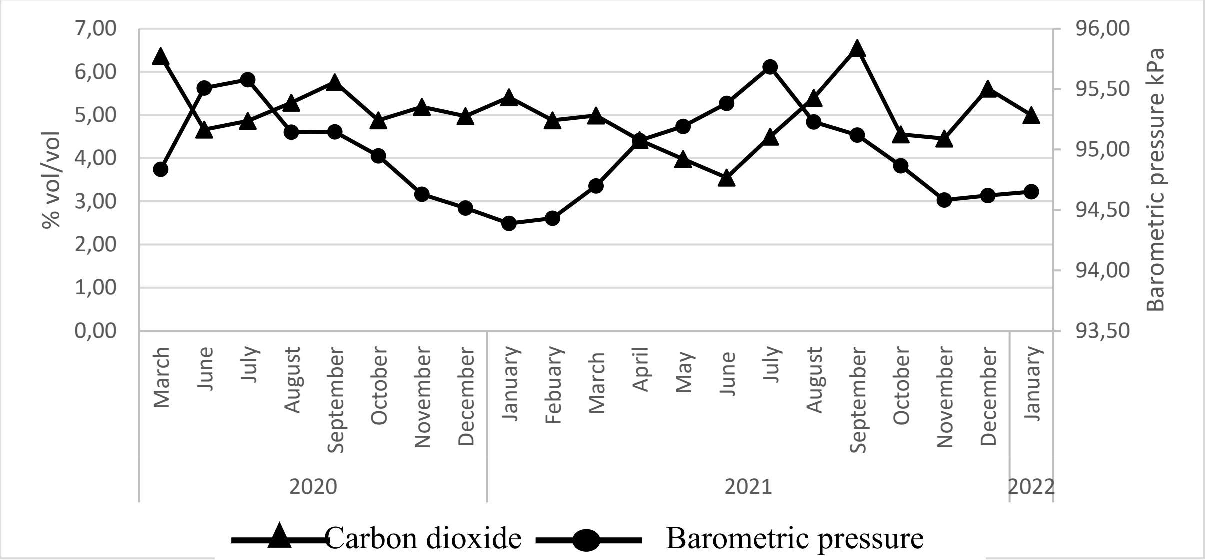

Figure 3.9. Average CO_2 concentration observed during each month (March 2020–January 2022) with barometric pressure.

The dependent variable (CO_2 concentration) was regressed on predicting variables (barometric pressure) (Table 5). The barometric pressure does not significantly predict the CO_2 emission concentrations (p = 0.82). However, there is a 15 % chance that the changes in barometric pressure influence the CO_2 concentrations ($R^2 = 0.15$) during the duration of the study. That is, the variations in the increase in barometric pressure have a 15% chance of influencing the CO_2 concentration emitted from the landfill.

3.5.3. Rainfall

Rainfall showed a weak correlation with CH_4 concentrations with a value of −0.17 for the duration of the study (Table 3). In addition, the relationship was statistically significant ($p < 0.01$). This means that there is a relationship between rainfall and CH_4 concentration. Rainfall increases the soil moisture content and decreases oxygen levels, which regulates nitrification and denitrification and also limits bacteria activities in the soil. Bian et al. (2020) observed that the degree of decrease in CH_4 emissions was closely correlated with the rainfall intensity. This is because a more significant increase in water content under heavier rainfall leads to a great reduction in LFG movement due to reduced microbial CH_4 oxidation activity.

Figure 3.10 illustrates the relationship between rainfall and the CH_4 concentration. It shows that the lowest CH_4 concentration (0.54% *v*/*v*) occurred in the year 2020; low rainfall was recorded at that time (value at 1.2 mm), in September 2020. The highest CH_4 concentration was recorded in the month of December 2020 (value at 2.2% *v*/*v*). This affirms that the increasing rainfall increased the moisture content in the topsoil and waste pile, thereby increasing bacteria activities and CH_4 generation and emission. Due to the low rainfall intensity, the moisture content of the top cover soil was low and permeability was not obstructed; therefore, the top cover soil did not impede CH_4 emissions. For 2021, Figure 3.10 shows that CH_4 in its lowest concentration was observed in the month of May (0.24% *v*/*v*) and there was no rainfall recorded in that month. The low rainfall affected the moisture content in the landfill, reducing bacteria activities and thereby reducing CH_4 generation and emission. In addition, it was observed that in November of 2021, the CH_4 concentration exhibited the highest readings of CH_4 emissions from the landfill.

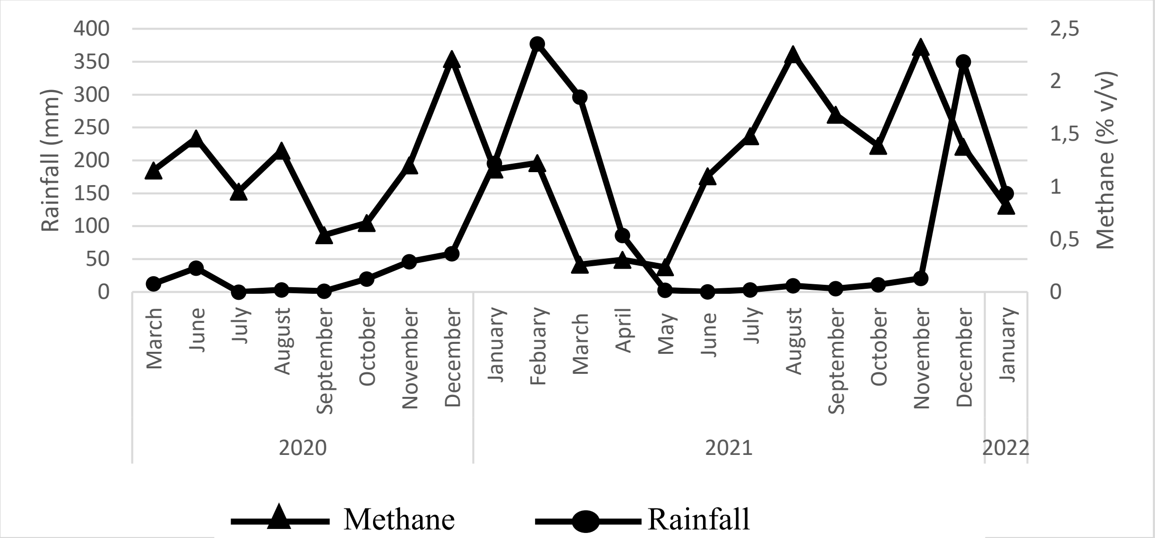

Figure 3.10. Average CH_4 concentration observed during each month (March 2020–January 2022) with rainfall

The dependent variable (CH_4 concentration) was regressed on predicting variables (rainfall) (Table 3.4). The rainfall does not significantly predict the CH_4 emissions at $p = 0.082$. However, there is a 1.5% chance that the changes in rainfall influence the CH_4 concentrations at $R^2 = 0.015$ during the duration of the study. According to Yang et al. (2016), heavy rainfall can cause the top cover soil of the landfill to be waterlogged, thereby decreasing the permeability of the top cover soil. Since LFG moves better in areas of high soil permeability, the decreased pores in the landfill cover restrict LFG emissions at that period of time.

Notwithstanding, a certain amount of moisture content in the landfill can increase bacteria activities and transports nutrients, thereby increasing LFG concentration in an anaerobic condition. A moisture content of 40% or higher, based on the wet weight of waste, encourages maximum LFG generation, especially in a closed landfill. A waterlogged top cover soil will inhibit LFG emission (Johari et al., 2012).

The dependent variable (CO_2 concentration) was regressed on predicting variables (rainfall) (Table 3.5). The results show that there is no significant difference between the rainfall and CO_2 concentrations emitted at $p = 0.18$. However, there is a 9.1% chance that the changes in rainfall influence the CO_2 concentrations at $R^2 = 0.091$ during the duration of the study. Figure 3.11 gives the average CO_2 concentration observed during each month (March 2020–January 2022) with rainfall.

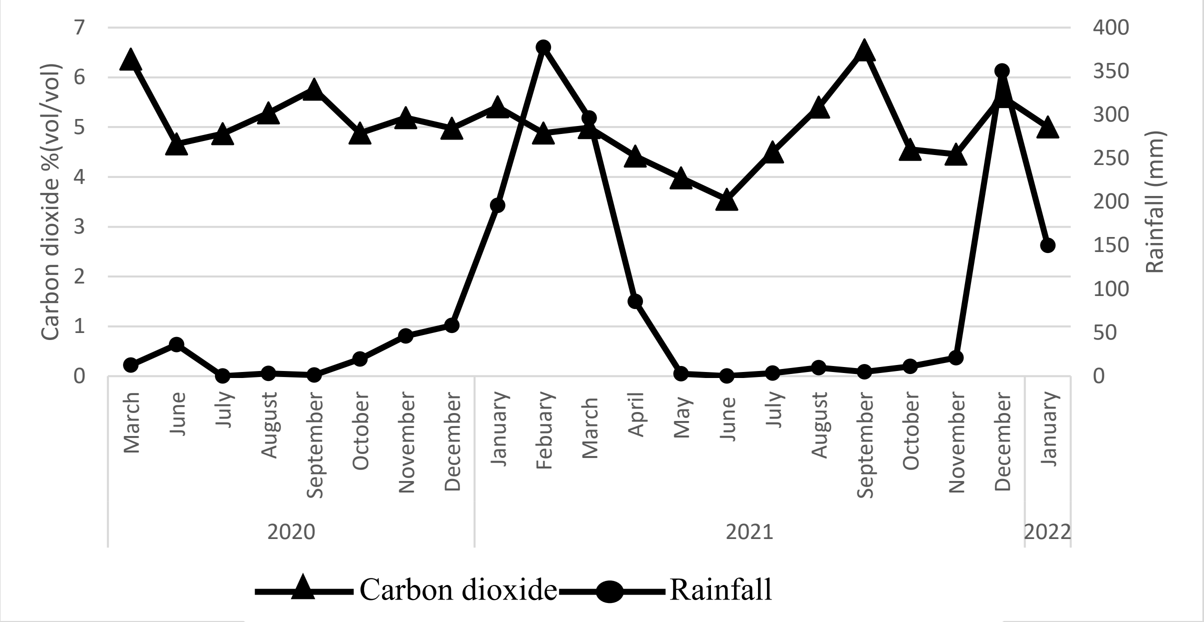

Figure 3.11. Average CO_2 concentration observed during each month (March 2020–January 2022) with rainfall.

3.5.4. Wind Speed

Table 3.3 shows a weak correlation between the wind speed and the CH_4 concentration for the duration of the study (value of 0.39), and the correlation is statistically significant ($p < 0.001$). Similar results were observed by Kissas et al. (2021), who showed a weak correlation between CH_4 fluxes and wind speed ($r = 0.21$, $p < 0.001$). Figure 3.12 shows that the lowest CH_4 concentration was recorded in September 2020 at 0.54% *v*/*v*, and a high wind speed was recorded in the same month (value at 2.72 m/s). In addition, the month of October recorded the highest wind speed at a value of 2.84 m/s, but there was a slight increase in CH_4 concentration (value at 0.66% *v*/*v*). Furthermore, the lowest concentration of CH_4 in 2021 was observed in the month of May at 0.24% *v*/*v* and with an average wind speed of 1.81 m/s. In addition, the highest concentration of CH_4 in 2021 was observed in the month of November at 2.33% *v*/*v* and an average wind speed of 2.76 m/s. Several studies have identified that wind induces advection as one of the dominant CH_4 emission mechanisms in windy conditions at landfills (Xin et al., 2016 and Aghdam et al., 2019). Wind blowing across a landfill can cause a pressure difference, which is the driving force for advective gas transportation. This means that a strong wind speed can create a pressure difference between the landfill body and the landfill surface, which in turn can affect LFG generation and emissions from landfills. CH_4 concentrations were regressed on predicting variables (wind speed) (Table 3.4). Wind speed does not significantly predict the CH_4 at $p = 0.66$. However, there is a 1.1% chance that the changes in wind speed influence the CH_4 concentrations at $R^2 = 0.011$ during the duration of the study. The predominant perception is that the effect of wind speed on LFG emissions is indirect, as it creates the pressure-pumping effect that facilitates advective gas transportation. Moreover, Kissas et al. (2021) suggested through model simulations how increased wind speed brings about changes in the pressure gradient between the soil and the atmosphere, resulting in increased surface CH_4 emissions.

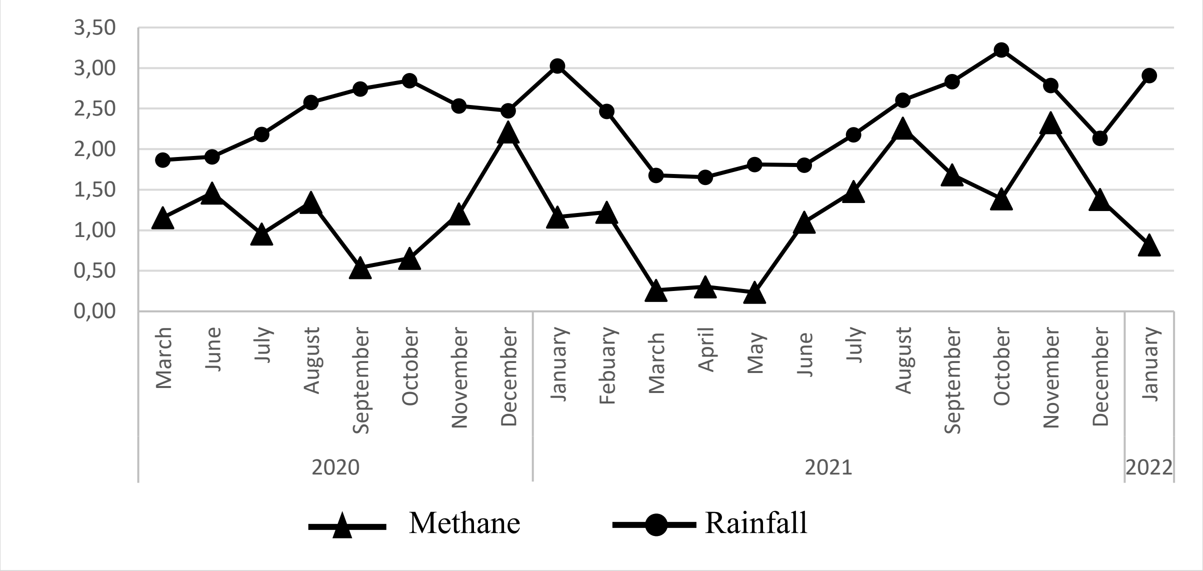

Figure 3.12. Average CH_4 concentration observed during each month (March 2020–January 2022) with wind speed.

Table 3.3 shows a weak correlation between wind speed and CO_2 concentration with a value of 0.10, which was statistically significant ($p < 0.001$). Figure 3.13 shows the results observed in the correlation between wind speed and CO_2 concentrations. The lowest CO_2 concentration was recorded in the month of June 2020 (value at 4.66% *v*/*v*); also, in the month of June 2020, the wind speed was recorded at one of its lowest values (1.91 m/s).

CO_2 concentration was regressed on predicting variables (wind speed) (Table 3.5). The results show that there is no significant difference between wind speed and CO_2 concentrations emitted $p = 0.029$. However, there is a 5.9% chance that the changes in rainfall influence the CO_2 concentrations at $R^2 = 0.059$ during the duration of the study.

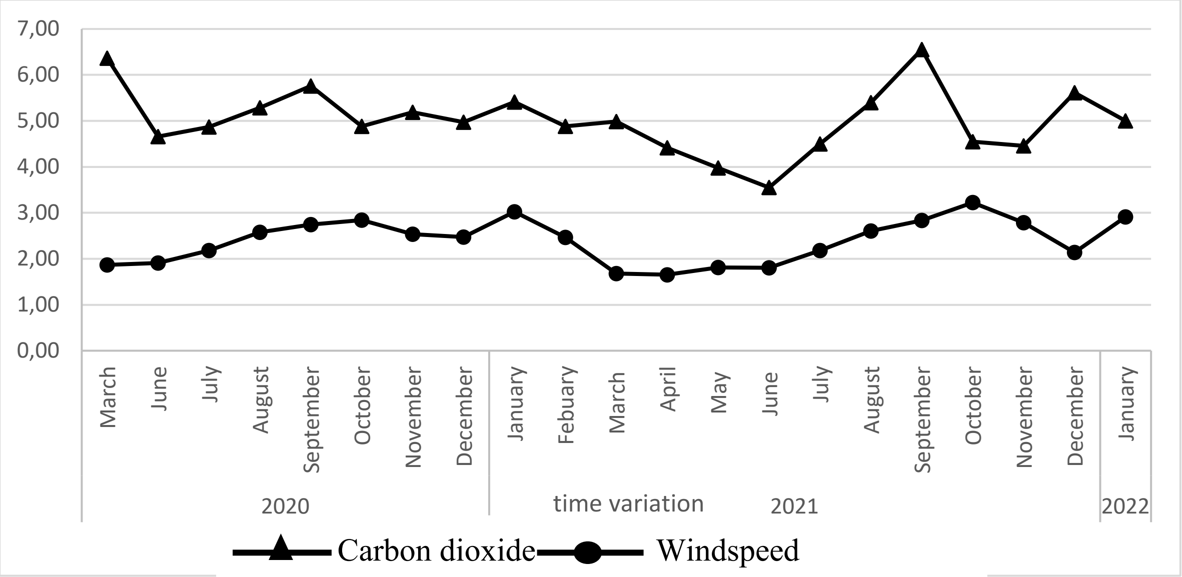

Figure 3.13. Average CO_2 concentration observed during each month (March 2020–January 2022) with wind speed.

3.6 Limitations of the study

Short Monitoring Period: The study's brief monitoring timeframe might not capture long-term trends or gradual changes in landfill gas emissions.

Study Area Specificity: The study's focus on Thohoyandou landfill restricts the general applicability of findings to other landfill sites with differing characteristics.

Limited Depth: The installation of monitoring probes at a depth of 1-3 meters might not capture the full vertical extent of gas migration, especially in deeper landfill layers. This could lead to an incomplete understanding of subsurface gas movement.

Vandalism and Theft: Despite efforts to prevent vandalism and theft by using non-metallic materials, the absence of proper security measures, like fencing, led to the vandalisation of some probes. This could impact on the data completeness.

3.7 Conclusions

Landfill gas monitoring probes were deployed on a landfill site, and LFG monitoring for a duration of two years (November 2019–January 2022) was successfully conducted. This study validates that LFG migrates along the subsurface of the landfill through the pores and cracks of the soil. The study concludes that CH_4 concentrations were observed to be lowest in areas far away from the landfill activities such as the entrance of the landfill. Higher concentrations of CH_4 were observed in areas where the landfill cells have been closed for a long time. However, the highest concentrations of CH_4 were recorded in areas closer to the current dumping of waste. These high CH_4 concentrations were above the South African CH_4 emission limits from landfills. CO_2 concentrations for the duration of the study surpassed the South African CO_2 emission limits from landfills.

Furthermore, the study concludes that the CH_4 and CO_2 generation and emission are complex processes influenced by landfill activities and meteorological conditions around the landfill. All meteorological conditions that were selected for this study, namely barometric pressure, temperature, rainfall, and wind speed, were either negatively or positively correlated with the LFG concentration and were all statistically significant.

The study relates to sustainability and demonstrates the importance of monitoring LFG emissions to ensure that they are within the South African emission limits. This is important for maintaining a sustainable environment, as LFG emissions can have a negative impact on air quality and climate change. By monitoring these emissions, based on the data captured important policies and legislations can be put in place to ensure the LFGs are kept within acceptable limits, thereby protecting the environment and promote sustainability.

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CHAPTER FOUR: Quantification and modelling of methane and carbon dioxide surface emissions from a South African landfill

Preamble

A comprehensive analysis of Thohoyandou landfill entails the monitoring of the sub-surface concentration, surface emission and ambient air quality surrounding the landfill. The sub-surface monitoring of LFG has been carried out in **Chapter 3**. The study used a combination of static flux chamber measurements and LandGEM to quantify the surface LFG emissions, with particular emphasis on understanding the impact of the seasons of the year, on the phenomenon. There is limited data on surface emissions of LFGs from South African landfills, especially in rural areas like Thohoyandou. Findings from this study, will contribute to filling this existing data gap and also holds significance for informing the development of policies, bylaws, and regulations pertaining to LFG emissions management. Furthermore, the data generated from this study will serve as a foundation for future studies on LFG emissions, facilitating more accurate assessments and informed decision-making in landfill management practices.

Abstract

LFG emissions, primarily composed of CH_4 and CO_2, result from the decomposition of organic waste in landfills. South Africa, like other developing countries, are faced with challenges related to managing emissions of LFG and effectively handling landfill sites. Uncontrolled LFG migration can lead to health hazards, environmental pollution, and even fires. The Thohoyandou landfill site was divided into four distinct sample areas - capped, active, leachate and virgin areas. For this study, a static flux chamber was used to sample CH_4 and CO_2 emissions; LFG samples were analysed using gas chromatography; a LandGEM was used to model the LFG emissions and emission rates were calculated based on concentration, sample area, chamber volume, and duration of sample collection. To validate the results from the LandGEM model, the real time results derived from the analysis from the gas chromatography was used.

The study showed that the CH_4 emission in the capped area had a concentration of 360819.80 mg/m^3, with an average emission rate of 433.00 g/m^2/day, resulting in 6363.43 Mg/year in wet season. The active area was observed to have emitted the highest CH_4 concentration (419863

mg/m^3). The lowest CH_4 concentration (45922.52 mg/m^3) was emitted from the virgin area, where, an average emission rate of 55.11 g/m^2/day, resulting in 605.72 Mg/year were recorded. Similar results based on the sampled area variations, were also observed during the dry season. In other words, the active and capped sample area experienced higher CH_4 emissions than the leachate and virgin sample areas and the concentrations and emission rates of LFGs emitted during the dry season were lower when compared to the wet season.

Similarly, the concentration of CO_2 emissions was higher during the wet season than the dry season. This could be as a result of increased moisture that made the environment favourable for LFG generation. Microbial activities thrive in these moderate moist conditions than in drier area which could have led to the increase in CO_2 generation and emission.

Keywords: Closed flux chamber; Carbon dioxide emissions; Landfill management; Methane emissions.

4.1 Introduction

Landfills are significant sources of GHG emissions, primarily due to the decomposition of organic waste. LFG is primarily composed of CH_4 and CO_2 and other pollutants (Njoku et al., 2018). CH_4, a potent GHG, has over 25 times the warming potential of CO_2 over a century (Kumaş and Akyüz, 2023). Proper waste management, including recycling and reducing organic waste in landfills, can reduce LFG emissions (Moazzem et al., 2021). CO_2, although less potent in the short term, is still a significant contributor to GHG emissions from landfills, which then gradually accumulate in the atmosphere (Yoro and Daramola, 2020). Landfills pose health and environmental risks, including, litter, dust, rodent infestations, and fires (Chaudhary et al., 2021; Anand et al., 2021; Njoku et al., 2019). Uncontrolled LFG migration can lead to fires, thereby impacting nearby communities (Manjunatha et al., 2023; Bihałowicz et al., 2021). Several recent landfill fires have occurred in South Africa (Lombard, 2020; Duze, 2019) and this has lead researchers and various stakeholders worldwide to conduct studies to quantify LFG emissions (Acker, 2020; Gallego et al., 2014; Atabi et al., 2014). This is in an effort to address and mitigate the environmental and public health challenges, associated with landfills. Monitoring and quantification of the surface LFG emissions are crucial for environmental protection and require the attention of scientists and policy-makers to develop effective strategies for reduction.

The Thohoyandou landfill has a significant environmental and public health concerns, currently it lacks any form of LFG monitoring system. Establishing such a system to monitor and quantify LFG emissions at this landfill is critical for effective environmental protection in the South African context. The specific data collected through this monitoring will play a pivotal role in shaping policies and strategies for landfill management, LFG control, and waste management practices. This, in turn, becomes a crucial step toward mitigating the adverse impact of landfills on both the environment and the well-being of humans, especially, those residing or working in Thohoyandou city.

To quantify the LFGs emissions, a static flux chamber has been developed and used by several scholars (Yilmaz et al., 2021; Gamez et al., 2019; Gollapalli and Kota, 2018). This flux chamber involves a closed chamber, typically cylindrical or square-shaped and impermeable to the gas being measured, being placed over the landfill surface. The chamber is sealed to create a closed system, thereby, preventing gas exchange with the surrounding atmosphere,; gas concentrations inside the chamber are monitored over time to calculate the gas flux (Gollapalli and Kota, 2018). This static flux was employed to assess CH_4 and CO_2 emissions from Thohoyandou landfill, followed by analysis using a thermal desorption-gas chromatography/mass spectrometry (TD–GC/MS) system. While previous research has contributed valuable insights into the LFG emissions across developed nations, there is still a significant need for further studies on quantifying LFGs emissions from South African landfills, with a specific focus on the Thohoyandou landfill as a case study. There is limited data on the surface emission of LFGs from landfills in South Africa, hence, this study aims to quantify the LFG fluxes from the Thohoyandou landfill site, building upon the earlier research conducted by Njoku et al. (2020). Njoku et al. (2020) utilised models, specifically the LandGEM and Afvalzorg models, to estimate CH_4 and CO_2 emissions from the Thohoyandou landfill site. Using standard parameters from literature for LFG emissions can be misleading due to different local factors, like climate and waste management practices. Determining site-specific LFG emissions should also be considered to improve model accuracy, thus, site-specific data is crucial for reliable LFG emission modelling. In this current study, a comparison of the results using the flux chamber and the LandGEM model was achieved.

The results from this study showed site-specific insights that were not captured by a broader or generalised studies. This local context enhanced the relevance and applicability of the findings, especially for stakeholders involved in managing the Thohoyandou landfill. Through the assessment of inefficiencies in current landfill management practices, particularly in relation to cap design and waste accumulation, this study also highlights opportunities for improvement in LFG control and mitigation in the Thohoyandou landfill. These improvements are crucial and should be addressed to avoid illnesses, premature death, and environmental destabilisation.

4.2 Methodology

4.2.1 Study area

Thohoyandou landfill was subdivided into four areas which included A (capped areas); B (active area); C (leachate) and D (virgin areas) as shown in Figure 4.1. The use of the static flux chambers has limitations in terms of not providing comprehensive coverage of the entire landfill area, and it may not effectively address the variability in emissions across the entire surface area of the landfill (Pehme et al., 2020). To mitigate this constraint, a systematic sampling strategy was employed, aiming to collect data from all four designated regions within the landfill. The data collection strategy involved the application of kriging interpolation methods to obtain measurements representative of the entire landfill area (Acker, 2020; Allen et al., 2019).

Figure 4.1: Map of Thohoyandou showing the sampling sections. Source: Google earth pro

Sample area A (capped area) - the capped area of the landfill refers to a section of the landfill that has been covered with topsoil (clay and construction rubbles) permanently. This is because the cells in that area are full and no longer receiving waste. The topsoil is designed to create a barrier that minimises the migration of gases vertically into the atmosphere.

Sample area B (active area) - the active area in the landfill refers to the area of the landfill that has not yet been covered with a final topsoil, unlike sample area A. This area is typically still active and receives new MSW daily.

Sample area C (leachate area) - The leachate area of the landfill refers to the portion of the landfill where liquid waste (leachate) is stored, collected, and managed.

Sample area C (virgin area) - This section of the landfill is unused for waste disposal purposes. As such, it does not show any accumulation or activity related to waste disposal, however, certain activities do take place in this area. Reclaimers at the landfill utilise it as a storage space for recyclable waste collected from waste piles; additionally, the offices of the landfill are situated in this area.

4.2.2 Quantification of LFG using LandGEM

The LandGEM model was used to model the LFG surface emission because of its ability to model diverse LFGs including CH_4, CO_2 and VOCs/HAPs. The VOCs/HAPs emission result are essential because these gases are very dangerous and can cause severe health challenges if inhaled. The surface emission data of VOCs/HAP was obtained using the LandGEM and then used in the assessment of the potential health risk (carcinogenic and non-carcinogenic) of the residents living close to the landfill. Firstly, the LandGEM results were calibrated or validated using the real-time data derived from the flux chamber sampling technique outlined in this chapter. Secondly, the potential health risk assessment was conducted using the results derived from the calibrated LandGEM model.

The LandGEM (Version 3.02) LFG emission model was created by the U.S. Environmental Protection Agency (EPA) in September 1998. This computational model served the purpose of quantifying emissions, encompassing total LFG, CO_2, CH_4, non-methane organic compounds (NMOCs), and additional airborne pollutants discharged from landfill sites. The model's foundational framework revolves around the utilisation of a first-order decomposition reaction rate, which provides the foundation for assessing LFG emissions. This fundamental equation, presented as Equation 4.1, is the key building block used to estimate LFG emissions within the LandGEM system (Njoku et al., 2020).

$Q_{CH_4} = \sum_{i=1}^{n} \sum_{j=0.1}^{1} kL_0 \left(\frac{M_1}{10}\right) e^{-kt_{ij}}$…………………. equation 4.1

where Q_{CH_4}= estimate annual CH_4 generation in the year of the calculation (Mg/year); *i* is the increment in one year time; n is (year of the calculation) – (initial year of waste acceptance); j is increment in 0.1 year time; k is methane generation rate (/year); Lo is the potential methane generation capacity (m^3 /Mg); M_i is the mass of waste accepted in the i^{th} year (Mg); ti_j is the age of the j^{th}section of waste mass M_i accepted in the i^{th} year.

To use the model, an initial reconnaissance survey was conducted to understand the landfill's operational dynamics and assess the potential feasibility of generating a substantial amount of LFG for potential utilisation. Subsequently, data on the amount of waste deposited in the landfill was sourced from both the local municipality and the South African Waste Information Center (SAWIC).

The input data for the LandGEM includes the

- quantity of MSW deposited at the landfill;
- the year of commencement of landfill operations,
- the landfill's designed full capacity, and
- the composition of waste deposited within the site.

Additionally, the parameters were estimated utilising context-specific values of South Africa, in conjunction with default values established by the IPCC (IPCC, 2006). These parameters included.

- The Degradable Organic Carbon (DOC) values (Table 4.1),
- The potential CH_4 generation capacity (L_0),
- the CH_4 Correction Factor (MCF) for managed anaerobic landfill conditions, and
- the degradation constant (k).

Table 4.1: Values of DOC in the Southern African region (Default parameters from the LandGEM)

DOC (by weight wet basis)	Default	Range
Food waste	0.15	0.08-0.20
Garden waste	0.20	0.18-0.22
Bulk MSW	0.20	0.12-0.28
Sewage sludge	0.05	0.04-0.05
Industrial waste	0.15	0-0.54

Source: IPCC, (2006)

The input data for both models is summarised in Table 4.2. The total amount of waste deposited in the landfill was obtained from the information provided on the SAWIC website and records from the landfill (Table 4.3).

Table 4.2: Input data for the simulation of LFG to run the LandGEM

Data	**Thohoyandou landfill**
landfill commenced operation	2005
Proposed closure year of landfill operation	2030
Degradation constant k (year^{-1})	0.05
Potential Methane Generation Capacity L_0 (m^3/Mg)	100
Methane concentration (%)	50

Table 4.3: The yearly amount of waste deposited in the landfill (data obtained from the SAWIC website and the records from landfill)

Years	**Waste deposited (tonnes)**
2005	56,072
2006	56,414
2007	56,759
2008	57,109
2009	57,463
2010	70,666
2011	92,637
2012	104,617
2013	97,967
2014	210,000
2015	298,705.90
2016	83,719
2017	44,704
2018	33892.7
2019	37,396
2020	9,759
2021	39,031
2022	31,068

The Figure 4.2 illustrates the waste composition within the Thohoyandou landfills.

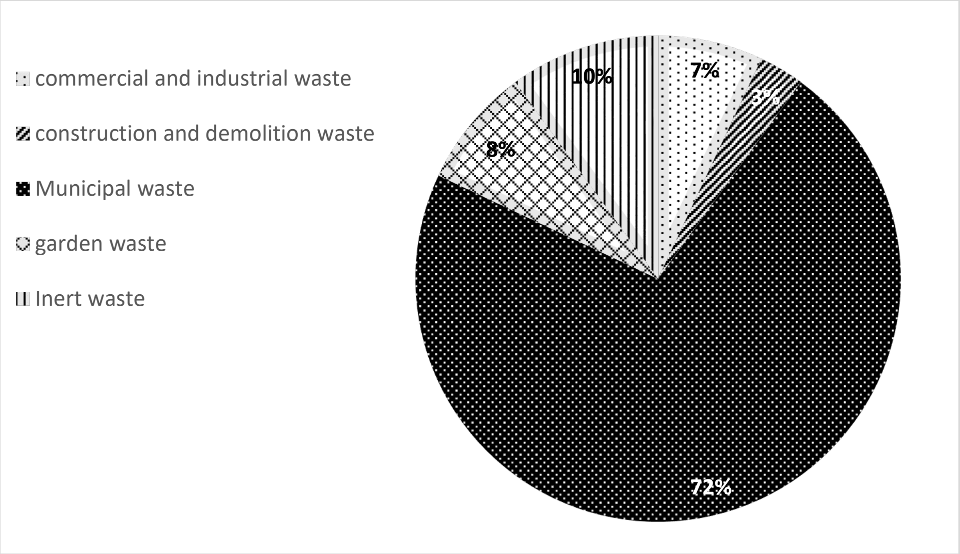

Figure 4.2. Pie chart showing the average annual composition of waste present in the Thohoyandou landfill (Source: Thulamela Municipality and SAWIC website).

4.2.3 Quantification of LFG using the flux chamber

The static flux chamber employed in this research was designed using a robust ceramic PVC material, incorporating a sharpened base to effectively prevent any gas leakage from within the chamber, as illustrated in Figures 4.3 and Plate 4.1.

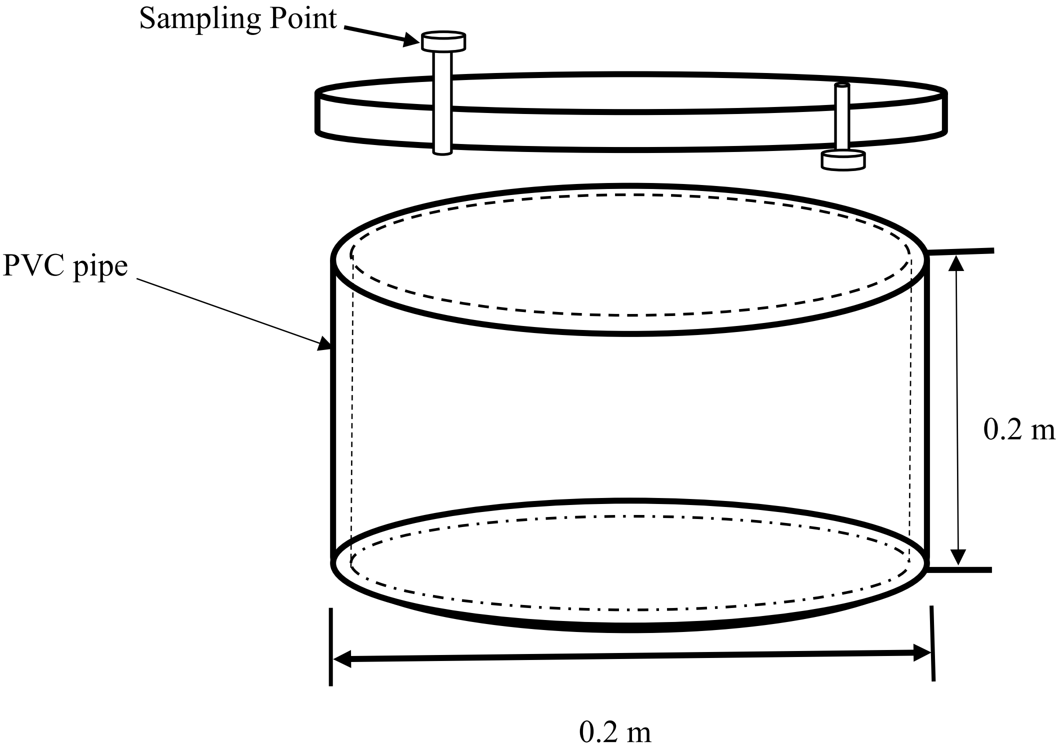

Figure 4.3: A schematic diagram showing a simple flux chamber.

Plate 4.1. During the collection of gases using the flux chamber and a handheld pump

The design of the flux chamber was informed by the methodology adopted in a prior research carried out by Bhailall (2015). During the installation phase, the flux chamber was carefully inserted into the ground, with a penetration depth of approximately 3 to 5 cm. The connection between the flux chamber and the associated canister was established, with the chamber then positioned on the surface of the landfill, allowing for an approximate 2-hour exposure period. Initially, the 2-hour duration was designated for the flux chamber-canister installation phase, however, upon subsequent laboratory analysis, it became evident that the quantity of gas accumulated within the canisters were insufficient for comprehensive analysis. This shortfall in gas volume was attributed to the insufficient pressure exerted by the gases, thereby hindering their effective entry into the canister. Consequently, an alternative method was used, involving an extension of the gas collection time from the flux chamber to 24-hours, during which no external disturbances were introduced. Unfortunately, this adjusted approach produced similar results, with only a small portion of LFG composition making its way into the canister. This was observed when the gas samples were taken to the laboratory for analysis. To address this limitation, manual pumps were introduced to generate the necessary pressure for transferring the gases from the chamber into the canister. Additionally, the canister was replaced with a tedlar bag, which was a more suitable storage option for the LFG collected from the chamber.

The flux chamber, now connected to the tedlar bag, was installed on the landfill surface until a sufficient quantity of gas was accumulated in the bag. In some instances, a manual pump was attached to the outlet of the chamber to facilitate the transfer of gases into the tedlar bags. This modified approach ensured more effective gas collection and storage during the study, enhancing the reliability and accuracy of subsequent analyses.

Outlined below is a step-by-step method outlining how the LFG samples were stored and collected from the landfill for easy replicability.

Step 1: A flux chamber, designed using a robust ceramic PVC material with a sharpened base, was prepared for gas collection. The chamber's design was informed by prior research and optimised to prevent gas leakage.

Step 2: The flux chamber was carefully inserted into the ground at selected sampling points within the landfill, with a penetration depth of approximately 3 to 5 cm.

Step 3: Once installed, the flux chamber was connected to a collection canister or tedlar bag, depending on the specific phase of the study. The chamber was positioned on the surface of the landfill to allow for gas collection.

Step 4: Initially, a 2-hour exposure period was designated for the flux chamber-canister setup, however, it was observed that the gas volume collected within the canister was insufficient for comprehensive analysis. To address the shortfall in gas volume, the collection duration was extended to 24 hours, during which no external disturbances were introduced to ensure accurate sampling. Also, at some point manual pumps were introduced to generate the necessary pressure for transferring gases from the chamber into the collection canister or tedlar bag. This ensured more effective gas transfer and storage.

Step 5: Throughout the gas collection period, the flux chamber setup was continuously monitored to ensure proper functioning and to prevent any potential leaks or disturbances.

Step 6: Once a sufficient quantity of gas was accumulated in the collection container, the samples were transported to the laboratory for analysis.

The placement location of each flux chamber, at the area of interest in the landfill, was specifically chosen using the methods described in literature by Acker (2020). To determine the number of sampling points, Equation 4.2 was used:

$SP \geq 6 + 0.15\sqrt{area\ of\ zone}$ Equation 4.2

where SP = number of sampling points, area of zone = total area of testing location (m^2). Figure 4.4 shows the sampling points of the flux chamber. The landfill site comprises a total area of 100,619 m^2, which is divided into four distinct areas for better management and monitoring. Sample area A, which covers a significant portion of the landfill, was 40,263 m^2; Secondly, sample area B encompasses a total area of 38,234 m^2, hence, similar to Area A, this section is considerable in size and plays a vital role in the landfill's operation. The, sample area C is the third section, covering 25,157 m^2, while sample area D occupies 30,113 m^2.

The set of samples were collected during the wet season (November – December, 2022) which is associated with the hottest months of the year and temperatures ranging from 25°C to 35°C. Samples were collected in the dry season (June, 2022), which is associated with the coldest months of the year and temperatures range from 7-10°C during the winter season.

Figure 4.4: Landfill area with sampling points (Google earth pro)

4.2.4 LFG sample analysis

To quantify the gas flux, continuous measurements of LFG concentrations were collected from the sample port connected to the flux chamber. Gas samples were collected using 50-liter tedlar gas bags attached to each flux chamber. Within 24 hours of gas collection, the samples were sent to the laboratory for chemical analysis. The SRI 8610C Gas Chromatography (GC) instrument was employed to analyse CH_4 and CO_2, using a flame ionisation detector (FID) and a thermal conductivity detector (TCD) (GC-FID, GC-TCD). The SRI 8610C Gas Chromatography (GC) instrument with a Restek Packed Propak, a 2 mm stainless steel column was utilised for sample analysis (Plate 4.2). A 2 ml sample was injected into the GC through an inlet. The carrier gas, helium was passed through the column at a flow rate of 15 ml/min. To enable the detection of flow CO_2 concentrations, a methaniser was incorporated into the GC system. The methaniser contained a powdered nickel catalyst and was heated to 380°C by the FID, while the sample temperature was maintained at 50°C. Importantly, the conversion of CO_2 to CH_4 occurred after the sample had passed through the column, ensuring that their retention times were not affected. Consequently, during analysis, the first peak represented CH_4, while the latter peak represented CO_2.

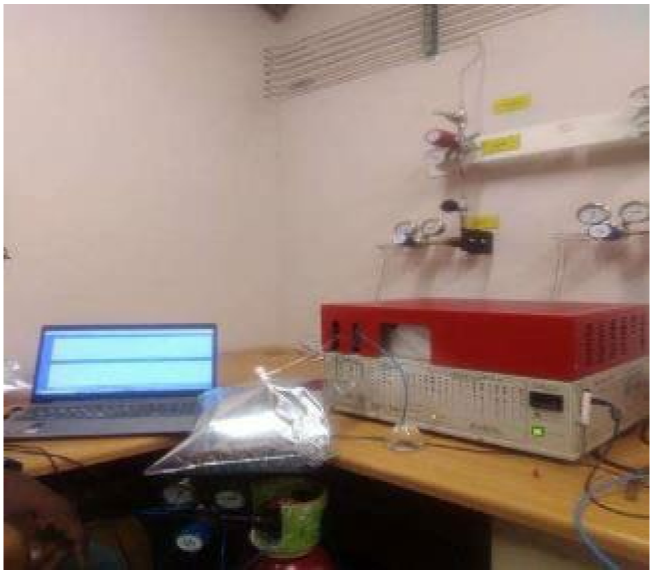

Plate 4.2: The analysis of the gases collected from the Thohoyandou landfill site

To determine the spatial distribution of CH_4 and CO_2 emissions from the landfills, kriging interpolation contour plots were employed. The accuracy of gas concentrations was limited to the monitoring probes, while values in other areas were interpolated using the grid feature of the Surfer software. Surfer, a grid-based contour program, facilitated data interpolation on a regular grid using the XYZ data file, where X and Y represented the latitudinal and longitudinal coordinates of the monitoring probes, and Z represented the gas concentrations. This analytical approach provided detailed insights into the gas composition and spatial distribution of CH_4 and CO_2 emissions.

Emission rate calculation

The emission rates of LFG (Equation 4.3) were measured by multiplying the concentration of LFG inside the chamber (in g/m^3) with the volume of the chamber (in m^3) to obtain the total amount of LFG emitted. This amount was then divided by the surface area of the site covered by the chamber (in m^2) and the duration of the measurement period (in hours) to obtain the emission rate using the emission rate's unit area per unit time (in $g/m^2/h$) (Gallego et al., 2014).

$$ER = \frac{\frac{\Delta C_1}{\Delta t}_1 V_1}{A} \qquad \text{Equation 4.3}$$

where *ER* is the emission rate; $\frac{\Delta C_1}{\Delta t}_1$ is the change in concentration with time; V_1 is the volume of the flux chamber and *A* is the surface area of the sample area within the landfill.

The total emission rate estimate for the different areas of the landfill was further calculated with unit in mass/time. By observing the concentration of CH_4 and CO_2 within the chamber, it becomes possible to compute the CH_4 and CO_2 flux across the covered chamber area. The emission rate ($g/m^2/h$) is multiplied by the total landfill area, and then the measurement in g/h is converted into Mg/yr (Chiemchaisri and Visvanathan, 2008).

4.2.4 Model calibration

A model calibration analysis was conducted to validate the results derived from the LandGEM model to make it more reliable and representative of the actual or real-time measurements. The comparison was between the modelled result (LandGEM) and actual results (static flux chamber).

Table 4.4 shows the input data for the different scenarios that were imputed into the LandGEM model. A sensitivity analysis was conducted to determine the most appropriate k and L_0 values to be used for the LandGEM model. The objective of this calibration process was to align the predicted LFG generation simulated by the LandGEM with the actual average measured from the CH_4 generation data for the year 2022; this ensured the reliability, consistency, and accuracy of the LandGEM.

Table 4.4: Input parameters for all scenarios during the LandGEM calibration with varying k and L_0 values

Data	**First scenario**	**Second scenario**	**Third scenario**	**Fourth scenario**	**Fifth scenario**	**Sixth scenario**
landfill commenced operation	2005	2005	2005	2005	2005	2005
Proposed closure year of landfill operation	2030	2030	2030	2030	2030	2030
Degradation constant k ($year^{-1}$)	0.05	0.1	0.18	0.18	0.18	0.18
Methane Generation Capacity L_0 (m^3/Mg)	170	170	170	200	210	220
Methane concentration (%)	50	50	50	50	50	50
Yearly number of wastes deposited in the landfill (from Table 4.3)	2005 – 2013	2005 – 2013	2005 – 2013	2005 – 2013	2005 – 2013	2005 – 2013

4.3 Results and discussion

4.3.1 CH_4 and CO_2 surface emission results during the wet and dry seasons using the closed flux chamber

Table 4.5 shows the summarised results of the analysis of CH_4 gas emissions using the flux chamber obtained, from the four distinct sample areas, during the wet and dry seasons of 2022.

Table 4.5: Average CH_4 surface emission rate for the year 2022

2022 surface emission rate for wet season				**2022 surface emission rate for dry season**		
Sample areas	**Concentration (mg/m^3)**	**Average Emission rate ($g/m^2/day$)**	**Annual emission rate Mg/year**	**Concentration (mg/m^3)**	**Average Emission rate ($g/m^2/day$)**	**Annual emission rate Mg/year**
A (capped area)	$3.6\times10^{5}\pm$ 1.8×10^{5}	$4.310^{2}\pm$ 2.2×10^{2}	$6.4\times10^{4}\pm$ 3.2×10^{3}	$23.0\times10^{5}\pm$ 7.5×10^{4}	$3.5\times10^{2}\pm$ 9.0×10^{1}	$5.2\times10^{3}\pm$ 1.3×10^{3}
B (active area)	$4.2\times10^{5}\pm$ 6.1×10^{4}	$5.0\times10^{2}\pm$ 7.3×10^{1}	$7.0\times10^{3}\pm$ 1.0×10^{3}	$3.3\times10^{5}\pm$ 1.1×10^{5}	$3.9\times10^{2}\pm$ 1.3×10^{2}	$5.5\times10^{3}\pm$ 1.8×10^{3}
C (Leachate area)	$1.2\times10^{5}\pm$ 2.4×10^{3}	$1.4\times10^{2}\pm$ 2.87	$1.3\times10^{3}\pm$ 2.6×10^{1}	$6.6\times10^{4}\pm$ 4.9×10^{3}	$7.9\times10^{1}\pm$ 5.9	$7.210^{2}\pm$ 5.5×10^{1}
D (virgin area)	$4.6\times10^{4}\pm$ 1.3×10^{3}	$5.5\times10^{1}\pm$ 1.50	$6.1\times10^{2}\pm$ 1.6×10^{1}	$3.3\times10^{4}\pm$ 1.1×10^{3}	$3.9\times10^{1}\pm$ 1.4	$4.3\times10^{2}\pm$ 1.5×10^{1}

Table 4.5 shows that during the wet season, CH_4 emissions consistently exhibit higher rates compared to the dry season across the sample areas. This suggests that environmental conditions during the wet season, such as increased moisture content and possibly higher temperatures, may have contributed to higher rates of anaerobic decomposition and consequently higher CH_4 emissions. This seasonal trend aligns with common expectations in landfill environments. During the wet season, which generally occurs from November to February in South Africa, signifies the hottest months of the year (summer months). The increased moisture content during the wet season can significantly impact CH_4 emissions. The percolation of precipitation in the landfill provides an ideal setting for enhanced microbial activity. This heightened microbial activity encourages the decomposition of organic waste, ultimately resulting in an increase in CH_4 production (Gámez et

al., 2019); also, the increased moisture levels restrict the availability of oxygen, creating anaerobic conditions. As noted in previous studies, CH_4 production is favored under anaerobic conditions, where oxygen is absent (Zhang et al., 2014). The increased precipitation also increases the generation of leachate, as supported by research from Wang et al. (2014). The leachate acts as a carrier for dissolved organic compounds and nutrients, thereby nourishing the methanogenic microbial community. This alignment with optimal temperature conditions facilitates the methanogenic microbial activity, further promoting CH_4 production. Methanogenic activities are optimised in areas of higher temperature, thereby producing more methane bacteria that contributes to the increased CH_4 emissions. The relationship between temperature, moisture, and microbial communities plays a crucial role in driving CH_4 production rates (Zainun and Simarani, 2018).

In both wet and dry seasons, sample areas A and B show high variability in concentration and emission rates compared to sample areas C and D. This suggests more fluctuation and diverse measurements in sample areas A and B, pointing to potential environmental differences and disturbances, prevailing between these areas. Sample areas C and D display relatively lower variability in their measurements across the wet and dry seasons. The high CH_4 emissions observed in the capped area, despite the permanent topsoil cover, suggest that the topsoil barrier may not be effectively mitigating vertical LFG migration. Studies indicate that compromised caps or design flaws can allow CH_4 to escape, leading to higher emissions (Fourie and Morris 2004; Stark and Newman, 2010; Albright et al., 2006; Wang et al., 2017). Wang et al. (2017) found that using a high-density polyethylene (HDPE) membrane as a cap achieved a CH_4 retention rate of 99.8% (mean flux of 0.288 $g/m^2/day$), compared to an air-permeable Open Windrow Composting (OWC) surface with a CH_4 mean flux of 142.40 $g/m^2/day$. The HDPE membrane's tight particle packing prevented LFG passage, however, the Thohoyandou landfill's cover material appears to have loose particles, leading to higher CH_4 emissions. Ng et al. (2019) demonstrated that increased moisture content and temperature increase can exacerbate CH_4 generation and surface emissions from landfills.

Sample area B is known for high influx of organic waste which introduces a steady source of decomposable matter. As more waste accumulates, more organic material is available for decomposition, leading to higher CH_4 production. The continuous source of organic material in this region results in higher CH_4 emissions during the wet season; similar results were observed in a study by Stark and Newman (2010).

In the leachate area (C) of the Thohoyandou landfill, LFG emissions were relatively lower. Leachate was collected and directed into a settling pond in this area, but there were no liners to prevent ground penetration. Occasionally, the leachate is recirculated within the landfill or taken to the wastewater treatment plant for disposal; it is also used to wet the ground for dust suppression. This management strategy helps reduce liquid waste accumulation and limits its interaction with organic matter, which may slow down the CH_4 generation process. Scientific findings indicate that proper isolation of leachate areas from other landfill sections and controlled collection of leachates can reduce the escape of CH_4 and other gases, limiting emissions (Garcete et al., 2022, Wang et al., 2014).

The virgin area (D) had the lowest emissions; this could be a result of the low presence of organic waste material. Unlike the active or capped areas, the virgin area has not yet been used for waste disposal.

Table 4.6: Average CO_2 emission rate (g/m^2/day) for the year 2022

2022 surface emission rate for wet season				**2022 surface emission rate for dry season**		
Sample areas	**Concentration (mg/m^3)**	**Average Emission rate (g/m^2/day)**	**Annual emission rate Mg/year**	**Concentration (mg/m^3)**	**Average Emission rate (g/m^2/day)**	**Annual emission rate Mg/year**
A (capped area)	$3.6\times10^{5}\pm1.8\times10^{5}$	$4.310^{2}\pm2.2\times10^{2}$	$6.4\times10^{4}\pm3.2\times10^{3}$	$23.0\times10^{5}\pm7.5\times10^{4}$	$3.5\times10^{2}\pm9.0\times10^{1}$	$5.2\times10^{3}\pm1.3\times10^{3}$
B (active area)	$4.2\times10^{5}\pm6.1\times10^{4}$	$5.0\times10^{2}\pm7.3\times10^{1}$	$7.0\times10^{3}\pm1.0\times10^{3}$	$3.3\times10^{5}\pm1.1\times10^{5}$	$3.9\times10^{2}\pm1.3\times10^{2}$	$5.5\times10^{3}\pm1.8\times10^{3}$
C (Leachate area)	$1.2\times10^{5}\pm2.4\times10^{3}$	$1.4\times10^{2}\pm2.87$	$1.3\times10^{3}\pm2.6\times10^{1}$	$6.6\times10^{4}\pm4.9\times10^{3}$	$7.9\times10^{1}\pm5.9$	$7.210^{2}\pm5.5\times10^{1}$
D (virgin area)	$4.6\times10^{4}\pm1.3\times10^{3}$	$5.5\times10^{1}\pm1.50$	$6.1\times10^{2}\pm1.6\times10^{1}$	$3.3\times10^{4}\pm1.1\times10^{3}$	$3.9\times10^{1}\pm1.4$	$4.3\times10^{2}\pm1.5\times10^{1}$

A trend observed in CH_4 was similarly observed in CO_2 emissions. Across both seasons, the capped area (A), high CO_2 concentrations were observed, indicating potential limitations in the cap's effectiveness in mitigating gas migration. The active area (sample area B) displayed elevated CO_2 concentrations, suggesting highest decomposition rates and CO_2 generation (Table 4.6). Similarly, Herath et al., in their 2023 results, showed that the average emission rates of CO_2 from an active Karadiyana MSW dumpsite was 978.65 g/m^2/day, and total emissions was 519.67 Mg/year which was the highest across the landfill. The leachate area (C) displayed lower CO_2 emissions, possibly due to leachate-containment measures limiting CO_2 generation. The virgin area (D) had the lowest CO_2 emissions, indicating minimal waste decomposition and gas generation.

4.3.2 Result of the total CH_4 and CO_2 surface emissions using the closed flux chamber

The observed significant variations in LFG emissions within the landfill are attributed to the spatial heterogeneity of the site. To comprehensively assess these differences, a Kriging analysis was conducted, focusing on the mean annual emissions of CH_4 and CO_2 across the entire study area. In Figure 4.5 and 4.6, a distinct separation is evident between the capped and active areas when compared to the leachate and virgin areas. These figures vividly illustrate the predominant hotspots of LFG emissions emanating from the landfill. Notably, this picture signifies that, during the year 2022, the active and capped areas of the landfill emerged as the primary pathways for LFG emissions.

Conversely, a lower concentration of hotspots is discernible in the leachate and virgin areas. This disparity may be attributed to the dynamic processes occurring within the landfill. In the leachate areas, the dissolution of leachate likely contributes to the LFG emissions, whereas the virgin areas may serve as conduits for lateral migration of LFG, resulting in fewer pronounced hotspots.

This phenomenon explains the consistency in the spatial distribution of CH_4 and CO_2 emissions, strengthening the credibility of these findings. These results align with existing studies in the field Mønster et al. (2019) and Gámez et al. (2019), corroborating the robustness of the current research.

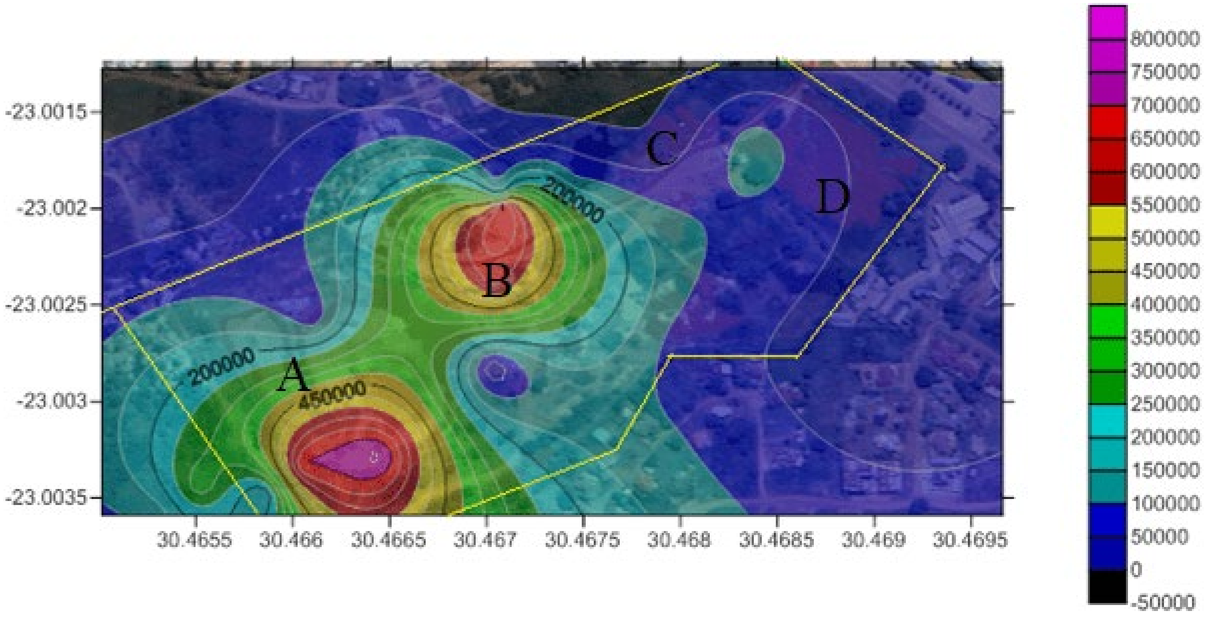

Figure 4.5: Spatial variation of CH_4 emissions from the landfill using the surfer software

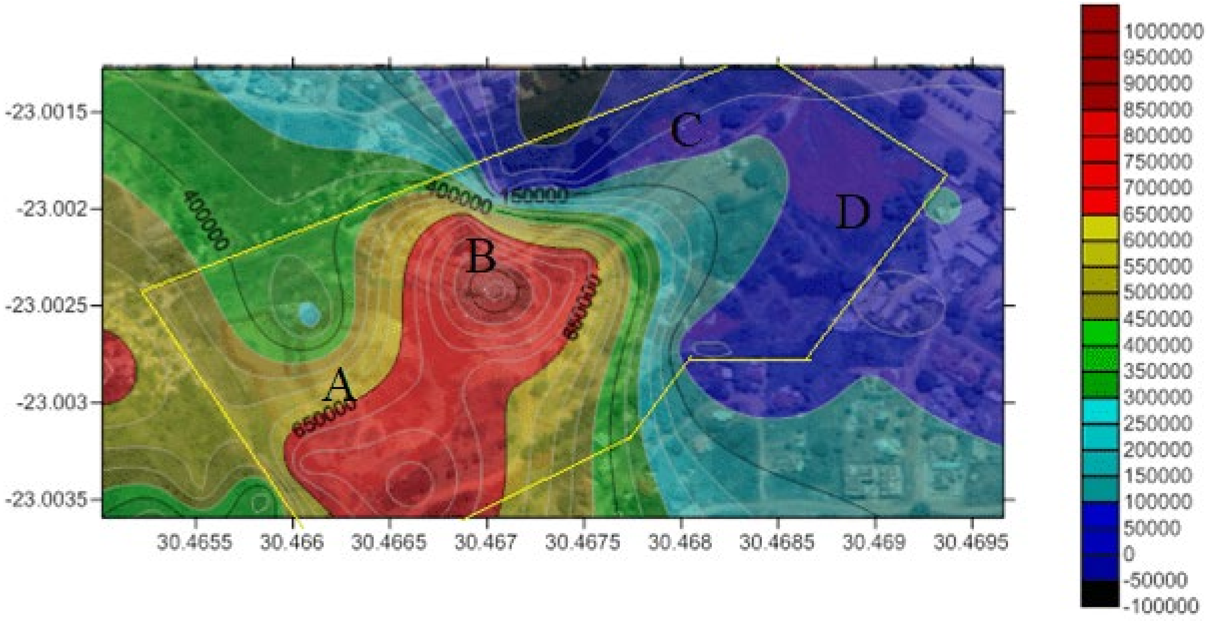

Figure 4.6: Spatial variation of CO_2 emissions from the landfill using the surfer software

In summary, the results shed light on the variability of LFG emissions across different areas within the landfill and how they are influenced by seasonal changes. This enhanced understanding is crucial for better management and development of mitigation strategies to reduce greenhouse gas emissions from landfills. This tailored approach, based on localised emission data, is unique to this study and provides a valuable tool for landfill operators and environment managers. In the context of the installation of LFG utilisation technology, from these results, there will be a better understanding of how to install LFG collection machinery. Additionally, the observation of high LFG emissions from capped areas, despite the presence of topsoil covers, explains the need for further research and development of more effective cap systems. This highlights a gap in current landfill management practices and suggests avenues for innovative solutions to minimise gas migration and emissions. Thohoyandou landfill managers and stakeholders can investigate into how to provide a more efficient capping system during the closure of cells in the landfill. Lower LFG emissions observed in areas with effective leachate management indicates the significance of proper containment and treatment of landfill leachate and the urgency of integrated leachate management systems, in reducing GHG emissions from landfills. The study highlights the seasonal trends of LFG emissions, with wet seasons exhibiting higher emission rates compared to dry seasons. This seasonal variation explains the dynamic nature of LFG production and the need for adaptive management strategies to address seasonal fluctuations.

The uniqueness of these findings lies in their contribution to understanding the specific dynamics of LFG emissions within the context of the Thohoyandou landfill in South Africa. While previous studies may have explored general trends in LFG generation and emissions, this research provides comprehensive insights into the variability of emissions across different areas within the landfill and their response to seasonal changes. This level of specificity is novel and contributes to a more targeted approach to LFG management and mitigation strategies.

4.4 Results from the LandGEM model

The LandGEM model was employed to simulate the cumulative LFG emissions from the Thohoyandou landfill. The simulation encompassed the CH_4 and CO_2 gases emitted from the landfill.

4.4.1 Sensitivity analysis

In the initial modeling of CH_4 generation, a range of decay rate constant (k) values, ranging from 0.05 to 0.18, along with a CH_4 generation capacity (L_0) value ranging from 170 m³/Mg to 220 m³/Mg of waste, were considered. Also, the k and L_0 values were simulated with waste deposited in the landfill from the year 2005 to 2013.

Firstly, during the calibration process, the k value of 0.05 and the L_0 value of 170 m³/Mg, were used in the model; the results showed that the CH_4 generation is underestimated when compared to field measurements using flux chambers. Subsequently, after conducting sensitivity tests, a k value of 0.18 was adopted as it yielded CH_4 generation results that closely aligned with measured data.

Regarding the CH_4 generation capacity (L_0), the initially determined value of 170 m³/Mg, based on default parameters in the LandGEM model for arid conditions were used. During the sensitivity analysis. The real-time measurement of CH_4 emissions was compared to CH_4 emissions' results from the LandGEM using L_0 values ranging from 170 to 220. The results revealed that predicted CH_4 emissions using the L_0 value of approximately 220 m³/Mg aligns more closely with the actual CH_4 emissions (Figure 4.7).

After the sensitivity analysis, the L_0 value of 220 m³/Mg, and k value of 0.18, fit the closest between the modelled CH_4 emissions and the real-time CH_4 emissions from the landfill in the year 2022.

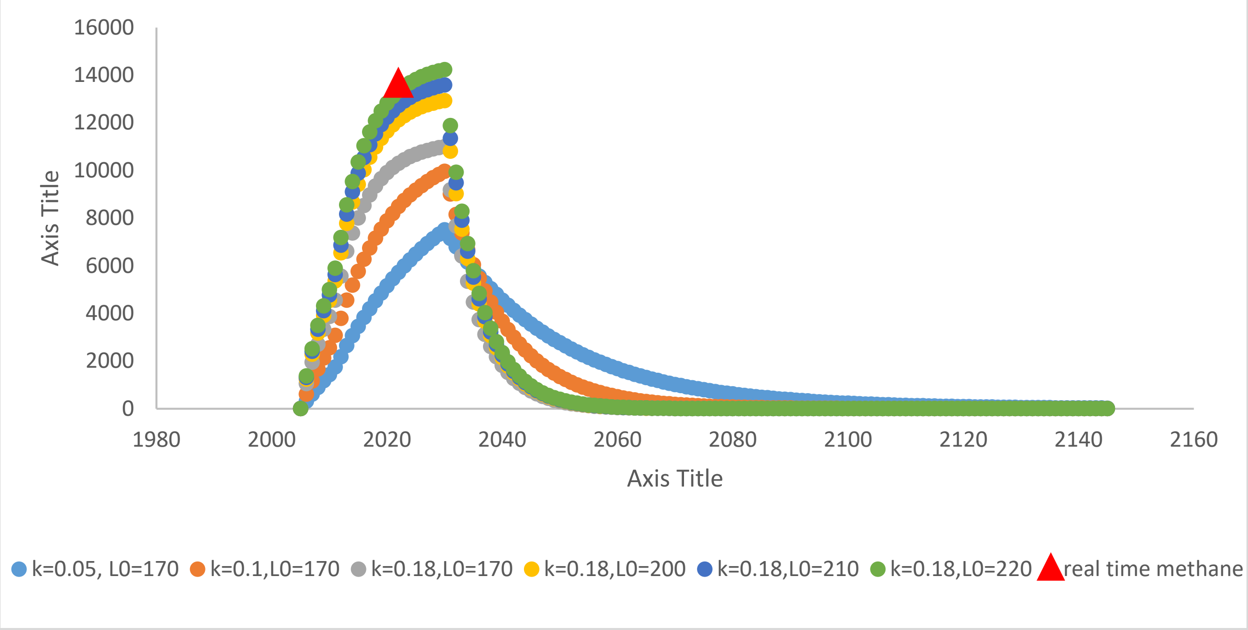

Figure 4.7: Annual CH_4 generations by varying k and L_0 values during the calibration process

4.4.2 Importance of calibrating the LandGEM model

The calibration process of the LandGEM model is essential for refining the accuracy of Thohoyandou LFG generation estimates within the landfill. Landfills, in general, exhibit considerable variability in waste composition, climate conditions and operational practices, necessitating adjustments to model parameters for a more default representation of LFG dynamics. By calibrating the model to site specific conditions, this study enhanced its predictive capability, thereby, enabling more accurate estimations of the LFG emissions over time. This alignment between model parameters and site-specific characteristics is crucial for effective LFG management strategies and mitigating environmental impacts.

Through the calibration process, model parameters such as the k and L_0 were fine-tuned based on comparisons with observed field data or measurements from the landfill site. This validation step served to validate the reliability of the model in accurately capturing the LFG generation trends within the Thohoyandou landfill context. By assessing the agreement between model predictions and actual data, the author was able to identify any discrepancies or biases, leading to a more robust representation of LFG emissions dynamics. Moreover, the calibrated LandGEM provided valuable insights into the effectiveness of LFG recovery and utilisation systems deployed in the Thohoyandou landfills. Accurate LFG generation estimates enable stakeholders to optimise the design and operation of gas collection systems, maximising methane recovery efficiency and energy generation potential. By aligning model predictions with observed LFG emissions, Thohoyandou landfill managers and stakeholder can make informed decisions regarding investment in gas recovery infrastructure and emission-reduction measures.

4.4.3 Comparison of results from the real-time and modelled surface emissions of CH_4 and CO_2

After the calibration process, the LandGEM model was run to simulate the CH_4 and CO_2 emissions. In the studied landfill the annual CH_4 emitted increased from 1367.94 Mg/year in the late 2006 up to 18220.05 Mg/year in 2016 (Figure 4.10). Also, the CO_2 generation increased similarly from the year 2006 at 3753.3 Mg/year to 49991.54 Mg/year in 2016. The LFG emitted from the landfill increased as a result of the continuous deposition of waste in the landfill from the opening of the landfill in 2005. Also, there was a significant increase in the waste deposited in the years 2014 and 2015 which was evident in the CH_4 generation from the landfill and the LFG which peaked in the year 2016; this brought about a significant increase in the LFG generation. This suggests that if more waste is deposited in the landfill, this will bring about an increase in the gases generate from the landfill.

Using the Flux chamber method to measure the LFG in the year 2022, the average total CH_4 and CO_2 emitted from the landfill was 13578.69 and 22785.65 Mg/year, respectively.

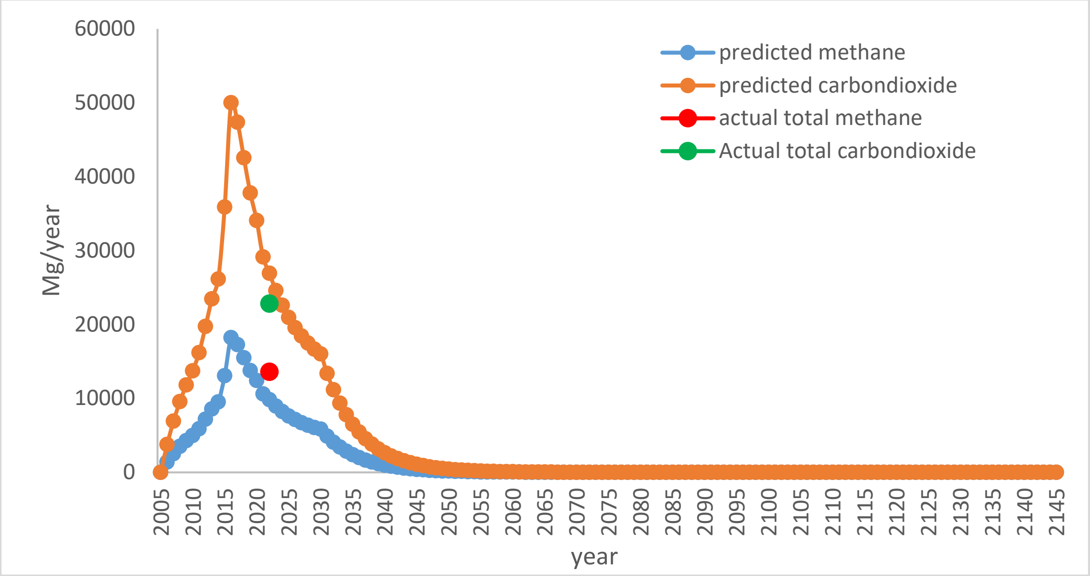

Figure 4.10: The annual average CH_4 and CO_2 measured and estimated from the landfill

One of the key advantages of the measured and estimated CH_4 and CO_2, from the Thohoyandou landfill lies in its detailed investigation of modelled and monitored LFG generations and emissions. While previous research may have explored similar themes, this study offers unique insights into the temporal evolution of CH_4 and CO_2 emissions. By integrating both modeling and empirical measurements, this study contributes to a more holistic understanding of LFG dynamics and highlights the importance of considering site-specific factors in emission estimation and management strategies. The projections of LFG generation and emissions can be done adequately using the LandGEM with the optimised impute parameters (k and L_0), which is a major contribution to science.

The observed increase in LFG emissions over time highlights the critical need for effective LFG management practices to mitigate environmental impacts and reduce greenhouse gas emissions. This study's findings emphasise the urgency of implementing strategies to minimise gas emissions from landfills, particularly in regions experiencing rapid urbanisation and waste accumulation. The combination of modeling and empirical measurements used in this study offers novel insights into LFG emissions dynamics, with a focus, specifically on Thohoyandou landfill. By elucidating the temporal trends and drivers of CH_4 and CO_2 emissions, this research contributes to the body of knowledge on LFG management.

4.5 Limitations

i. Limited spatial representativeness: Flux chambers provide point measurements, which means that the measurements obtained are only representative of the specific area covered by the chamber. The LFG emissions can exhibit significant spatial variability due to differences in waste composition, microbial activity, and gas migration patterns, therefore, extrapolating chamber measurements to the entire landfill site can lead to inaccuracies.

ii. COVID season: the research team was not allowed access into the landfill site during some certain periods of the study.

iii. There were limitations with collection of the gaseous samples due to low pressure, necessitating the introduction of pumps. If samples are not properly sealed to prevent the ingress of air, this could affect the integrity of the samples.

iv. Limitations were established regarding the accuracy and reliability of available waste quantity data for input into the LandGEM model.

4.6 Conclusion

The analysis of CH_4 and CO_2 emissions from the Thohoyandou landfill site provides valuable insights into the dynamics of gas emissions in different sample areas and across seasons. These findings have important implications for landfill management and environmental impact assessment. The study observed the CH_4 emission rate were higher during the wet season than in the dry season. This was as a result of the increase in moisture content from the precipitation and temperature around the landfill area. Sample areas A and B, characterised by capped landfill and active waste deposition, consistently exhibited the highest CH_4 emissions due to concentrated landfill activities and waste decomposition. Similarly, CO_2 emissions show a same trend as the CH_4 emissions, with higher rates were during the wet season. This increase is linked to the presence of moisture, which accelerates the decomposition of organic waste within the landfill. Microbial activity, crucial for waste breakdown, thrives in wet conditions, leading to greater CO_2 production. The decomposition pathways also shift towards aerobic processes in wetter conditions, favoring CO_2 generation over CH_4.

Simulation results from the LandGEM model provide insights into long-term emissions' outlook. The modelled result predict a peak in CH_4 and CO_2 emissions around 2016, associated with a surge in waste disposal in the preceding year. Using the default parameters for k and L_0 values in the LandGEM model led to an underestimation of LFG emissions, however, calibrating the LandGEM model with site-specific data improved the accuracy of k and L_0 values, resulting in measurements closer to those obtained from the flux chamber. In conclusion, this study highlights the importance of considering seasonal variations and sample area characteristics when assessing gas emissions from landfills. Proper landfill management and cover-integrity maintenance during dry seasons are essential for mitigating CH_4 emissions. Additionally, the study highlights the significance of microbial activity and moisture levels in CO_2 emissions. The simulation results from both models offer insights into the long-term emission trends, emphasising the need for continued monitoring and management of LFG emissions to mitigate their environmental impact.

4.7 References

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CHAPTER FIVE: Assessing the ambient air quality and health risks posed by landfills' gas emissions

Preamble

Following an extensive analysis of both sub-surface and surface measurements of LFG in previous **Chapters 3 and 4**, it becomes imperative to explore the ambient air quality surrounding the landfill and understand its dispersion patterns. This chapter presents a comprehensive assessment of air quality, emissions, and associated health risks at the Thohoyandou landfill. A significant aspect of the novelty of this chapter lies in its comprehensive approach to assessing air quality and emissions using the AERMOD model and TROPOMI satellite data. The AERMOD dispersion model predicted the dispersion patterns of CH_4, CO_2, and VOCs/HAPs within the ambient atmosphere surrounding the landfill site. The specie of the TROPOMI data used for this study is the CH_4 at a spatial resolution of approximately 5.5×7 km^2. The CH_4 data derived from the TROPOMI was used to add another layer of precision, comparison and confirm to the CH_4 data derived from the AERMOD. By combining satellite imagery, data processing techniques, and ground-based validation, this study achieves a high level of accuracy in capturing gaseous emissions and their dispersion patterns.

, This chapter goes beyond mere emissions quantification by also conducting a detailed health risk assessment, specifically focusing on inhalation exposure risks associated with VOCs/HAPs. The inclusion of comprehensive metrics such as hazard index, carcinogenic, and non-carcinogenic health risks provide valuable insights into the potential health impacts on nearby communities.

Abstract

Landfills play a pivotal role in waste management but pose significant environmental challenges, especially concerning air quality and human health. This study focuses on understanding the dispersion and potential impacts of LFG emissions from the Thohoyandou landfill in South Africa. These emissions not only affect air quality but also contribute to greenhouse gas emissions. These LFG emitted into the atmosphere can also cause significant health effects on humans living close to the landfill site. To address these concerns, the study utilised the AERMOD dispersion model coupled with TROPOMI satellite data for accurate modelling and analysis of LFG emissions. The study area covers a 5 km radius around the landfill. The methodology involves the use of AERMOD to predict pollutant dispersion, emission rates, meteorological conditions, and topography.

The results shows that the highest hourly concentration of CH_4 was 456,056 $\mu g/m^3$, while the annual maximum concentration was 15,699 $\mu g/m^3$. For CO_2 emissions, the dispersion modelling showed a maximum 1-hour concentration of 735,108 $\mu g/m^3$, an annual maximum concentration of 30,590 $\mu g/m^3$, and an 8-hour maximum concentration of 456,840 $\mu g/m^3$. For non-cancer health risks, the analysis assessed 26 identified toxic VOCs/HAPs; the process followed a USEPA methodology, focusing on inhalation exposure routes. The calculated HQs for most compounds were below 1, indicating generally acceptable non-carcinogenic risks, however, a recorded 1,1,2-Trichloroethane exceeded this threshold, with a value of 1.27, suggesting a potential health risk. The total HQ for all compounds was 1.86, indicating an overall non-acceptable level of non-carcinogenic health risk for residents near the landfill; in terms of carcinogenic health risk, the study identified 13 specific compounds with Hydrogen Sulfide presenting the highest potential for cancer risk, while Tetrachloroethylene exhibited the lowest cancer risk probability. The investigation concluded that residents near the landfill, and workers employed in landfill sites, may face an increased risk of developing cancer due to exposure to LFGs.

Keywords: AERMOD model, Air quality, Cancerous, Landfills, Methane, TROPOMI satellite

5.1 Introduction

Landfills play a crucial role in modern waste management systems, providing a means to dispose of various waste materials, however, their operation can have significant environmental consequences, particularly concerning air quality (Dave et al., 2020). Landfill sites release a wide range of pollutants into the surrounding atmosphere, leading to concerns about potential adverse effects on both air quality and human health. To effectively address these concerns and develop mitigation strategies, it is essential to understand how these emissions disperse and their potential impacts (Elmi et al., 2021). The dispersion of airborne pollutants from sources like landfills is influenced by a complex interplay of factors, including atmospheric dynamics, emission rates, meteorological conditions, and local topography. Of particular concern are pollutants like methane

(CH_4) and carbon dioxide (CO_2) and Non-Methanic Organic Compounds (NMOC); these emissions raise questions about the potential health risks for landfill workers, nearby residents, and passers-by. Furthermore, the continuous release of these pollutants into the environment significantly contributes to South Africa's growing greenhouse gas (GHG) emissions (Nisbet et al., 2020), hence, it is crucial to address these environmental challenges and find sustainable solutions to minimise their impact.

Methane has a direct influence on climate change, as well as an indirect effect on human health, plant yield, and productivity due to its role as a significant precursor to ground-level ozone formation. As a major component of natural gas, CH_4 is colorless, odorless, and tasteless. CH_4 becomes highly flammable at very elevated concentrations, typically ranging from 50,000 to 150,000 ppm (5% to 15%) (Berisha and Osmanaj, 2021). The National Institute for Occupational Safety and Health (NIOSH) recommends a maximum safe CH_4 concentration, expressed as a Threshold Limit Value (TLV), for workers for an 8-hour workday, set at 1,000 ppm (0.1%) due to potential health concerns (Homayoonnia et al., 2021). Extremely high concentrations, around 500,000 ppm, can render CH_4 an asphyxiant and displace oxygen in the blood.

Carbon dioxide (CO_2), similarly is a colorless, odorless, but non-flammable gas naturally occurring in the atmosphere. Occupational Safety and Health Administration (OSHA) has established a Permissible Exposure Limit (PEL) for CO_2 at 5,000 ppm (0.5% CO_2 in air) averaged over an 8-hour workday time-weighted average (TWA) (Eftekhari et al., 2023). The American Conference of Governmental Industrial Hygienists (ACGIH) recommends a TLV of 5,000 ppm for an 8-hour TWA and sets a ceiling exposure limit of 30,000 ppm for 10 minutes. Any value surpassing 40,000 ppm is considered extremely dangerous to life and health (IDLH value). These TLVs aim to minimise the potential for asphyxiation and undue metabolic stress as supported by long-term exposure studies (Lopez et al., 2023). NMOCs constitute a range of gases, including volatile organic compounds (VOCs), hazardous air pollutants (HAPs), and odorous compounds such as hydrogen sulfide. Specific VOCs and HAPs have been identified as contributors to both carcinogenic and non-carcinogenic adverse health effects. VOC emissions significantly contribute to the formation of ozone, a known respiratory irritant upon inhalation, thereby, exacerbating respiratory problems (Talaiekhozani et al., 2018a).

Addressing these concerns from LFG emissions necessitates the use of accurate assessment tools capable of modeling the dispersion and concentration of pollutants originating from the Thohoyandou landfill concerning the ambient air. Such tools, hence, are essential for evaluating the potential environmental impact of pollutant emissions. Additionally, many countries and regions have established air quality standards and regulations aimed at safeguarding public health and the environment (Al-Zboon et al., 2022; Hesami Arani et al., 2021). Precise modeling ensures that emissions from sources like landfills conform to these regulations and dispersion modeling aids in identifying potential health risks associated with pollutant exposure, particularly for nearby residents vulnerable to deteriorating air quality stemming from emissions.

The main objective of this study is to utilise the AERMOD dispersion model, coupled with TROPOMI satellite data, to simulate and analyse CH_4 and CO_2 concentrations from the Thohoyandou landfill. Furthermore, this study will quantify the public health risks associated with inhalation exposure to LFGs of the residents living close to the landfill.

5.2 Methodology

5.2.1 Study area (Please refer to Chapter 4 for the study area)

The study was conducted in Thohoyandou landfill which is the primary waste management facility for Thulamela Municipality in the Limpopo Province of South Africa. The study area was sub-divided into four areas - A (capped areas), B (Active area), C (leachate) and D (virgin areas) as shown in Figure 5.1.

Figure 5.1: Map of Thohoyandou showing the sampling sections.
Source: Google Earth Pro

Sample area A (Capped area) - the capped area of the landfill refers to a section of the landfill that has been covered with topsoil (clay and construction rubbles) permanently. This is because the cells in that area are full and no more receiving waste. The topsoil is designed to create a barrier that minimises the migration of gases vertically.

Sample area B (Active area) - the active area in the landfill refers to the area that has not yet been covered with a final topsoil, unlike sample area A. This area is typically still active and receiving new waste material daily.

Sample area C (Leachate area) - The leachate area of the landfill refers to the portion of the landfill where liquid waste (leachate) is stored, collected and managed.

Sample area C (Virgin Area) - This is a section of the landfill that has not yet been used for waste disposal, therefore, exhibits no waste accumulation or disposal activity.

5.2.2 AERMOD dispersion model

The AERMOD model, developed collaboratively by the American Meteorological Society (AMS) and the U.S. Environmental Protection Agency (EPA), was employed in this study through a commercial interface known as ISC-AERMOD View (Version 11.0.1) (Sharifi et al., 2022). This model played a pivotal role in predicting the dispersion of CH_4, CO_2, and VOC/HAP pollutants in the Thohoyandou landfill area. Simulations for these gases were conducted over distances of up to 5 km in both the horizontal (x and y) directions, originating from the landfill site, which served as the pollutant source.

To execute the AERMOD simulations, data like the meteorological data, which include - the wind speed, wind direction, cloud cover, humidity, temperature, and hourly precipitation - were utilised. Additionally, the data on land use, coordinates, and the altitude of the meteorological station above sea level were inputted into the software. The meteorological data used for model input was purchased from the Lakes Environment dataset at a coverage of 50 km from the Thohoyandou landfill (Lakes Environment, 2024). The meteorological data was from the period of Jan 2019 to Dec 2022. Upper air meteorological observations and hourly surface monitoring are two important parameters for the AERMET input.

The topographical effects of the site were addressed by using the elevated terrain option in the software, whereby contour lines with a resolution of approximately 90 m are obtained from the Shuttle Radar Topography Mission (SRTM3) database maintained by the U.S. National Geospatial-Intelligence Agency (NGA) and the U.S. National Aeronautics and Space Administration (NASA). The terrain data were pre-processed with AERMAP before modelling in AERMOD. The modelling results were captured in average time intervals of 1 hour, 8 hours, 24 hours, and an annual statistical period. For this study, a comprehensive cartesian receptor grid of about 441 receptor points gave a comprehensive gaseous emission of the study area. The focus ambient area of concern for this study extends to 5 km from the Thohoyandou landfill, which is the emission source. Seven discrete receptors located within a 2 - 5 km radius of the landfill were set in the modelling domain. The receptors were in different shapes and were randomly located to represent sensitive sites, such as residential areas, school hostels and hotels. Meteorological data and AERMAP data acquired gave credence to the results obtained.

The emission rates for CO_2 and CH_4 were derived from a previous study (refer to **Chapter 4**) conducted alongside this study titled - "*Quantification and modelling of methane and carbon dioxide surface emissions from a South African landfill*". The static flux chamber method was used to collect CH_4 and CO_2 samples which were analysed by a Gas Chromatography (GC) to obtain the concentration from the total surface area of the Thohoyandou landfill; subsequently, the emission rate was calculated.

To derive the emission rate of the VOC/HAPs from the landfill, using the LandGEM model. The model calibration and sensitivity analysis were conducted in **Chapter 4.** Table 5.1 is the summary of the input parameters inputted into the AERMOD model software, during the model run, for easy replicability.

Table 5.1: Summary of the Input parameters for the AERMOD model software

Input parameter	**Implications**
Averaging time options	1-hour, 8-hours, 24-hours and annual
Source Input	
Source type	Area Poly source
X, Y coordinates	855155.37 m; 7451963.16 m
Base elevation	562.77 m
Release height	20 m
Emission rate for CH_4 and CO_2	Refer to **chapter 4**
Emission rate for VOCs/HAP (was derived using the LandGEM)	Sensitivity analysis and LandGEM calibration was conducted in **Chapter 4,** therefore, the calibrated input data for k and L_0 was used to calculate the chapter's VOC/HAP emission rates using the LandGEM model.
Receptor pathway	
Discrete receptors (5 km away from the source)	Comprehensive cartesian receptor grid with 441 receptor point. Some discrete receptors included, residential areas, malls, higher institution, hotels and student hostels
Meteorological data (2019 – 2022)	Purchased from the Lakes environment
AERMAP	An elevated terrain with contours lines with resolution of approximately 90 m are obtained from the SRTM3 database

5.2.3 TROPOMI

TROPOMI, a spaceborne spectrometer, has been meticulously engineered for the precise measurement of air quality and atmospheric chemistry. This cutting-edge instrument offers remarkable spatial resolution and sensitivity, making it an indispensable tool for monitoring air pollution and pinpointing its origins. The TROPOMI explorer is an application used to visualise and easily download air pollutant time series from the Sentinel-5P Data (European Commission/ESA/Copernicus). The process of gathering gaseous data through TROPOMI involves a seamless combination of satellite imagery, data processing, and ground-based validation (Ialongo et al., 2020; Magro et al., 2021). The TROPOMI data was downloaded from the TROPOMI Explorer, Earth Engine App... The time series data was downloaded in CSV format for easy visualisation and analysis (Manual, 2021). The Level 2 calibrated and georeferenced processed data for the TROPOMI was used for this study. At this level 2, comprehensive CH_4 data was derived at a resolution of $5.5 \times 7.7\ km^2$ (Magro et al., 2021). The CH_4 data derived from the TROPOMI was used to add another layer of precision, comparison and confirm to the CH_4 data derived from the AERMOD. The data can be downloaded from this link TROPOMI Explorer (earthengine.app).

5.2.4 Model Evaluation

To assess the performance of the dispersion pattern model using AERMOD and data derived from TROPOMI, Fractional Bias (FB) and Normalized Mean Squared Error (NMSE) were used (Vijay et al., 2021). FB is a key metric, which can be defined as follows in Equation 5.1.

$$FB = \frac{2(\bar{C}_0 - \bar{C}_p)}{(\bar{C}_0 + \bar{C}_p)} \qquad \text{Equation 5.1}$$

The NMSE is given by Equation 5.2.

$$NMSE = \frac{\overline{(C_0 - C_P)^2}}{\bar{C}_0 \bar{C}_P} \qquad \text{Equation 5.2}$$

where the Cp and Co are the predicted and observed concentrations, respectively. Overbars indicate averages over the sample.

The FB serves as a measure of mean bias, where a FB value of 0.6 signifies an approximate twofold under-prediction by the model, while a negative value indicates over-prediction. The FB varied between −2 and +2, with a negative value indicating overprediction and good performance is indicated by a value close to zero. In contrast, the NMSE reflects variance, with a value of 1.0 suggesting that the typical difference between predictions and observations aligns with the mean. These metrics, as outlined in Ruggeri et al. (2020), are well-suited for assessing model performance when the dataset exhibits a relatively low range of values, typically spanning from 0.01 to 100, and when the typical difference between predictions and observations is around twofold. For this study, however, the minimum to maximum CH_4 concentrations ranged from 1210.23 - 50273 µg/m³ for the AERMOD software. The TROPOMI results ranged from 1165828 µg/m³ to 1224638 µg/m³, hence, the use of the log-transformed approach to mitigate errors between observations and predictions. In these scenarios, the more balanced log-transformed dataset was used in computing the geometric mean bias (MG) and the geometric mean variance (VG) as shown in Equations 5.3 and 5.4, respectively (Yang et al., 2023; Madiraju and Kumar 2022). This offers a more appropriate evaluation of the model performance given the broader concentration range in this study's dataset.

$$MG = \exp\,(\overline{\ln C_0} - (\overline{\ln C_P}) \qquad \text{Equation 5.3}$$

$$VG = \exp\overline{[(\ln C_O - \ln C_p)^2]} \qquad \text{Equation 5.4}$$

where the Cp and Co are the predicted and observed concentrations, respectively. Overbars indicate averages over the sample.

A geometric mean (MG) bias value of 0.5 suggests that the model tends to over-predict by a factor of two, while a value of 2.0 indicates an under-prediction by the same factor. Similarly, a VG value of 1.6 signifies that there is approximately a twofold difference between the predicted and observed data pairs.

In the context of model evaluation, ideal performance would yield FB and NMSE values of 0, indicating no bias and perfect accuracy. Similarly, MG, and VG values of 1.0 would reflect a perfect match between predicted and observed data. The MG and VG are more appropriate as they normalise the data sets by log transformation; MG and VG values also ensure a balance between the data sets.

5.2.5 Health Risk Assessment

The assessment of inhalation exposure risks associated with carcinogenic and non-carcinogenic VOCs/HAPs followed the methodology recommended by the United States Environmental

Protection Agency (USEPA) (Lin et al., 2020). The concentration of exposure (EC) for individuals exposed to VOCs/HAP through inhalation was determined using Equation 5.5.

$$EC_i = \frac{C_i \times ET \times EF \times ED}{AT \times 365 \times 24} \qquad \text{Equation 5.5}$$

where EC_i is the EC of compound i, µg/m^3; C_i is the concentration of compound i in the air, µg/m^3; ET is the exposure time, h/d^1; EF is the exposure frequency, day/year^1; ED is the exposure duration, year; AT is the average time that humans are impacted by the non-carcinogenic/ carcinogenic effects, year. For non-carcinogenic risk, AT is equal to the exposure time, while for carcinogenic risk, AT is equal to the average life expectancy of the population. The individual and cumulative non-carcinogenic health risks were expressed as the hazard index (HI) which can be calculated using Equations 5.6 and 5.7 as follows:

$$HI_i = \frac{EC_i}{RfC_i} \qquad \text{Equation 5.6}$$

$$HI_T = \sum_{i=1}^{n} HI_i \qquad \text{Equation 5.7}$$

where HI_i is the individual non-carcinogenic health risk of compound I; RfC_i is the reference concentration of compound i, µg/m^3; and HI_T is the cumulative non-carcinogenic health risk of compounds. If HI ≤ 1, the non-carcinogenic health risk is deemed acceptable. The individual and cumulative carcinogenic health risks were defined as the probability of developing cancer during a lifetime, which can be calculated using Equations 5.8 and 5.9, respectively.

$$R_i = EC_i \times IUR_i \qquad \text{Equation 5.10}$$

$$R_T = \sum_{i=1}^{n} R_i \qquad \text{Equation 5.11}$$

where R_i is the individual carcinogenic health risk of compound i; IURi is the inhalation unit risk of compound i, (µg/m^3)$^{-1}$; and R_T is the cumulative carcinogenic health risk of compounds. Following the criteria established in prior research (Cheng et al., 2019; Petrovic et al., 2018), this study applied the following classification for carcinogenic risk assessment: $R \leq 1 \times 10^{-6}$ implies negligible carcinogenic risk; $1 \times 10^{-6} < 1 \times 10^{-3}$ suggests a moderate carcinogenic risk, and $R \geq 1 \times 10^{-3}$ indicates a significant carcinogenic risk. The values for RfC and Inhalation Unit Risk (IUR) were sourced from the Integrated Risk Information System (IRIS, https://www.epa.gov/iris) and Risk Assessment Information System (RAIS, https://rais.ornl.gov). Details of default and site-specific parameters are shown in Table 5.2.

Table 5.2: EPA default and site-specific values used in the exposure assessment calculations

Variable	Resident Ambient Air Default Value	Site-Specific Value
ED_{res} (exposure duration) years	26	25
EF_{res} (exposure frequency) days/year	350	250
ET_{res} (exposure time) hours/day	24	8
AT (carcinogenic)	365 days/year × 70 years if	365 days/year × 70 years if
AT (non-carcinogenic)	Same as ED	Same as ED

5.4 Results and Discussion

5.4.1 Results for emission rates of CH_4 and CO_2

The emission rate for LFGs served as an important input variable for the AERMOD model, playing a pivotal role in predicting the dispersion of pollutants in the Thohoyandou landfill area. Table 5.3 and 5.4 present the results of the emission rates for CH_4 and CO_2, as determined in **Chapter 4**. The data includes concentrations and emission rates for CH_4 and CO_2, during both the wet and dry seasons of 2022.

Table 5.3: Average CH_4 emission rate (g/m^2/day) and standard deviation for the year 2022

	Wet season		**Dry season**	
Sample Areas	**Average emission rate g/m^2/day**	**Annul CH_4 Mg/year**	**Average emission rate g/m^2/day**	**Annual CH_4 Mg/year**
A	433.00±219.55	6363.43±3226.48	354.28±90.22	5206.44±1325.81
B	503.86±73.73	7031.57±1028.93	393.64±132.04	5493.41±1842.73
C	141.71±2.87	1301.23±26.40	78.73±5.88	722.91±54.78
D	55.11±1.50	605.72±16.50	39.36±1.35	432.66±14.79

Table 5.4: Average CO_2 emission rate (g/m^2/day) and standard deviation for the year 2022

	Wet season		Dry season	
Sample Areas	Average emission rate g/m^2/day	Annual CO_2 Mg/year	Average emissions rate g/m^2/day	Annual CO_2 Mg/year
A	691.24±79.05	10158.46±1161.67	669.64±28.22	9841.03±414.78
B	756.04±73.08	10550.85±1019.83	712.84±69.67	9947.97±972.26
C	194.41±7.79	1785.13±71.49	151.21±7.82	1388.46±71.78
D	108.01±648.06	1187.16±7122.98	64.80±1.57	712.23±17.24

The emissions inventory of VOCs/HAP is detailed in Table 5.5, which showed that carbon monoxide and toluene have the highest emission rate of 4.80 and 4.39 Mg/year, respectively. Similarly, benzene and xylenes stand out with emission rates of 1.054, and 1.56 Mg/year, respectively, and a considerable amount was present in the LFG samples. Chloroform and mercury at 0.0044 and 0.000071 Mg/year, respectively, had relatively lower individual contributions, to the LFGs' emissions.

Table 5.5: Emissions inventory of VOC/HAP were determined using the LandGEM for the year 2022.

Gas Pollutant	**Emission rate (Mg/year)**
Acetone	0.50
Acrylonitrile	0.41
Benzene	1.054
Bromodichloromethane	0.62
Carbon Disulfide	0.054
Carbon Monoxide	4.80
Carbonyl Sulfide	0.036
Chlorobenzene	0.034
Chlorodifluoromethane	0.14
Chloroform	0.0044
Chloromethane	0.10
Dichlorobenzene	0.038
Dichlorodifluoromethane	2.37
Dichloroethane, 1,2-	0.050
Dichloroethylene, trans-1,2-	0.33
Dichloropropane, 1,2-	0.025
Dimethyl Sulfide	0.59
Ethanol	1.52
Ethyl Chloride	0.10
Ethyl mercaptan	0.17
Hexane, N-	0.63
Hydrogen Sulfide	1.50
Mercury (elemental)	0.000071
Methyl Ethyl Ketone (2-Butanone)	0.63
Methyl Isobutyl Ketone (4-methyl-2-pentanone)	0.23
Methyl Mercaptan	0.15
Methylene Chloride	1.46
Pentane, n-	0.29
Tetrachloroethylene	0.45
Toluene	4.39
Trichloroethane, 1,1,1-	0.078
Trichloroethane, 1,1,2-	0.23
Trichloroethylene	0.45
Vinyl Chloride	0.56
Xylenes	1.56

5.4.2 Assessment of LFGs dispersion in the surrounding atmosphere through the TROPOMI and AERMOD models

The TROPOMI and AERMOD models were used to evaluate the dispersion of LFGs within the ambient air in the vicinity of the Thohoyandou landfill. A 24-hourly modelled CH_4 concentration was obtained using the AERMOD software and compared with the real time satellite data extracted from the TROPOMI satellite. The results from the AERMOD and TROPOMI were captured over the same land area to make sure the data was from the same domain and covered the same surface area. Figure 5.2 shows the time series comparison of the AERMOD CH_4 concentration with results from the TROPOMI satellite. The temporal data for the comparison was from January 1st 2019 to December 31st 2022 - the period of the study. The data from both the AERMOD and the TROPOMI satellite were converted into time series of 9 days interval during the data cleaning. This was due to missing data from the TROPOMI satellite as a result of high cloud cover in the atmosphere. The data cleaning helped to give a consistent result across the modelled and real-time data of CH_4 concentration.

The results showed that the real-time measured CH_4 concentrations were higher than the modelled CH_4 concentrations (Figure 5.2). This is because the AERMOD model results does not consider the CH_4 emissions from other sources around the study area site. The modelled results only considered the CH_4 emissions from the Thohoyandou landfill site as the only source, unlike the CH_4 concentration results from the TROPOMI satellite. The TROPOMI results considered all sources of CH_4 emissions within the study area site, therefore, the concentration of pollutants obtained from modeling was less than the amount of the measured concentrations in the study area (Langner and Klemm, 2011).

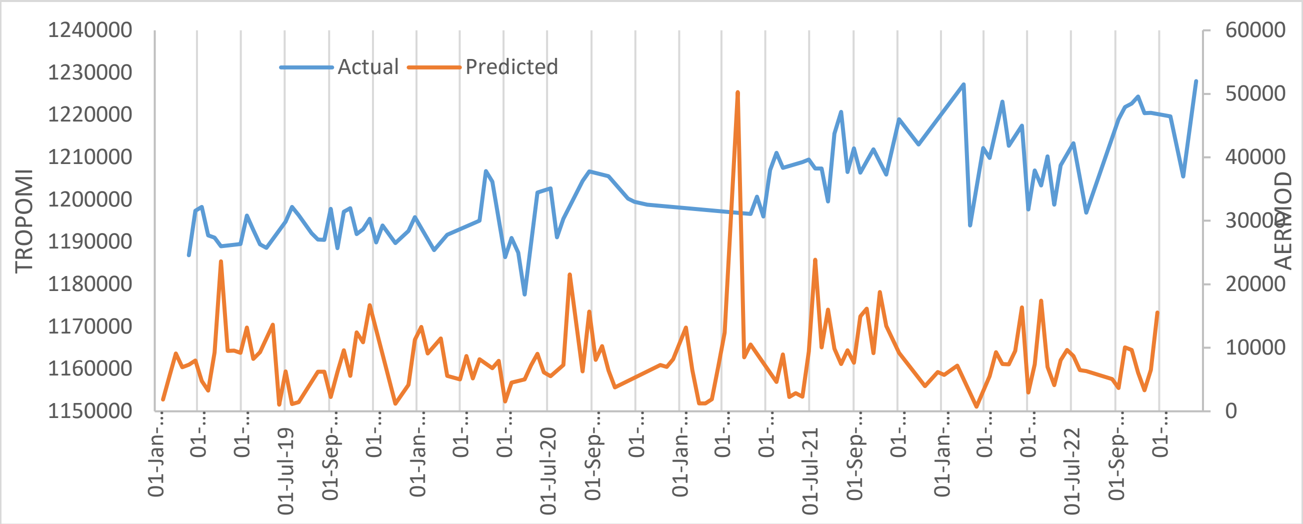

Figure 5.2: Time series data showing the comparison of AERMOD model and TROPOMI software in µg/m^3

With the help of statistical indicators, the accuracies and reliabilities of the predicted AERMOD daily CH_4 concentrations were assessed within the TROPOMI satellite-measured concentrations. This study employed four statistical indicators to validate the model performances through USEPA guidelines- FB, MG, VG and the R^2 value - from the scatter plot.

There were visual pattern observed in the plot of the AERMOD model and TROPOMI results, despite this, it was imperative to evaluate the performance of the models statistically in order to determine their reliability and accuracy with the real-time values. The FB value of 1.009 represented a moderate positive bias, indicating that the model is, on average, moderately overestimating pollutant concentrations (Table 5.6). The positive FB suggests that the AERMOD model might benefit from calibration or adjustment to bring its predictions closer to the TROPOMI observations, despite this bias, the AERMOD model's predictions is still within an acceptable range. This means that the model results can be considered reliable for many practical purposes, such as regulatory compliance assessments or trend analyses.

Table 5.6: Model Evaluation using several statistical tools

	FB	R^2	MG	VG
Value	1.009	0.8	0.2	1.4
Range	Varies between -2 and +2	$R^2 = 1$, best fit for the model prediction	$0.75 \leq MG \leq +1.25$	Best Fit model at value of 1

The VG of 1.4 for the AERMOD to TROPOMI log-transformed data, spanning a range of 0 to 14, indicates that the data is quite variable (Table 5.6). This suggests that the concentrations of the air pollutants being measured can vary considerably across the study area or time period. It also implies the presence of local hotspots with significantly higher pollutant concentrations compared to the average. These hotspots can be of concern for public health and may require targeted mitigation measures (Madiraju and Kumar, 2022).

The R^2 is a statistic that measures how well a regression model fits the data. In the context of modelled and real-time concentrations, the R^2 (0.8) suggests that 80% of the variability in the real-time concentrations can be explained by the model's predictions (Figure 5.3). That is, the model is quite effective at capturing the underlying patterns and relationships between the independent and dependent variables, indicating that the model is a good fit for the data and provides accurate predictions. Also, the R^2 value indicates a strong correlation between the AERMOD predicted concentrations and TROPOMI actual concentrations.

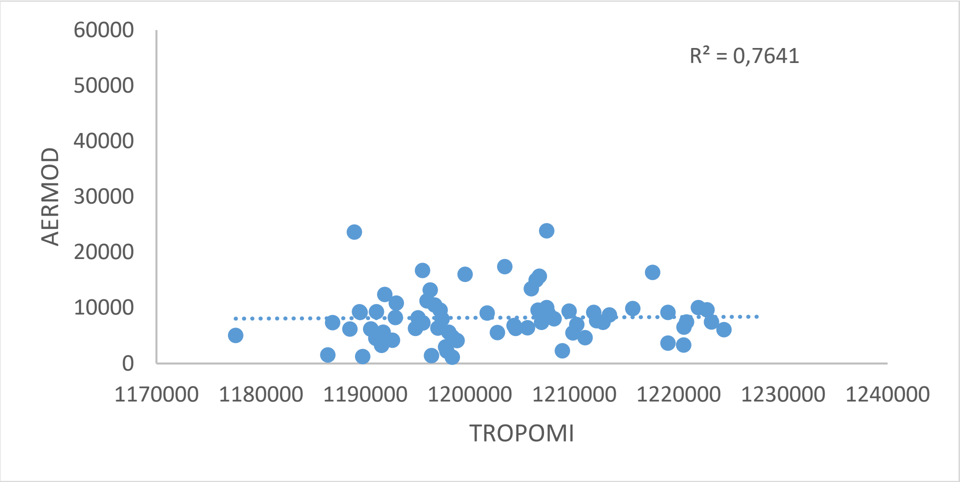

Figure 5.3: Scatter plot showing the predicted and actual concentrations

5.3.2 Wind rose analysis

The meteorological data obtained from the Lakes environment dataset, as indicated by Tran et al., (2022), covering the period between 2019 and 2022, revealed a complex wind pattern influenced by various factors. These included large-scale sea circulations and daily mountain-valley effects, with local topography playing a role in modifying wind characteristics. The daily climate in this region was notably shaped by seasonal winds and interactions in the area (Pandey and Sharan, 2019). Analysing the wind rose diagram, it becomes evident that the prevailing wind direction predominantly originated from the southeast, often accompanied by high wind velocities, as shown in Figure 5.4. This wind pattern was crucial in assessing the model's ability to describe the dispersion of CH_4 and CO_2 emissions from the Thohoyandou landfill site (de Melo et al., 2012). Based on the wind rose, 1.01% of recorded winds in this area were calm, while a significant 94.9% exhibited notable direction and speed. There were notably fast winds observed, both from the southeast and the north. These winds played a crucial role in dispersing the pollutants emitted from the landfill site. On the average, the prevailing wind direction in the study area was southwest, occasionally accompanied by winds from the north, with an average wind speed of 3.23 m/s.

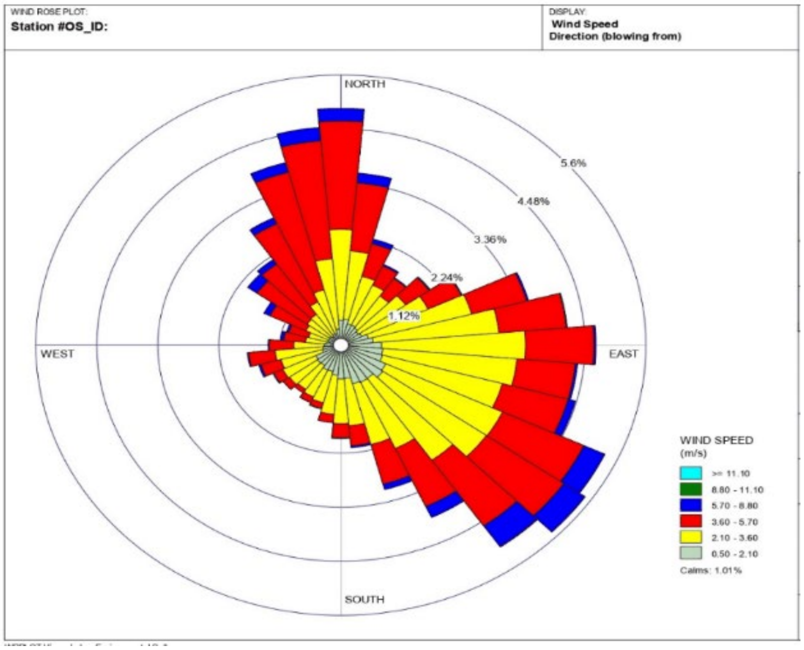

Figure 5.4: Wind rose for the surface area during from (2019 to 2022)

5.3.3 Evaluation of CH_4 and CO_2 emissions using the AERMOD model

The spatial data map of the study area, within 5 km away from the landfill site was first converted into a reference land map using global mapper software and loaded with coordinates in the AERMOD model. Figure 5.5 a, b, c and d, illustrate the dispersion modelling of CH_4 emission for 1-hour, 8-hour, 24-hour and annual emissions, respectively. It was observed that the 1-hour maximum concentration of CH_4 was 4.6×10^5 µg/m^3, while the annual rate was 1.6×10^4 µg/m^3. The maximum CH_4 8-hour maximum concentration for CH_4 was 1.2×10^5 µg/m^3 and the areas closest to the landfill experienced the highest concentration of CH_4 emissions. In a similar study, Wijaya et al. (2021) assessed CH_4 emissions from the Sarimukti landfill using AERMOD. Results showed peak CH_4 concentrations of 8.9×10^4 µg/m^3 (1-hour), 1.6×10^4 µg/m^3 (24-hours), and 1.7×10^3 µg/m^3 (1-year) at UTM coordinates of 9.6×10^4 m, 9.2×10^6m. High concentrations were near the landfill on open land with minimal impact on the surrounding vegetation. Also, Talaiekhozani et al. (2018a) identified a maximum CH_4 concentration of 3.0×10^4 µg/m^3 near the landfill, with variations between 1.0×10^3 and 2.5×10^3 µg/m^3 in different Shahrekord areas. Talaiekhozani et al. (2018b) study of the Borujerd landfill, observed the highest CH_4 1-hour concentrations ranging from 1.2×10^5 to 1.0×10^5 µg/m^3 near the landfill.

Figures 5.6 a, b, c, and d show CO_2 dispersion simulation for different time periods: 1 hour, 8 hours, 24 hours, and the entire year (2019 - 2022). The simulation revealed that the highest 1 h concentration of CO_2 recorded was 7.4×10^5 µg/m^3 and the annual maximum concentration of CO_2 reached 3.1×10^4 µg/m^3. The maximum 8-h concentration of CO_2 was 4.6×10^5 µg/m^3 whilst the highest concentrations were found in areas closest to the landfill. Similarly, the annual CO_2 emissions from the Borujerd landfill, ranged from 8.2×10^2 to 3.5×10^3 µg/m^3 in various parts of the landfill. These emissions were independent of CO_2 from other sources, like vehicles and industries.

The prevailing wind in the study area is from the southeast, with occasional wind from the northwest. Figures 5.5 and 5.6 show CH_4 and CO_2 dispersion on a 1h and annual average basis. For the 1h dispersion, the maximum ground level concentration (GLC) occurred approximately 1 km south of the emission source, whereas the influence of southeast wind direction was obvious in all the dispersion results. Among the discrete receptors, the residential area experienced the highest concentration in all cases due to its proximity to the emission source. Focusing on the annual average, the comparison of the ambient concentration of LFGs emitted along the regulatory standards of CH_4 and CO_2 showed that the discrete receptors, mostly those within 5 km north from the landfill were exposed to a very low concentrations of CH_4 and CO_2 gaseous pollutants. Similar results was observed in Mousavi et al. (2021), when they were examining CO_2 pollutants, the modelled results revealed that the maximum 8-hour concentration of CO_2 during the warm season was 2.9×10^5 µg/m³, and during the cold season, it reached 8.1×10^5 µg/m³.

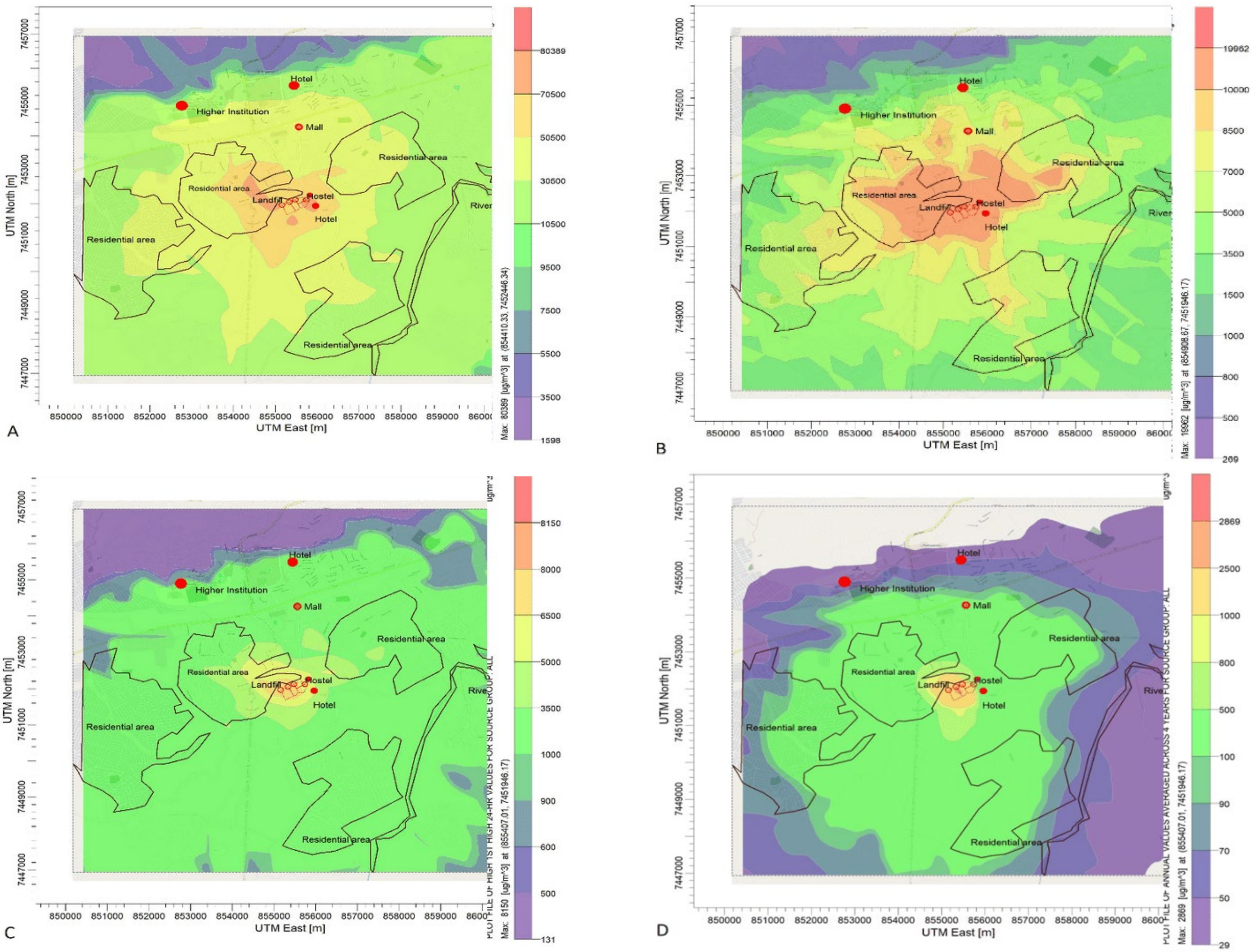

Figure 5.5: CH_4 dispersion emissions using the AERMOD model, a. 1 hour b. 8 h c. 24 h and d. annual average concentration in the study area

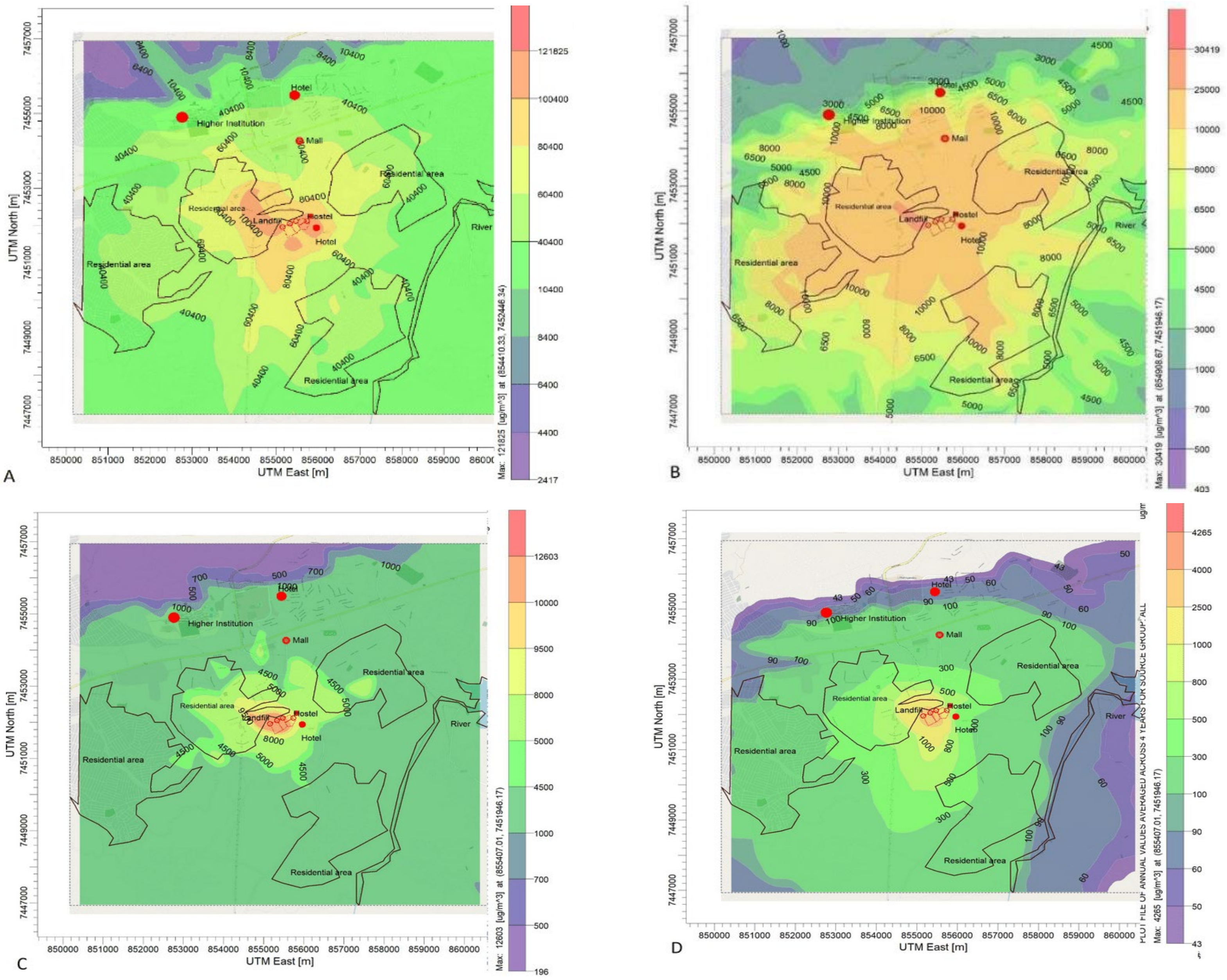

Figure 5.6: CO_2 dispersion emissions using the AERMOD model, showing the a)1 h, b) 8 h, c) 24 h and d) annual dispersion in the study area.

5.3.4 Evaluation of VOCs/HAP emissions using the AERMOD model

Table 5.7 presents the concentrations of VOCs/HAP emitted from the Thohoyandou landfill, indicating their formation through the decomposition of organic MSW. Toluene, with a peak concentration of 94.3 µg/m^3, suggests potential sources such as, paints, adhesives, or industrial processes contributing to ambient air pollution (Su et al., 2014). Carbon monoxide follows with the second-highest concentration at 23.6 µg/m^3, indicating an incomplete combustion process during MSW decomposition (Talaiekhozani et al., 2018b). Dichlorodifluoromethane, ranking third with a concentration of 11.6 µg/m^3, historically used as a refrigerant, may have originated from waste disposal practices, posing environmental concerns due to it facilitating ozone layer depletion (Khan et al., 2023). Ethanol and Methylene Chloride exhibit concentrations of 7.49 µg/m^3 and 7.16 µg/m^3, respectively, both of which are commonly associated with industrial processes (Yogesh, et al., 2023). Xylenes, presenting a concentration of 7.67 µg/m^3, represents a group of isomeric compounds found in various industrial products, indicating the presence of industrial waste as potential sources of pollution (Demikhova et al., 2021). Certain compounds, such as Chloroform (0.022 µg/m^3) and Mercury (0.00035 µg/m^3), demonstrate relatively low concentrations, suggesting effective containment measures or reduced emissions from the landfill.

Table 5.7: Concentrations (µg/m^3) of VOCs/HAP emitted from the Thohoyandou landfill,

VOCs/HAP	**maximum concentration (µg/m^3)**	**average concentration (µg/m^3)**	**standard deviation**
Acetone	2.45	1.65	0.92
Acrylonitrile	2.01	1.61	0.49
Benzene	0.89	0.60	0.32
Bromodichloromethane	3.06	2.056	1.38
Carbon Disulfide	0.27	0.095	0.11
Carbon Monoxide	23.6	17.52	5.01
Carbonyl Sulfide	0.18	0.098	0.064
Chlorobenzene	0.17	0.11	0.065
Chlorodifluoromethane	0.68	0.46	0.20
Chloroform	0.02	0.0049	0.0096
Chloromethane	0.37	0.24	0.10
Dichlorobenzene	0.19	0.060	0.084
Dichlorodifluoromethane	11.60	7.12	4.33
Dichloroethane, 1,2-	0.24	0.11	0.11

Dichloroethylene, trans-1,2-	1.63	0.81	0.58
Dichloropropane, 1,2-	0.12	0.068	0.054
Dimethyl Sulfide	2.92	1.96	0.95
Ethanol	7.49	5.70	1.79
Ethyl Chloride	0.51	0.30	0.16
Ethyl mercaptan	0.86	0.33	0.35
Hexane, N-	3.43	2.91	0.54
Hydrazine Sulfate	7.39	5.16	2.39
Mercury (elemental)	0.00035	0.00014	0.00014
Methyl Ethyl Ketone (2-Butanone)	3.08	2.46	0.78
Methyl Isobutyl Ketone (4-methyl-2-pentanone)	1.15	0.88	0.38
Methyl Mercaptan	0.72	0.38	0.26
Methylene Chloride	7.16	5.21	2.02
Pentane, n-	1.43	0.94	0.49
Tetrachloroethylene	3.69	3.08	0.67
Toluene	94.3	57.86	34.93
Trichloroethane, 1,1,1-	0.39	0.24	0.11
Trichloroethane, 1,1,2-	1.11	0.81	0.33
Trichloroethylene	2.22	1.79	0.53
Vinyl Chloride	2.75	1.68	0.77
Xylenes	7.67	6.87	0.81

5.5 Potential health and environmental risk from the inhalation of VOCs/HAP

Due to the proximity of residents to the landfill, possible exposure to atmosphere-borne toxic VOCs/HAP prompted an assessment of potential chronic health effects, encompassing both non-cancer and cancer risks, through inhalation. The evaluation of non-carcinogenic risk considered all 26 detected and quantified species of toxic VOCs/HAP, while the assessment of cancer risk, specifically focused on the 13 identified species.

5.5.1 Non-carcinogenic health risk effects

The health risk assessment in terms of non-carcinogenic aspects focused on the potential adverse health effects, not related to cancer development. Table 5.8 provides a comprehensive summary of non-carcinogenic compounds and their corresponding health risk parameters. The assessment of human-health risk involves evaluating the nature and extent of adverse health effects in individuals exposed to LFG emissions. In this study, exposure and risk assessments following the

USEPA methodology, specifically considered human exposure to LFG, primarily through inhalation. The toxicity of LFG to human health is directly linked to daily inhalation exposure. Results for a non-carcinogenic analysis involves calculating non-carcinogenic CDI values, as presented in Table 5.8.

Table 5.8 presents a comprehensive overview of noncarcinogenic and carcinogenic compounds and their associated health risk parameters

Chemical	**IUR $(\mu g/m^3)^{-1}$**	**RfC (mg/m^3)**	**Maximum Air Concentration $(\mu g/m^3)$**	**Inhalation Noncarcinogenic CDI (mg/m^3)**	**Inhalation Carcinogenic CDI $(\mu g/m^3)$**	**Inhalation HQ**	**Inhalation Risk**
Acetone	-	-	2.45	5.6×10^{-4}	2.0×10^{-1}	-	-
Acrylonitrile	6.8×10^{-5}	2.0×10^{-3}	2.01	4.6×10^{-4}	1.6×10^{-1}	**2.3×10^{-1}**	1.1×10^{-5}**
Benzene	7.8×10^{-6}	3.0×10^{-2}	0.89	2.0×10^{-4}	7.3×10^{-2}	6.8×10^{-3}	5.7×10^{-7}
Bromodichloromethane	3.7×10^{-5}	-	3.06	6.9×10^{-4}	2.5×10^{-1}	-	**9.2×10^{-6}** **
Carbon Disulfide	-	7.0×10^{-1}	0.27	6.2×10^{-5}	2.2×10^{-2}	8.8×10^{-5}	-
Carbon Monoxide	-	-	0.24	5.4×10^{-3}	1.92×10^{1}	-	-
Carbonyl Sulfide	-	1.0×10^{-1}	0.18	4.1×10^{-5}	1.6×10^{-2}	4.1×10^{-4}	-
Chlorobenzene	-	5.0×10^{-2}	0.17	3.9×10^{-5}	1.4×10^{-2}	7.8×10^{-4}	-
Chlorodifluoromethane	-	5.0×10^{-1}	0.68	1.6×10^{-4}	5.5×10^{-2}	3.1×10^{-6}	-
Chloroform	2.3×10^{-5}	9.8×10^{-2}	2.2×10^{-2}	5.0×10^{-6}	1.8×10^{-3}	5.1×10^{-5}	4.1×10^{-8}
Chloromethane	1.8×10^{-6}	9.0×10^{-2}	3.7×10^{-1}	8.5×10^{-5}	3.0×10^{-2}	9.4×10^{-4}	5.4×10^{-8}
Dichlorobenzene	-	-	1.9×10^{-1}	4.3×10^{-5}	1.6×10^{-2}	-	-
Dichlorodifluoromethane	-	1.0×10^{-1}	1.2×10^{1}	2.7×10^{-3}	9.5×10^{-1}	2.7×10^{-2}	-
Dichloroethane, 1,2-	2.6×10^{-5}	7.0×10^{-3}	2.4×10^{-1}	5.5×10^{-5}	1.9×10^{-2}	7.8×10^{-3}	5.1×10^{-7}
Dichloroethylene, trans-1,2-	-	4.0×10^{-2}	1.63	3.7×10^{-4}	1.3×10^{-1}	9.3×10^{-3}	-
Dichloropropane, 1,2-	3.7×10^{-6}	4.0×10^{-3}	1.2×10^{-1}	2.7×10^{-5}	9.8×10^{-3}	6.9×10^{-3}	3.6×10^{-8}
Dimethyl Sulfide	-	-	2.92	6.7×10^{-4}	2.4×10^{-1}	-	-
Ethanol	-	-	7.49	1.7×10^{-3}	6.1×10^{-1}	-	-
Ethyl Chloride	-	4.00	5.1×10^{-1}	1.2×10^{-4}	4.2×10^{-2}	2.9×10^{-5}	-

Ethyl mercaptan	-	-	8.6×10^{-1}	1.9×10^{-4}	7.0×10^{-2}	-	-
Hexane, N-	-	7.0×10^{-1}	3.43	7.8×10^{-4}	2.8×10^{-1}	1.1×10^{-3}	-
Hydrogen Sulfide	4.9×10^{-3}	-	7.39	1.7×10^{-3}	6.0×10^{-1}	-	**$2.9\times10^{-3}***$**
Mercury (elemental)	-	3.0×10^{-4}	3.5×10^{-4}	7.9×10^{-8}	2.9×10^{-5}	2.7×10^{-4}	-
Methyl Ethyl Ketone (2-Butanone)	-	5.00	3.08	7.0×10^{-4}	2.5×10^{-1}	1.4×10^{-4}	-
Methyl Isobutyl Ketone (4-methyl-2-pentanone)	-	3.00	1.15	2.6×10^{-4}	9.4×10^{-2}	8.8×10^{-5}	-
Methyl Mercaptan	-	-	7.2×10^{-1}	1.6×10^{-4}	5.9×10^{-2}	-	-
Methylene Chloride	1.0×10^{-7}	6.0×10^{-1}	7.16	1.6×10^{-3}	7.06	2.7×10^{-3}	7.1×10^{-8}
Pentane, n-	-	1.00	1.43	3.3×10^{-4}	1.2×10^{-1}	3.3×10^{-4}	-
Tetrachloroethylene	2.6×10^{-7}	4.0×10^{-2}	3.69	8.4×10^{-4}	3.0×10^{-1}	2.1×10^{-2}	7.8×10^{-8}
Toluene	-	5.00	9.4×10^{-1}	2.2×10^{-2}	7.69	4.3×10^{-3}	-
Trichloroethane, 1,1,1-	-	5.00	3.9×10^{-1}	8.8×10^{-5}	3.2×10^{-2}	1.8×10^{-5}	-
Trichloroethane, 1,1,2-	1.6×10^{-5}	2.0×10^{-4}	1.11	2.5×10^{-4}	9.1×10^{-2}	**1.27**	**$1.5\times10^{-6}**$**
Trichloroethylene	4.1×10^{-6}	2.0×10^{-3}	2.22	5.1×10^{-4}	6.7×10^{-1}	**2.5×10^{-1}**	**$2.8\times10^{-6}**$**
Vinyl Chloride	4.4×10^{-6}	1.0×10^{-1}	2.75	6.3×10^{-4}	2.97	6.3×10^{-3}	**$1.3\times10^{-5}**$**
Xylenes	-	1.0×10^{-1}	7.67	1.8×10^{-3}	6.3×10^{-1}	1.8×10^{-2}	-
Total Risk/HI	-	-	-	-	-	***1.86***	***3.0×10^{-3}***

Note: ** moderate carcinogenic risk; *** significant carcinogenic risk

From Table 5.8, All the studied LFGs had total HQs below 1 except for 1,1,2-Trichloroethane with a value of 1.27. Accordingly, the health-risk estimation of the identified LFGs revealed the mean HQs suggesting a non-acceptable level of non-carcinogenic harmful health risk in all LFGs from Thohoyandou landfill. A total HQ of 1.86, which is above 1, therefore poses health risk to the residents living close to the Thohoyandou landfill. The residents are likely to suffer from cardiovascular diseases (such as heart disease and stroke), respiratory diseases (such as asthma and chronic obstructive pulmonary disease), diabetes, arthritis, and many others. From the summation of the total HQs, it can be concluded that the contribution of the LFGs to the carcinogenic health risk was from – Chlorodifluoromethane<1,1,1-Trichloroethane< Ethyl Chloride< Chloroform<Methyl Isobutyl Ketone (4-methyl-2-pentanone)< Carbon Disulfide< Methyl Ethyl Ketone (2-Butanone)< Mercury (elemental) < Pentane, n-< Carbonyl Sulfide < Chlorobenzene <Chloromethane < Hexane, N- < Methylene Chloride < Toluene < Vinyl Chloride>Benzene < 1,2- Dichloropropane < 1,2 – Dichloroethane < trans-1,2- Dichloroethylene< Xylenes<Tetrachloroethylene < Dichlorodifluoromethane<Trichloroethylene < Acrylonitrile <1,1,2-Trichloroethane (Table 5.8). These results corroborate those obtained from Njoku et al., (2019); this strengthens the validity and reliability of the results derived in both studies.

5.5.2 Carcinogenic health risk

Some LFGs can potentially enhance the risk of cancer in humans. Long-term exposure to low amounts of these toxic LFGs could, therefore, result in many types of cancers. The total exposure of the residents was assessed based on the mean carcinogenic CDI values given in Table 5.8. Also, the carcinogenic risk assessment for residents living close to the landfill are given in Table 5.8.

Among the studied VOCs/HAPs compounds, hydrogen sulfide presents the highest potential for cancer risk (2.95×10^{-3}), while tetrachloroethylene exhibits the lowest cancer risk probability (7.82×10^{-8}) (Table 5.8). The current investigation identified an elevated risk of cancer associated with the inhalation of these LFGs. The findings suggest that residents residing near the Thohoyandou landfill sites may experience, an increased risk of developing cancer due to the emission of LFGs. Additionally, workers in landfill sites are also at a heightened risk of cancer.

The study also assessed other compounds such as benzene, Trichloroethane, 1,1,2-, Trichloroethylene, and vinyl chloride. Each of these compounds was evaluated for their carcinogenic risk based on their respective CDI values. Benzene showed a carcinogenic risk of 5.7×10^{-7}, indicating a moderate risk and suggesting a higher probability of cancer compared to tetrachloroethylene but lower than hydrogen sulfide. Trichloroethane, 1,1,2-, Trichloroethylene, Vinyl Chloride had a carcinogenic risk of 1.5×10^{-6}; 2.8×10^{-6}, 1.3×10^{-5}, 9.23×10^{-5}, respectively, indicating a moderate risk and highlighting its noticeable impact on cancer risk. Acrylonitrile exhibited a moderate carcinogenic risk with a probability of 1.1×10^{-5}, highlighting it as another substantial contributor to cancer risk.

These findings are consistent with previous research that identifies LFGs as sources of carcinogenic risk. For instance, a study by Lin et al. (2020) indicated that VOCs and HAPs emitted from landfills significantly contribute to cancer risks in nearby populations. Similarly, Petrovic et al. (2018) highlighted the carcinogenic potential of hydrogen sulfide and other landfill gases, further supporting our findings. These findings suggest that residents residing near the Thohoyandou landfill sites may experience an increased risk of developing cancer due to the emission of LFGs.

This study applied the following classification for carcinogenic risk assessment: $IR \leq 1 \times 10^{-6}$ implies negligible carcinogenic risk, $1 \times 10^{-6} < 1 \times 10^{-3}$ suggests a moderate carcinogenic risk, and $IR \geq 1 \times 10^{-3}$ indicates a significant carcinogenic risk.

5.6 Conclusion

In this study, a thorough analysis was done on the dispersion of LFG emissions from the Thohoyandou landfill site, spanning the period 2019 to 2022. The investigation incorporated a complex interplay of meteorological factors influencing wind patterns in the region, with a focus on understanding how these emissions disperse into the surrounding environment. The meteorological data obtained from the LAKES environment dataset provided crucial insights into the intricate wind patterns affecting the study area. Notably, prevailing winds predominantly originated from the southeast, often accompanied by high wind velocities. These wind patterns played a pivotal role in assessing the model's ability to describe the dispersion of LFG emissions from the Thohoyandou landfill site.

These intricate wind patterns provided the backdrop for the evaluation of LFG emissions using the AERMOD model. The results of the dispersion modelling for CH_4 emissions across different time periods—1 hour, 8 hours, 24 hours, and annually - revealed that the highest hourly concentration of CH_4 was 456,056 µg/m³, while the annual maximum concentration was 15,699 µg/m³.

For CO_2 emissions, the dispersion modelling showed a maximum 1hour concentration of 735,108 µg/m³, an annual maximum concentration of 30,590 µg/m³, and an 8-hour maximum concentration of 456,840 µg/m³. Crucially, these findings have revealed the role of wind direction in pollutant dispersion. Prevailing winds from the southeast and occasional winds from the northwest have a substantial impact on the distribution of emissions. This was particularly evident in the higher concentrations observed in the residential area due to its proximity to the emission source.

The AERMOD model results were compared with data from the TROPOMI satellite. The comparison showed that the measured CH_4 concentrations were generally higher than those predicted by the model. This discrepancy was attributed to TROPOMI measurements considered all sources of CH_4, unlike the AERMOD model that only simulates CH_4 emissions from the landfill area. Consequently, the concentrations predicted by the model were lower than the measured concentrations in the study area and despite this positive bias in the model's predictions, the assessment indicated that the AERMOD model remains a reliable tool for various practical purposes, such as regulatory compliance assessments and trend analyses.

For non-cancer health risks, the analysis considered 26 identified toxic VOCs/HAPs. The assessment followed USEPA methodology, focusing on inhalation exposure. The calculated HQs for most compounds were below 1, indicating generally acceptable non-carcinogenic risks, however, 1,1,2-Trichloroethane exceeded this threshold with a value of 1.27, suggesting a potential health risk. The total HQ for all compounds was 1.86, indicating an overall non-acceptable levels of non-carcinogenic health risks for residents near the landfill.

In terms of carcinogenic health risk, the study identified 13 specific compounds. Hydrogen Sulfide presented the highest potential for cancer risk, while Tetrachloroethylene exhibited the lowest cancer-risk probability. The investigation concluded that residents near the landfill and workers employed in the landfill sites may face an increased risk of developing cancer due to exposure to LFGs.

It is important to note that these LFGs remain in high concentration in some areas especially those close to the Thohoyandou landfill. Also, as stated earlier, the continuous negligence of the continuous emissions of the LFG into the atmosphere can contribute significantly to South African air pollution. It is therefore, imperative for there to be a form of LFG-collection system in these landfills. The municipality should, also consider moving towards improving reuse and recycling to reduce the waste going into the landfill thereby ultimately reducing the gases emitted from the landfills. Improving recycling and waste reduction efforts, adopting sustainable landfill practices, and engaging the public in environmental initiatives are actions that will not only reduce the environmental impact of landfills but also contribute to a more sustainable and healthier future for communities near landfill sites.

5.7 References

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CHAPTER Six: SWOT analysis as a tool to analyse landfill management practices in South Africa

Preamble

To understand MSW management strategies, conducting a thorough Strength Weakness Opportunity and Threat (SWOT) analysis was undertaken in this chapter. Serving as a foundational component, this chapter lays the groundwork for developing a Solid Waste Management conceptual framework tailored to the South African context. It researches into landfill management practices in South Africa, where approximately 90% of MSW is deposited, although, almost 100% of the MSW generated in the Thulamela Municipality is directed to the landfill. By employing a SWOT analysis and the Analytical Hierarchy Process, this chapter identified the strengths, weaknesses, opportunities, and threats associated with current waste management practices. Through engagement with waste experts, landfill operators, citizens, and stakeholders, critical weaknesses were unearthed, necessitating exploration of alternative waste management methods, such as recycling, biogas production, and composting. This study stands out as novel due to the absence of prior SWOT analyses conducted for landfills in South Africa, particularly for rural-based ones, like the Thohoyandou landfill. This comprehensive examination sheds light on area mature for improvement and focuses on the urgency of transitioning towards more sustainable waste management practices. By advocating for the exploration and adoption of alternative methods, this chapter aims to unlock both economic and environmental benefits while addressing pressing challenges within the current waste management landscape.

Abstract

The study focuses on a comprehensive analysis of landfill management in South Africa, by identifying the Strengths, Weaknesses, Opportunities and Threats (SWOT) associated with this practice. In South Africa, approximately 90% of MSW is directed to landfills. The environmental implications of landfill operations encompass direct contributions to - gaseous and particulate matter emissions, the potential for explosions and fires, soil and water contamination, and the

generation of environmental nuisances that adversely impact human health and the environment - as observed in the previous chapters.

The methodology employed in this study integrates two essential analytical frameworks: the SWOT analysis technique and the Analytic Hierarchy Process (AHP). Data for this research was gathered through engagement with diverse stakeholders, including landfill workers, truck drivers, waste reclaimers, and waste researchers. Additionally, the researchers consulted existing literature and documents related to waste and landfill management in both South Africa and the global context. A judicious application of purposive random sampling techniques resulted in the inclusion of 44 participants in this study.

This chapter systematically evaluated multiple factors, including - regulatory and policy frameworks, the availability of skilled professionals, public engagement, waste collection infrastructure, and the development of alternative waste management practices. The findings illustrated the strength of landfill practices in South Africa, with their ability to effectively manage nearly 90% of the nation's waste, over several decades. Nevertheless, the survey of stakeholders highlighted significant weaknesses, predominantly the role of landfills as breeding grounds for insects, flies, rodents, and unpleasant odours, which, in turn, pose health risks to the local population.

This study highlights the urgency of exploring alternative waste management practices. The conventional landfill management system is increasingly regarded as outdated, inhibiting the harnessing of resources embedded within MSWs. There exists an urgent call for South Africa to prioritise alternative systems such as - recycling, biogas production, biofertilizer manufacturing, composting, and incineration. Embracing these alternatives can potentially offer substantial economic benefits, including - improvements in energy production, agriculture, and the transportation sectors.

6.1 Introduction

The alarming rise in waste generation is a major concern across the globe. Research conducted by the World Bank revealed that in 2016, the earth produced a staggering amount of 2.01 billion tons of waste. This figure is projected to surge to 3.4 billion by 2050, representing a 70% increase in waste production within a span of 30 years (World Bank, 2018). Unfortunately, the negative consequences of living in a ‘throw-away’ society are becoming more evident as the world grapples with what to do with its mounting waste. Currently, a staggering 85% of global waste is disposed of in landfills (Njoku et al., 2018). Similarly, in South Africa, a significant proportion (90%) of MSW is dumped in landfills and dumpsites. The situation is worsened by the fact that only a small 10% of the waste is recycled, and a negligible 0.1% undergoes thermal treatment. Regrettably, only waste oils and batteries are the fractions of hazardous waste recycled (Adeleke et al., 2021). Even when done under regulated conditions, burying waste in landfills causes damage to the environment.

This study hypothesise that landfills have contributed to a lot of environmental degradation and have affected health of communities. Landfills can contribute to climate change by generating and emitting LFGs into the atmosphere, thereby contributing to global warming. CH_4 and CO_2 are the primary components of LFG that contribute to climate change and the global temperature rise. Landfill sites will be responsible for 10% of GHG emissions by 2025 if the current scenario persists (Kaza et al., 2018). Landfill operations can also pose a risk of explosions and fires, as occasionally, the CH_4 generated by the decomposition of waste in landfill sites can lead to such incidents and obviously, this can be detrimental to humans and properties around the landfill (Bihałowicz et al., 2021). Landfill sites are frequently accountable for the pollution of soil and groundwater. The contaminating materials, such as heavy materials like lead and mercury, from the landfilled waste, can spread to the soil and water close to the site. Furthermore, even though waterproofing-membrane ruptures are uncommon, the soil and groundwater are severely polluted when they do. Landfill sites can significantly harm the bird population as some looking for food near these sites, often inadvertently ingest pollutants such as plastic, aluminum, gypsum, and other common waste materials that are harmful; in addition, landfills endanger birds by disrupting their migratory patterns. As a result of the limitless food supply landfills offer, an increasing number of bird species have stopped migrating to the south in recent years and are instead choosing to nest in landfills. This is problematic because this trend can eventually cause premature death to the birds (Kaza, 2018; Marcelino et al., 2021; Noreen and Sultan, 2021). Furthermore, landfills lower the value of properties in the neighbourhood; property values drop in locations close to the landfill facilities, thus contributing to the socio-economic woes of underprivileged communities (Akinjare et al., 2011; Ready, 2010).

The landfill management system is becoming an outdated system that hinders the harnessing of resources found in MSW generation. Consequently, there is an urgent need for the country to focus more on other alternative management systems, such as recycling, biogas production, bio-fertilizer, and composting (Mirdar Harijani, 2017; Ghosh et al., 2019). These alternative systems have the potential to boost the economy of South Africa in the energy, agriculture, and transportation sectors. There is an urgent need, hence, to perform a SWOT analysis on the management of landfills in South Africa to enable a comprehensive evaluation of the situation. The present study employs the SWOT analytical approach to evaluate South Africa's landfill management practice, with reference to the Thohoyandou landfill a site in the rural area of South Africa.

Traditionally, the SWOT technique was utilised in the business and marketing sectors, however, it has gained popularity in diverse fields, including waste management; for instance, studies by Umarov et al. (2022) and Shahba et al. (2017) successfully applied the SWOT analysis to waste management. The significance of this study lies in its potential to inform strategic decision-making regarding landfill management practices in South Africa. By identifying the strengths, weaknesses, opportunities, and threats associated with current landfill management practices, this study will provide valuable insights for policymakers and waste management professionals.

6.2 Methodology

The method used in this study was the SWOT analysis, which draws on data from various relevant stakeholders, including landfill workers, truck drivers, reclaimers, waste researchers, and extant literature on waste and landfill management. To achieve the research aims, a purposive sampling technique was used to select a representative sample of 44 participants across South Africa. The participants were selected based on their relevance to the study, including their expertise and experience in the waste management industry. Using a purposive sampling approach to the selection of participants aimed at ensuring that a diverse range of perspectives and experiences were represented in the study. Data collection for this study involved various methods - semi-structured interviews, questionnaires and review of relevant literature. Interviews were conducted with stakeholders in the waste management industry, including landfill workers, truck drivers, reclaimers, and waste researchers. Questionnaires for a survey were distributed to a wider range of stakeholders, including representatives from local government, non-governmental organisations

(NGOs), and the public. The survey aimed to gather information about the public's perceptions and attitudes towards landfill management practices in South Africa. Finally, relevant literature on waste and landfill management practices were reviewed to provide a comprehensive understanding of the current state of landfill management practices in South Africa. The data collected was processed using the SWOT analytical approach. This involved identifying the strengths, weaknesses, opportunities, and threats associated with landfill management practices in South Africa and the Analytical Hierarchy Process (AHP). The data was then presented in tables and graphs to provide a visual representation of the findings.

6.2.1 Analytical Hierarchy Process (AHP)

In the work of De Klerk (2022), the AHP is highlighted as a valuable method for simplifying complex decision-making processes into a series of pairwise comparisons. By utilising this approach, biases in the decision-making process can be minimised, and the consistency of individual decisions can be assessed. In using this method, M (see Equation 6.1) is denoted as the pairwise comparison matrix that represents the relative preference or intensity of an expert's preference between factors or individual criteria to be considered. For a given study involving n criteria, the judgment matrix is represented by Equation 6.1, which captures the pairwise comparisons among the criteria.

$$M = \begin{vmatrix} c_{11} & c_{12} & \cdots & c_{1(n-1)} & c_{1n} \\ c_{21} & c_{22} & \cdots & c_{2(n-1)} & c_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ c_{n1} & c_{n2} & \cdots & c_{n(n-1)} & c_{nn} \end{vmatrix} \qquad \text{Equation 6.1}$$

Where M = C_{ij} represents the comparative importance of the criterion C_i over C_j.

The matrix (M) $n \times n$ matrix where each element cij is specified by its row i and column j. The matrix includes both diagonal and off-diagonal elements, covering all possible combinations of i and j from 1 to n.

To calculate the criterion weight for each factor identified within the SWOT analysis quadrants, Saaty's fundamental scale was employed; this scale, is also known as the 9-point scale (Table 6.1) (Nilsson et al., 2016). By applying this scale, the weights for each criterion can be determined, providing a quantitative assessment of their importance within the analysis. To check for consistency in these judgments, the Consistency Ratio (CR) was used. Saaty, a prominent figure in the AHP, recommends that the CR should, ideally not exceed 0.10% or 10% (Nilsson et al., 2016). When the CR is below this threshold, it suggests that the judgments are reasonably consistent and reliable. If, however, the CR exceeds this value, it implies that the judgments are inconsistent, and it may be necessary for the decision-maker to re-evaluate the pairwise comparisons to improve the reliability of the decision-making process.

Table 6.1: Saaty's 9-point scale

Intensity of importance	**Definition**	**Explanation**
1	Equal importance	Two activities contribute equally to the objective
3	Weak importance of one over another	Experience and judgment slightly favor one activity over another
5	Essential or strong importance	Experience and judgment strongly favor one activity over another
7	Demonstrated importance	An activity is strongly favoured, and its dominance is demonstrated in practice
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate value between two adjacent judgments	When compromise is needed

Source: (Nilsson et al., 2016)

The data obtained from the respondents were ranked according to the various identified criteria. To consolidate the experts' judgments, the geometric mean (GM) method was used. For this study, the priorities are represented by p_i for every expert which are then assessed using the row geometric mean method (RGMM). The following mathematical relations equations 6.2 – 6.4 were used:

$$r_i = exp\left[\frac{1}{N}\sum_{j=1}^{N} \ln\left(c_{ij}\right)\right] = \left(\prod_{i=1}^{N} c_{ij}\right)^{1/N} \qquad \text{Equation 6.2}$$

Equation 6.2 was normalised using Equation 6.3.

$$p_i = \frac{r_i}{\sum_{i=1}^{N} r_i} \qquad \text{Equation 6.3}$$

Equation 6.4 was used to estimate the geometric consistency index (GCI).

$$GCI = \frac{2\sum_{i<j} lnc_{ij} - ln\frac{p_i}{p_j}}{(N-1)(N-2)} \qquad \text{Equation 6.4}$$

6.3 Results and discussion

In this section, the outcomes of the literature review, interviews, and discussions are presented along with the various criteria used for analysis, as detailed in Table 6.2. The AHP approach was used to assign weights to each criterion, as the decision-making process depends on the relative importance of each issue. In identifying the factors within each quadrant, as listed in Table 6.2, the respondents' inputs were highly valuable to the study's success. In total, 28 input criteria were evaluated using pair comparison. The findings of each area of the SWOT analysis are presented in Table 6.2.

Table 6.2: Summary of SWOT analysis

Strength	**Weakness**
Controls and manages approximately 90% of MSW (S1)	Not sustainable (W1)
Nationally acceptable and easy to use (S2)	Relatively expensive for a standardised sanitary landfill (W2)
Helps in gathering data essential in development of bylaws and governance (S3)	Poor harnessing of LFG and mostly not viable for LFG utilisation (W3)
Reliability in managing MSW (S4)	Breeding ground for insects, flies, rodents, and bad odour (W4)
Helps in improving human health and environmental aesthetics (S5)	Increases sicknesses in workers, reclaimers, and neighbouring town (W5)
Creates employment (S6)	Low income (W6)
	Difficulty in waste collection (W7)

Opportunity	**Threats**
Waste to energy (O1)	Unavailability of land and overfill of landfill before anticipated date (T1)
Enhances sorting recycling and reuse (O2)	The inability to sustain long term perspectives (T2)
Opportunity for local and international collaboration (O3)	Fire outbreaks (T3)
Improve countries economy (O4)	Increase in MSW generation (T4)
	Contributes significantly to climate change (T5)

6.4 Strengths

6.4.1 Controls and manages approximately 90% of MSW (S1)

In South Africa, the MSW management system holds a notable strength in its ability to control and manage approximately 90% of MSW. Landfills have been the predominant method in managing MSW in the country since the late 1980s (Pires and Martinho, 2019). The high volume of waste effectively managed demonstrates a robust waste disposal system in place. One respondent emphasised the lack of alternatives, stating that the landfill in Muledani (Thohoyandou landfill) is the sole option for waste disposal in their community.

> "*The landfill in Muledani is the only one we have where we take our waste to………. there is no other way…….*".

Another respondent echoed this sentiment, highlighting the necessity of landfills for domestic waste disposal.

> "*…. Without a landfill, where will we dispose our house waste? …….*".

These viewpoints illustrate the dependence of local communities on landfill practices as the primary means of waste management. According to the findings of Idowu et al. (2019), numerous developing countries have indicated landfilling as their primary approach for MSW management. This finding aligns with the results obtained from the present study. The reliance on landfills as a major waste management method appears to be a common trend among developing nations, thereby, highlighting the consistency between the current findings and those of Idowu et al. (2019). This convergence reinforces the significance and relevance of the current study's outcomes within the broader context of waste management practices in developing countries.

6.4.2 Nationally acceptable and easy to use (S2)

Landfill practices have gained widespread acceptability among municipalities and private stakeholders in South Africa as a practical and legally recognised solution for managing MSW. This acceptability has granted municipalities the authority to continue the use of landfills for MSW management. The opinions expressed by the respondents in this study further support the prevalence and acceptability of landfill practices in South Africa As stated by a waste management expert.

> *"Landfills are found in virtually every municipality in South Africa and generally an easy technique".*

This reflects the widespread presence of landfills throughout the country. Another respondent suggested that landfill is not a complicated system, therefore, is easy to use.

> "*.... Managing a landfill is not a complicated system; it is easy to use and straight forward....*"

The perception that landfills are not complex and can be easily managed by municipalities highlights the perceived simplicity associated with landfill practices. These sentiments were also expressed in several studies, including those of Allen, (2001) and Vaverková, (2019). These viewpoints highlight the general acceptability of landfills as a feasible waste management solution. The nationally accepted and user-friendly nature of landfill practices, in South Africa has led to significant advancements in landfill operational activities.

6.4.3 Helps in gathering data essential in development of bylaws and governance (S3)

Landfills play a crucial role in the development of bylaws and legislations aimed at improving the management of MSW in South Africa. The availability of data on the amount and types of waste generated and disposed in landfills is critical in informing policymakers and other relevant stakeholders on the appropriate measures to manage MSW effectively. Through the continued utilisation of landfill practices, municipalities have gained valuable insights into the quantity and timing of waste generation. This understanding plays a crucial role in enabling the planning and implementation of effective MSW management strategies. Furthermore, it is mandatory of all registered South African operating landfills to release their data on their monthly operations and upload it to the SAWIC website - www.SAWIC.com which is accessible to all. An example of one of the latest South Africa's bylaws on waste is the National Environmental Management Laws Amendment Act 2 of 2022.

By relying on landfills as a means of waste disposal, municipalities can gather data and information regarding the patterns and volumes of waste produced by their communities. This knowledge serves as a foundation for informed decision-making processes, allowing authorities to develop comprehensive waste management plans that are tailored to the specific needs and demands of their respective regions (Rupani et al., 2019).

> *"… The data we get from the landfill management helps inform us on how we can manage the landfill properly",* said a Thulamela Municipal waste official.

With the landfill being available, the Municipality has been able to identify the types of waste been generated, amount of waste generated and at what time the community generates most waste. In addition, the researcher notes the significant role of landfill practice as a crucial component of waste management meetings. A respondent during the interview highlighted the indispensability of data derived from landfills in informing and shaping discussions and decisions during waste management meetings. The respondent, who works in the Municipality and conducts research on waste management said:

> *We need the data from the landfill for our waste management meetings*".

The respondent's statement shows the recognition of landfill practice as a fundamental system that contributes essential data to facilitate productive and meaningful discussions aimed at enhancing waste management practices.

6.4.4 Reliability in managing MSW (S4)

Landfill practices have a rich historical background, dating back to approximately 3,000 B.C. The first documented landfill was established in Knossos, Crete during ancient times. This early method involved digging large holes in the earth for the disposal of refuse. Over the centuries, landfill practices have evolved significantly, from the Middle Ages to the industrial revolutions, and into the 20th and 21st centuries (Długoński and Dushkova, 2021). The longevity and historical continuity of landfill practices have instilled confidence and reliability in their use, making them a significant asset in waste management. The enduring presence of landfill practices has provided a sustainable competitive advantage over other waste management methods for MSW. The long history of landfilling has gradually reduced people's fears on the perceived risks associated with its continuous use. This has fostered a sense of acceptance and trust in landfill practices among the public.

Municipal workers also expressed their reliance on landfilling as an effective waste management solution. One worker emphasised the dependability of landfills in solving waste challenges, stating,

> "*...The landfill is dependable and is solving our waste challenges... It is used all over the world, not just in South Africa*."

This perception of dependability further reinforces the confidence placed in landfill practices and their effectiveness in addressing MSW management needs. While there are alternative methods for managing MSW, such as recycling, composting, incineration, these practices, however, are often deemed too expensive, requires sophisticated equipment and expertise (Honma and Hu, 2021; Zhang et al., 2019). In contrast, landfilling provides a more cost-effective and viable option, particularly in South Africa. The organisational and governmental backing of landfill practices, with ongoing designing of laws and regulations, further contribute to the over-reliance on landfills in the country's waste management system.

6.4.5 Helps in improving human health and environmental aesthetics (S5)

Landfills play a crucial role in promoting cleanliness within communities, thereby reducing potential health risks and improving environmental aesthetics associated with improper waste disposal. Improperly managed waste can attract various vectors, insects, and flies, posing health hazards to individuals who encounter or ingest such waste. The utilisation of landfills, however, ensures that waste is transported away from the community and deposited in designated areas, thereby mitigating the health risks within the immediate vicinity of the community. As one respondent aptly stated,

> *"....Because our waste has been carried away, we do not fall sick."*

This observation highlights the perceived health benefits derived from the removal of waste from the community. The presence of landfills provides an effective mechanism for waste removal and containment, ensuring that it is no longer within proximity to residents, consequently, the risk of exposure to disease-carrying vectors and the associated health ailments is greatly reduced.

By utilising landfills, communities can maintain a cleaner environment, which is free from the immediate health risks associated with improperly managed waste. The practice of transporting waste to designated landfill sites helps to ensure the containment and proper disposal of waste materials, preventing the proliferation of disease vectors and minimising potential health hazards for community members.

6.4.6 Creates employment (S6)

The high unemployment rate in South Africa (32.9%) in the third quarter of 2022, has been a pressing issue for the country (Stats SA, 2022), however, the waste management sector, including landfilling, has played a role in addressing this challenge due to its labour-intensive nature and the economic significance it holds. With the growing population, urbanisation, and increasing waste generated per person, landfilling has provided job opportunities and contributed in mitigating unemployment issues. A landfill worker expressed gratitude for the job provided, stating,

> *"...this landfill provided a job for me, and I am able to put food on my family's table..."*

Another landfill reclaimer shared his experience, saying,

> *"...I was looking for a job, but I did not get. My friend introduced me to this business, and I like it...I have a job now with money for myself."*

The number of landfill reclaimers in South Africa is estimated to be between 60,000 and 90,000 (Yu et al., 2020). These individuals play a significant role in the waste management process by sorting and picking recyclable materials from landfills. Their contribution is not only environmentally beneficial but also economically advantageous. The Council for Scientific and Industrial Research (CSIR) reported that landfill reclaimers saved municipalities between R309 and R748 million in landfill airspace in 2014 (Sekhwela and Samson, 2020). The employment opportunities provided by landfilling, particularly through the involvement of landfill reclaimers, have contributed to reducing some of the impact of high unemployment rates in South Africa. The reclaimers have been able to earn income, support their families, and make a valuable contribution to waste management efforts.

6.5 Weaknesses

6.5.1 Not sustainable (W1)

Landfills, despite their long-standing use, are considered unsustainable due to factors such as population growth, increasing waste generation, and the persistent environmental pollution caused by buried waste. Even after closure, the buried waste in landfills continues to pose a threat to the environment for many years. Scholars have proposed various methods to rehabilitate or extract waste from closed landfills (Alzouby et al., 2019; Yi, 2019). Some respondents expressed concerns about the future of closed landfill sites and one respondent highlighted the uncertainty surrounding the fate of the area once the landfill is closed.

> *"…. Landfills are a common burial ground where rubbish is buried and is awaiting problem kept for the future generation……. We do not really know what will become of the place when they close the landfill."*

Another respondent questioned the justification of burying waste underground without utilising it for any purpose, suggesting that landfill practices may soon become outdated as better waste management options are being implemented in developed countries.

> *"…. You know what I do not believe in landfills, the idea is not justifiable, how can all these wastes be buried underground and be used for nothing. You think about it… landfill will soon be extinct because better options for managing our waste are coming out and has already been used in developed countries…."*

An environmental expert called for the government of South Africa to abandon landfill practices, citing examples from other developed countries, like Sweden, where waste is utilised for various purposes and even contributes to addressing energy challenges like load shedding.

> *"…landfill is an old technology that needs to be scraped by the government of South Africa, these wastes can be used for other purposes and even help in this load shedding problem.*

Considering these perspectives, it becomes crucial to consider the long-term implications of landfill practices and explore alternative waste management approaches that prioritise sustainability and resource utilisation.

6.5.2 Relatively expensive for a standardised sanitary landfill (W2)

The establishment and maintenance of a standardised sanitary landfill can be a costly enterprise, considering various factors involved in its implementation. Prior to setting up a landfill, an Environmental Impact Assessment (EIA) is conducted to assess the suitability of the chosen land area and this initial step incurs costs. Once approved, - the construction of landfill cells, installation of liners, systems for LFG collection and leachate management, as well as the provision of monitoring equipment, machinery, office space, and dedicated areas for recycling, among others - contribute to the overall expenses. Research conducted in Italy by Pivato et al. (2018) sheds light on the cost and design of a sanitary landfill. Their study revealed that the total cost for constructing and maintaining a sanitary landfill amounted to 68,833,045.87€ (approximately R1,242,910,049.31). This includes the expenses associated with design, authorisation, and construction of the landfill alone, which accounted for approximately 18,901,741.3€ (around R341,306,474.45). A landfill manager highlighted the challenges of building a proper sanitary landfill due to the stringent government regulations and the associated costs involved. They mentioned that it used to be easier and more cost-effective to establish a landfill in the past.

> *"…. To build a proper sanitary landfill will be too expensive because there are a lot of government rules, we need to follow for approval…. before now it was easier and cheaper to start a landfill*"

When asked about relocating the landfill due to concerns of landfill's impacts on health, the landfill manager expressed that building a new landfill would be expensive due to the rigorous approval process and associated costs. Furthermore, the installation of LFG utilisation plants and collection systems also carries a significant financial burden for municipalities. Njoku and Edokpayi, (2022) used a model to estimate the cost of implementing LFG utilisation plant in the Thohoyandou landfill located in South Africa. It was concluded in the study that the installation of LFG utilisation plants is very expensive and not economically viable in the long run. The study showed that using a Combined Heat and Power microturbine engine, the total capital cost will amount to approximately 65 million rands with an annual operations cost of 5 million rands. The study observed that, in general, the installation of most big LFG utilisation plant is very expensive and not economically viable in the landfill. Overall, the expenses associated with the construction, maintenance, and installation of necessary systems in a sanitary landfill present considerable challenges for municipalities, often necessitating careful planning and consideration of alternative waste management strategies.

6.5.3 Poor harnessing of LFG and mostly not viable for LFG utilisation (W3)

The inadequate harnessing of LFG and the challenges associated with implementing utilisation plants have been significant drawbacks in landfill operations. The generation of LFG is influenced by various factors such as - the type of waste, temperature, moisture content, and waste volume. Several studies, such as those by Coskuner et al. (2020) and Manyuchi et al. (2017) have revealed that landfills often do not produce enough gas to support the operation of utilisation plants, although, there are also studies suggesting that profitability can be achieved through the installation of LFG utilisation plants by selling carbon credits (Njoku and Edokpayi, 2022).

One landfill manager acknowledged this issue, stating that a feasibility study on the landfill he is managing had been conducted to collect and utilise gases, but the landfill did not produce enough gas to make it economically viable for the municipality to implement the project. The landfill manager, who was already collecting LFG, highlighted the challenges encountered during gas collection, including blocked pipes that could cause engine failures. In particular, , the manager mentioned the low gas production, necessitating induced measures to increase gas availability.

> *"We have encountered a lot of challenges during the collection of gases from the landfill, sometime the pipes get locked which can make the engine to fail…. low gas that is formed…"*

The occurrence of pipe blockages poses a significant operational risk, potentially leading to engine failures and interruptions in the gas collection process, hence, the challenge of low gas formation further complicates the efficiency of LFG collection efforts.

6.5.4 Breeding ground for insects, flies, rodents and bad odour (W4)

The presence of unpleasant odours, the breeding of flies, insects, and mosquitoes. are common characteristics associated with landfills in South Africa. These undesirable conditions arise because of the decomposition process occurring within the landfill, leading to the release of noxious gases such as hydrogen sulfide (H_2S), which significantly contributes to the elevated odour levels (Njoku et al., 2019); the waste present in the landfill provides a conducive environment for the proliferation of flies and insects, further exacerbating the issue. The regular inhalation of these foul odours can have detrimental effects on human health. Studies have corroborated the prevalence of strong odours and the abundance of insects within landfills (Njoku et al., 2019; Siddiqua et al., 2022). One waste picker shared her experience of falling sick on several occasions due to the overpowering smell emanating from the landfill. She described how the persistent odour lingers on her clothes and body, significantly affecting her daily life. She complained:

> *"This is a bad smell and makes me sick. I even smell of waste when I go home…. I have a friend who stopped coming to this business because the smell was too much for her".*

Another landfill reclaimer expressed concern about the presence of flies and other insects in the landfill, which not only affects their well-being but also poses a potential health risk to their household.

> *"…. Sometimes there is a lot of flies and other insects in the landfill which make us sick………"*

An resident living near the landfill expressed dismay regarding the overwhelming odour emanating from the site, demonstrating the adverse impact it has on the quality of life.

> *"We do not sleep with the windows open because of bad smell and mosquitoes…. I am planning on relocating out from this place with my family".*

6.5.5 Increases sicknesses in workers, reclaimers, and neighbouring town (W5)

The adverse health effects associated with landfilling activities have been a significant concern, particularly for workers, reclaimers, and residents living near landfills, especially in South Africa. Extensive research conducted by Njoku et al. (2019) and Ferronato and Torretta (2019) has demonstrated the detrimental impacts of long-term exposure to landfill environments on human health. These studies have shown a correlation between living near landfills and the development of various illnesses, including, flu-like symptoms, body weakness, headaches, and other health issues. The respondents interviewed expressed their belief that falling sick is almost inevitable for those who work in landfills or live near these sites. One reclaimer, who has experienced recurring health problems, shared her personal struggles, including body aches, headaches, and back pain, which she attributed to the foul odours emitted by the landfill. She also mentioned that her colleagues have faced similar health issues, demonstrating the adverse effects of prolonged exposure to the landfill environment. She said,

> *"…. I have suffered from bad body rashes, headaches, and back pain…. the job can be hard …. Some of other reclaimers here do complains of the same problem……. if we are staying in the place too much, we fall sick…."*

Another respondent who lives close to a landfill, highlighted the regularity of sickness, attributing it to the unhygienic conditions and surrounding filth.

> "*We fall sick regularly because of the dirt around us…*"

These quotations reflect the overall sentiments that the unsanitary environment in and around landfills contribute to increased health risks for those exposed to them.

Interestingly, some respondents mentioned that they had not experienced any health issues since working in the landfill. One reclaimer said.

> *"I have never fallen sick before since I started picking here (shaking his head)."*

This appears surprising, although, it could be attributed to various factors, such as individual resilience, differences in susceptibility to environmental factors, or limited exposure periods, nonetheless, it is crucial to consider the experiences of the majority, as the potential health hazards associated with landfill activities, cannot be overlooked.

6.5.6 Low income (W6)

Landfill operations in South Africa face a significant challenge in the form of low wages paid to the workforce. This issue is multifaceted and has far-reaching implications for the effectiveness and sustainability of landfill management (Iddrisu and Debrah, 2021).

A landfill manager expressed dissatisfaction with the situation, highlighting the disparity in remuneration between landfill workers and municipal staff. He said,

> "*The landfill managers in Municipality do not know anything and are paid very well……they have permanent positions….*"

Another manager expressed his grievance when he said,

> *"… We earn peanuts here in the landfill, they don't want to pay us well because we are not working as Municipal staff……"*

He pointed out that landfill managers, despite their limited knowledge and skills, are well-compensated due to their permanent positions within the municipality. This discrepancy in pay creates a demoralising environment for landfill workers, who feel undervalued and underpaid for their significant contributions. Low wages directly and negatively impact employee morale and motivation As when workers feel undervalued and inadequately compensated, their job satisfaction diminishes. This affects not only their performance but also their commitment to the responsibilities associated with landfill management. A landfill worker stated,

> "*…… It's depressing to work hard and still earn very little……".*

In addition to resulting in low employee morale, the quality of service delivered in landfill operations can suffer due to low wages. Landfill workers who are responsible for waste management, site upkeep, and environmental protection need proper training and motivation to offer high-quality services. Inadequate compensation, hence, can demotivate employees, leading to lapses in waste management practices and increased safety and environmental risks. A participant mentioned this point:

> "*….We want to do our best, but it's challenging when we don't have the resources and incentives we need……*"

Recruitment challenges also loom large when low wages are a persistent issue. The landfill industry depends on a steady influx of skilled and dedicated workers, however, low wages can deter potential candidates from considering careers in landfill management. This narrows the pool of qualified applicants, making it difficult for landfills to find and hire skilled personnel. As one participant put it,

> "*Not many people will be interested in working in landfills because the pay is little…….*"

One notable consequence of low wages, hence, is the difficulty in attracting and retaining a skilled workforce. Skilled landfill workers are essential for the proficient operation of landfill sites, including tasks like waste compaction, maintenance, and environmental monitoring.

6.5.7 Lack of expertise (W7)

In the realm of landfill management in developing countries including South Africa, one conspicuous challenge is the dearth of expertise among the workforces. This deficit in knowledge and experience significantly impedes the effective operation of landfill sites and compounds the existing challenges faced by this sector (Mmereki, 2015). The insights gathered from participants, including both a landfill manager and a worker, shed light on the discontent and frustrations experienced by those directly involved in landfill operations. In the words of a landfill worker,

> "*The contractors do not possess the requisite knowledge on how a landfill should be designed and operate. We are lacking in experienced individuals working here.*"

This sentiment explains the prevailing issue of expertise in landfill management. The absence of a well-informed and skilled workforce affects multiple aspects of landfill operations, from waste compaction and environmental monitoring to safety and regulatory compliance. As a result, operational efficiency and effectiveness are hampered, creating additional hurdles in establishing and maintaining a well-functioning landfill.

Furthermore, this shortage of expertise has broader implications for environmental stewardship and public health. Landfill sites inherently carry environmental risks, and mitigating these risks necessitates a team with the expertise to navigate complex regulatory requirements and safety protocols. When expertise is lacking, environmental hazards may go unchecked, potentially leading to contamination of soil and groundwater, air pollution, and other adverse ecological impacts. As a researcher pointed out,

> "*Without experienced staff, we struggle to manage environmental concerns effectively.*"

The ramifications of this issue extend beyond the technical aspects of landfill management. The absence of expertise can also lead to inefficiencies in waste disposal and resource recovery. Skilled personnel are essential in optimising waste segregation, recycling, and the extraction of valuable resources and without this expertise, valuable opportunities for resource utilisation may be overlooked, thus impeding efforts towards sustainability and economic growth.

6.6 Opportunities

6.6.1 Waste to energy and other resources (O1)

The deposition of waste in landfills over time leads to the emission of gases, presenting an opportunity to harness them for various beneficial purposes. When collected and properly cleaned, LFG can serve as a valuable fuel source for electricity generation, powering vehicular transportation, providing heating systems, and producing biogas and biofertilizers for farming. Successful transformations of waste to energy have been achieved in numerous landfills worldwide, including some parts of South Africa (Njoku et al., 2018). The potential for harnessing LFG and utilising it as a source of energy holds promise for improving the country's economy and sustainable development.

A landfill worker emphasised the significant gas emissions from the landfill and the need for caution due to the potential explosiveness of these gases.

> *"…this landfill emits a lot of gases and they are very explosive……we are very careful with anything that can catch fire. We can harness that gas and use it to generate electricity and power our vehicles".*

This statement highlights the worker's awareness of the hazards associated with LFG and their vigilance in preventing potential fires., The worker recognises the potential of harnessing these gases for electricity generation and powering vehicles, indicating a positive outlook on utilising LFG as a valuable resource.

The utilisation of LFG has the potential to bring about several benefits. By capturing and utilising these gases, landfills can significantly reduce GHG emissions, contributing to environmental sustainability and mitigating climate change. The generation of electricity from LFG can help meet energy demands and reduce dependence on fossil fuels, promoting energy diversification and security. Harnessing LFG also presents economic opportunities; for instance, the generation of electricity from waste can create jobs, stimulate local industries, and attract investment in renewable energy technologies. Additionally, the production of biogas and biofertilizers can support agricultural activities, improve soil fertility, and contribute to sustainable farming practices.

6.6.2 Enhances sorting, recycling and reuse (O2)

Landfill operations can play a significant role in promoting recycling and the reuse of waste materials. In developed nations, where waste collection and disposal systems are often centralised, there are better opportunities to implement recycling initiatives on a large scale. The centralised collection of waste facilitates easier access to recyclable materials, enabling municipalities and other stakeholders to develop effective recycling and reuse methods. By integrating recycling processes into landfill operations, valuable resources can be recovered, reducing the amount of waste that ultimately ends up in the landfill.

A researcher in waste management highlighted this fact:

> *"…landfill is a great tool to help recycle different waste, it is easier to separate and sort the waste there all together".*

This concept embraces the idea of sorting and separating recyclable items from general waste, maximising the recovery of valuable materials, however, it is necessary to also consider the associated challenges and costs involved in implementing such a system.

Incorporating recycling facilities within landfill operations is a promising strategy, however, the process requires significant resources in terms of manpower, equipment, and infrastructure. During the interviews with waste management professionals, concerns about the practicality and costs associated with extensive sorting and cleaning were raised. One respondent highlighted the labour-intensive nature of waste sorting,

> *"Sorting and cleaning waste materials for recycling is a time-consuming and demanding task. It requires a substantial workforce and specialised equipment to separate different types of recyclables from the general waste stream. This is a challenge, especially when dealing with high volumes of waste."*

There are challenges and costs involved in incorporating recycling initiatives into landfill operations, despite this, the process can yield significant environmental and economic benefits. By diverting recyclable materials from landfills, valuable resources can be conserved, energy can be saved, and greenhouse gas emissions can be reduced., Recycling activities can, moreover, generate employment opportunities, foster innovation, and contribute to the development of a circular economy. The idea of incorporating recycling plants within landfill operations is a promising concept, although it requires careful consideration of the associated challenges and costs. By optimising recycling practices, waste can be transformed into valuable resources, contributing to sustainability, resource conservation, and economic growth.

6.6.3 Opportunity for local and international collaboration (O3)

Landfills have the potential to facilitate local and international collaborations among organisations, municipalities, and countries in the realm of waste management. Such collaborations can lead to the sharing of knowledge, resources, and best practices, ultimately contributing to more effective and sustainable waste management systems. One notable example of international collaboration in LFG utilisation is the partnership between the World Bank and the Durban Municipality, which resulted in the establishment of the first LFG utilisation plant in South Africa (Strachan et al., 2006). This collaboration demonstrates the value of combining financial support from international institutions with the local expertise and infrastructure of municipalities to implement innovative waste management solutions. The success of this collaboration not only addressed environmental concerns associated with LFG emissions but also provided a platform for knowledge-sharing and capacity-building in the field of waste-to-energy technologies.

Collaborations between municipalities within a country can also yield significant benefits. In some countries, different municipalities join forces to effectively manage their waste, recognising the shared challenges and opportunities they face (Ferdous et al., 2021). This collaborative approach allows municipalities to pool resources, share experiences, and collectively develop strategies for waste management. By learning from one another's successes and failures, municipalities can enhance their waste management practices and drive continuous improvement. The potential for collaborations between municipalities in South Africa regarding waste management has been widely acknowledged, as highlighted by Gumbo and Simelane (2015). These collaborations offer valuable opportunities for knowledge exchange and cooperation, fostering a stronger bond between municipalities and driving overall improvements in waste management practices.

Capacity-building initiatives are also a key aspect of collaborations in waste management. Municipalities can pool their resources and expertise to develop training programs, workshops, and knowledge-sharing platforms. One respondent highlighted this aspect,

> "*Collaborations can enable capacity-building initiatives, where municipalities can jointly invest in training programs and knowledge-sharing activities*."

Collaborations in waste management extend beyond technical and operational aspects, encompassing broader environmental and social dimensions. They create opportunities for sharing experiences and lessons learned, as well as exploring innovative solutions to common waste management issues. Respondent expressed this point, explaining that collaborations foster a culture of learning and innovation.

6.6.4 Improve South Africa's economy (O4)

Landfill operations possess significant potential for stimulating a country's economy through the proper utilisation of the resources that are sent to landfills. By harnessing these resources effectively, various economic benefits can be realised, contributing to sustainable development and job creation. One notable opportunity lies in the utilisation of LFG generated by decomposing organic waste in landfills (Agamuthu and Fauziah, 2011). LFG, primarily consisting of methane, can be captured, and utilised as a source of renewable energy. This can be achieved by employing gas collection systems and utilising the collected gas to generate electricity or power vehicles. As a result, the landfill can become a valuable energy resource, reducing dependence on fossil fuels, and offering economic benefits.

Landfill operations can facilitate the establishment of improved recycling facilities. By investing in state-of-the-art recycling plants, the waste received at landfills can be more efficiently sorted and processed, leading to increased recycling rates (Ferdous et al., 2021). This not only helps to reduce the amount of waste ending up in landfills but also creates opportunities for job growth and economic development. With proper waste management practices in place, recycling can become a robust industry, promoting resource conservation, and generating employment opportunities.

In addition to LFGs' production and recycling, landfills can also contribute to the economy through the beneficial reuse of specific waste materials; for instance, garden waste, when collected and diverted from landfills, can be composted, and utilised as organic fertilizers for agricultural activities. This promotes soil health, reduces the need for chemical fertilizers, and enhances crop productivity. The utilisation of garden waste as compost aligns with the principles of circular economy and sustainable agriculture, thereby benefiting both the environment and the economy.

By effectively harnessing the resources present in landfills, such as LFGs, recyclable materials, and compostable waste, economies can experience multiple advantages. These include reduced reliance on non-renewable energy sources, increased employment opportunities within the recycling sector, and enhanced agricultural productivity.

6.7 Threats

6.7.1 Unavailability of land and overfill of landfill before anticipated date (T1)

The limited availability of land and the increasing generation and disposal of solid waste pose significant threats to landfill operations. As landfills reach their capacity earlier than anticipated, the need for new landfill sites arises (Ismail and Latifah, 2013). In regions with limited land resources, such as South Africa, the scarcity of suitable land can lead to major threats to landfill operations, communal clashes and social unrest (Hall, 2011).

Landfills have a finite capacity, and their lifespan depends on factors such as waste generation rates, disposal practices, and land availability, however, the anticipated time of closure may be accelerated due to the limited availability of land or the rapid increase in solid waste generation and disposal. This situation is further exacerbated in densely populated regions or urban areas, where land resources are particularly scarce. The scarcity of land for landfill operations is a pressing issue in South Africa. The country's rapid urbanisation, population growth, and limited land resources contribute to the challenge of finding suitable sites for new landfills. This scarcity can lead to the early closure of existing landfills and the need for alternative waste management strategies (Şener et al., 2006).

With limited available land, municipalities may struggle to find suitable locations for waste disposal, leading to increased costs for transportation and longer distances for the process. This can strain existing waste management infrastructure and hinder efficient and cost-effective waste disposal practices. Furthermore, the lack of available landfill space can lead to increased reliance on sub-optimal waste management methods, such as illegal dumping or the use of inadequate facilities, thereby, further exacerbating environmental and health risks.

The limited availability of land for landfill operations can have wide-ranging implications, including environmental, social, and economic challenges. The inability to establish new landfill sites can result in improper waste disposal practices, such as illegal dumping or the use of substandard waste management facilities, leading to environmental pollution and health risks.

Additionally, the scarcity of land for landfill operations can exacerbate existing social and communal tensions. Competition for land resources and disagreements over landfill site selection can escalate into communal clashes and social unrest. The South African context highlights the severity of the land-availability challenge, for the scarcity of land has not only impeded effective waste management practices but has also contributed to societal unrest (Ani, 2020). As a result, finding sustainable solutions that balance the needs of waste management and land allocation become imperative.

6.7.2 The incapacity for landfills to be sustained over a long term (T2)

Landfills, despite being a common waste management solution, face inherent limitations in long-term sustainability. While some closed landfills are rehabilitated into parks and playgrounds, the generation, and emissions of gases from these sites continue to pose risks to human health and the environment. This section delves into sustainability challenges associated with landfills, particularly after their closure, highlighting the potential threats they pose and the need for effective mitigation strategies.

Landfills have inherent limitations when it comes to long-term sustainability. As waste decomposes in landfills, it produces gases like CH_4 and CO_2, which are major contributors to greenhouse gas emissions and climate change. According to the United Nations Environment Programme (UNEP, 2021):

> "*landfills are one of the largest sources of human-made methane emissions globally*".

A respondent pointed out some of the risks associated with CH_4 emissions from closed landfills,

> *"Methane, is a combustible gas, which can create the potential for explosions or fires in closed landfill sites if proper management measures are not in place. ….. The migration of gases, through the soil and into surrounding areas can contaminate groundwater."*

These concerns raised about the limitations and risks of landfills align with the point that landfills have inherent challenges in terms of long-term sustainability. The reference to the UNEP statement supports the significant contribution of landfills to methane emissions on a global scale.

The WHO acknowledges the potential health risks associated with landfill emissions, stating that - "exposure to landfill gas emissions can cause various adverse health effects, including respiratory and cardiovascular diseases" (WHO, 2018).

The release of VOCs and other hazardous substances from decomposing waste can also pose risks to nearby communities, especially those living near closed landfill sites, therefore, to mitigate the risks associated with post-closure landfill emissions, effective strategies are required. Methane-capture and utilisation systems, such as landfill gas recovery systems, can help mitigate the release of methane into the atmosphere.

6.7.3 Fire outbreaks (T3)

The issue of landfill fires stands as a significant and multifaceted challenge within the realm of waste management, and its implications for landfill operations are far-reaching. These fires present a complex threat that touches upon various critical aspects, from environmental and safety concerns to resource management and economic considerations. Landfill fires pose a formidable environmental hazard and emit harmful array of harmful substances and toxic fumes into the atmosphere (Milosevic et al., 2018). Among the pollutants released are VOCs, heavy metals, and various hazardous materials, all of which can lead to severe air pollution. According to Agunbiade and Odukoya (2021), the environmental implications of landfill fires extend to the release of greenhouse gases, particularly CH_4. Methane, a potent contributor to global warming, can significantly compound the environmental impact of landfill fires. The emission of greenhouse gases perpetuates the larger issue of climate change, underlining the overarching ecological concerns associated with these fires.

Safety is another pivotal consideration in the context of landfill fires. The hazardous conditions they create are not confined solely to the environmental sphere As landfill workers and emergency responders are faced with risks that stem from the heat, flames, and toxic fumes generated by these fires. The unique challenge here lies in the uncertain nature of the materials present in the waste, making firefighting efforts intricate and perilous. Ensuring the safety of landfill personnel and the nearby population, thus becomes an imperative concern demanding comprehensive risk mitigation measures (Wagner and Bilitewski, 2009). Additionally, landfill fires result in a considerable loss of valuable resources that could otherwise be harnessed for recycling, repurposing, or energy generation through methods such as waste-to-energy facilities. This resource loss underscores a missed opportunity in the context of sustainable waste management. The incineration of materials in landfill fires not only carries economic implications but also runs counter to the principles of responsible waste disposal, wherein resource conservation and sustainability are paramount.

Operational disruption and financial repercussions further compound the problem. Managing a landfill fire demands substantial resources, ranging from specialised firefighting equipment to skilled personnel. The financial burden can be significant, extending to costs for securing the site, controlling the fire, and addressing the aftermath (Jakhar et al., 2023). These unplanned expenses can disrupt regular landfill operations and strain budgets and financial planning.

Legal and regulatory consequences also loom large. Landfill operators may find themselves subject to penalties or legal actions for failing to manage waste effectively or for inadequately preventing and addressing fires. Regulatory bodies may respond by imposing stricter requirements and more rigorous monitoring, potentially increasing operational complexity and compliance costs.

6.7.4 Increase in MSW generation (T4)

The issue of waste management has become increasingly critical in South Africa due to the rising generation of waste. The most recent available data indicates that the country produces approximately 122 million tonnes of waste annually (Nyika et al., 2020). This surge in waste generation poses significant challenges for municipalities, particularly with regards to providing adequate waste management services. Furthermore, a substantial portion of the generated waste, around 3.67 million tonnes, remains untreated and uncollected by formal waste collection systems each year, leading to illegal dumping practices. As a result, landfill capacities are being strained, and the sustainability of landfilling activities is being threatened (Nyika et al., 2020).

Several factors contribute to the rapid increase in waste generation in South Africa - population growth and urbanisation play crucial roles in this trend. The country's population has been steadily increasing, resulting in greater consumption and consequently, higher waste generation. Additionally, urbanisation leads to lifestyle changes, increased consumption patterns, and the concentration of economic activities in urban areas, all of which contribute to elevated waste production (Cayumil et al., 2021). A lack of compliance and overall negative attitudes towards proper waste management also contribute to the growing waste generation problem. Insufficient enforcement of waste management regulations allows for irresponsible disposal practices, such as illegal dumping, which further exacerbate the waste management challenge. Additionally, public awareness and attitudes toward waste management practices need improvement to promote responsible waste disposal and recycling behaviours among individuals and businesses.

6.7.5 Contributes significantly to climate change (T5)

The issue of uncollected and unused LFG emissions is a significant concern, not only in South Africa but also globally. Landfills have been recognised as a substantial source of CH_4 emissions, a potent greenhouse gas that contributes to climate change and global warming. The magnitude of this problem is evident from the fact that, according to the USEPA (2022), landfills accounted for approximately 17% of the total methane emissions in 2020. In South Africa, the lack of adequate means for the collection and utilisation of LFGs emitted from landfills is a prevailing challenge. This situation poses serious implications for the environment and exacerbates the climate change crisis. CH_4, the primary component of LFG, has a significantly higher global warming potential compared to carbon dioxide. When released into the atmosphere, methane has the ability to trap heat more effectively, thereby contributing to the greenhouse effect. If methane emissions from landfills continue to go unaddressed, the consequences for climate change could be severe, as this could further exacerbate global warming and its associated impacts.

6.8 Pairwise comparison matrix for the associated factors during the SWOT analysis

Strength

Regarding the overall strength of landfill practices, the respondents indicated that the strength of landfill operations can be credited to the reliable management of more than 90% of the generated waste in South Africa (the factor, S1). Table 6.3 shows the pairwise comparison matrix for strengths associated with landfill practice. Figure 6.1 provides a visual representation of the criteria weight assigned to the different strengths; these emphasise the significant contribution to the overall effectiveness of landfill practices in the waste management landscape.

Table 6.3 Pair wise comparison matrix for strengths associated with landfill practice

$$\left(\begin{array}{ccccccc} \boldsymbol{Criteria} & \boldsymbol{S1} & \boldsymbol{S2} & \boldsymbol{S3} & \boldsymbol{S4} & \boldsymbol{S5} & \boldsymbol{S6} \\ \boldsymbol{S1} & \mathbf{1} & \mathbf{3} & \mathbf{5} & \mathbf{3} & \mathbf{4} & \mathbf{7} \\ \boldsymbol{S2} & \mathbf{0.33} & \mathbf{1} & \mathbf{3} & \mathbf{3} & \mathbf{4} & \mathbf{5} \\ \boldsymbol{S3} & \mathbf{0.2} & \mathbf{0.33} & \mathbf{1} & \mathbf{0.33} & \mathbf{3} & \mathbf{3} \\ \boldsymbol{S4} & \mathbf{0.33} & \mathbf{0.33} & \mathbf{3} & \mathbf{1} & \mathbf{3} & \mathbf{3} \\ \boldsymbol{S5} & \mathbf{0.25} & \mathbf{0.25} & \mathbf{0.33} & \mathbf{0.33} & \mathbf{1} & \mathbf{4} \\ \boldsymbol{S6} & \mathbf{0.14} & \mathbf{0.2} & \mathbf{0.33} & \mathbf{0.33} & \mathbf{0.25} & \mathbf{1} \end{array}\right)\left(\begin{array}{c} \boldsymbol{Eigen\ vector\ (priority)} \\ \mathbf{0.41} \\ \mathbf{0.24} \\ \mathbf{0.1} \\ \mathbf{0.15} \\ \mathbf{0.07} \\ \mathbf{0.04} \end{array}\right)$$

CR = 0.085

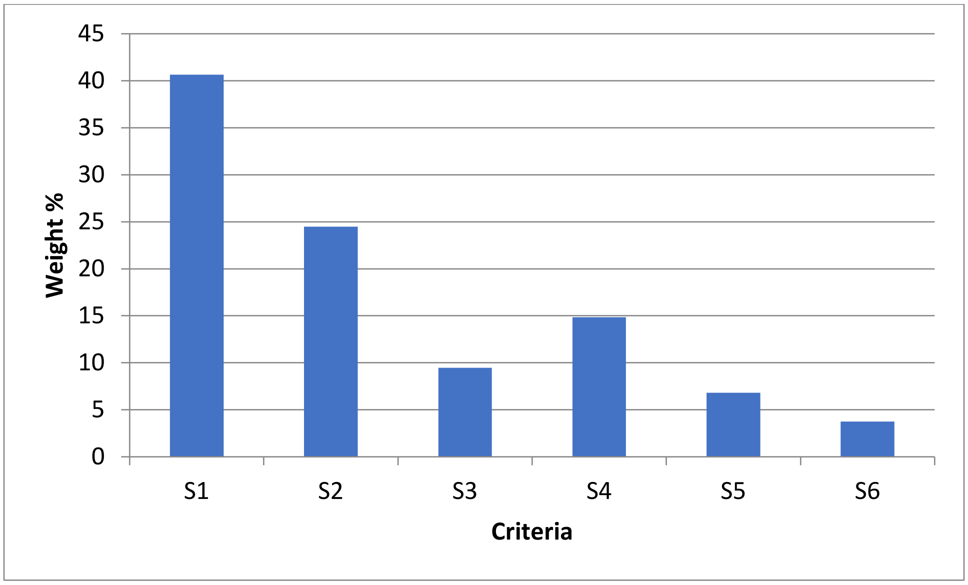

Figure 6.1: Relative priorities for various landfill criteria, under strengths

The factor (S1) is ranked the highest by the respondents with recorded weight of 41% (Figure 6.1). According to Table 6.3, the Consistency Ratio (CR) is 0.085, this is an indication that the opinions of the respondents were consistent and reliable. The factor (S2) was ranked second on the respondent performance ranking with recorded weight of 24%. This is because the respondents identified the landfill practice as an easy technology to use and it is nationally available. The factor (S6) was ranked the lowest with a recorded criteria weight of 4%.

Weaknesses

Table 6.4 shows the pairwise comparison matrix for weakness associated with landfill practice which indicated the overall weakness in the study. The CR value equals 0.095, suggesting that the pairwise comparison matrix has a reasonable level of consistency, which is a positive indicator for the reliability of the decision-making process. According to Figure 6.2, factor (W2) was ranked the lowest with a record weight of 3.5 % by the respondents. Most of the respondents did not agree to the fact that operating a landfill is very expensive. This is because the respondents were not familiar with the technologies involved in operating a sanitary landfill, such as the installation of a LFG collection and utilisation system, installed linear, machine maintenance and other logistics, however, factor (W4) ranked the highest with a record weight of 44.7 % by the respondents. Most respondents agreed to the issues of landfill being a breeding ground for insects, flies, rodents and bad odour. This could be due to the direct impacts these issues have had on the community and the environment, such as health hazards, disturbance, and overall degradation of the living environment. The presence of insects, flies, rodents, and bad odour in landfills is not only unpleasant but also poses health risks and indicates poor waste management practices. As such, respondents may have ranked this factor highest due to its immediate and tangible effects on their daily lives and surroundings.

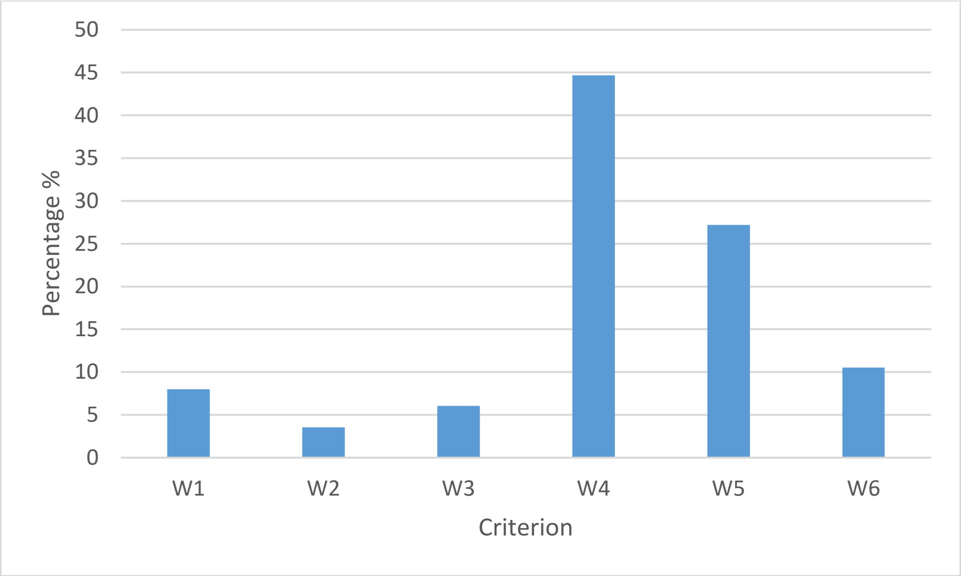

Figure 6.2: Relative priorities for various landfill criteria under weaknesses

Table 6.4: Pairwise comparison matrix for weaknesses associated with landfill practice

$$\left(\begin{array}{ccccccc} \boldsymbol{Criteria} & \boldsymbol{W1} & \boldsymbol{W2} & \boldsymbol{W3} & \boldsymbol{W4} & \boldsymbol{W5} & \boldsymbol{W6} \\ \boldsymbol{W1} & \mathbf{1} & \mathbf{3} & \mathbf{3} & \mathbf{0.14} & \mathbf{0.17} & \mathbf{0.5} \\ \boldsymbol{W2} & \mathbf{0.33} & \mathbf{1} & \mathbf{0.25} & \mathbf{0.14} & \mathbf{0.17} & \mathbf{0.33} \\ \boldsymbol{W3} & \mathbf{0.33} & \mathbf{4} & \mathbf{1} & \mathbf{0.13} & \mathbf{0.17} & \mathbf{0.33} \\ \boldsymbol{W4} & \mathbf{7} & \mathbf{7} & \mathbf{8} & \mathbf{1} & \mathbf{3} & \mathbf{5} \\ \boldsymbol{W5} & \mathbf{6} & \mathbf{6} & \mathbf{6} & \mathbf{0.33} & \mathbf{1} & \mathbf{4} \\ \boldsymbol{W6} & \mathbf{2} & \mathbf{3} & \mathbf{3} & \mathbf{0.2} & \mathbf{0.25} & \mathbf{1} \end{array}\right)\left(\begin{array}{c} \boldsymbol{Weights\ (Eigen\ Vector)} \\ \mathbf{0.08} \\ \mathbf{0.035} \\ \mathbf{0.06} \\ \mathbf{0.45} \\ \mathbf{0.27} \\ \mathbf{0.11} \end{array}\right)$$

CR = 0.095

Opportunities

The factor (O1) is ranked the highest by the respondents with recorded weight of 58 % (Figure 6.3). The CR is 0.080, this is an indication that the judgments of the consulted respondents are consistent and reliable. The respondents believe that waste buried in the landfill can be transformed to energy or other forms of resources. This is because of the already existing implementations that have been ongoing in some developed countries. The factor (O3) was ranked the lowest with a recorded weight of 5.9 %. The respondents identified that landfilling can be a major access to different forms of internationalisation and collaboration between municipalities. Criteria (O3) was ranked the lowest because there are limited collaborations between municipalities in South Africa

(Jessa and Uys, 2019). Table 6.5 shows the pair-wise comparison matrix for opportunities associated with landfill practice.

Table 6.5: Pairwise comparison matrix for opportunities associated with landfill practice

$$\left(\begin{array}{ccccc} \mathbf{Criteria} & \mathbf{O1} & \mathbf{O2} & \mathbf{O3} & \mathbf{O4} \\ \mathbf{O1} & \mathbf{1} & \mathbf{4} & \mathbf{7} & \mathbf{6} \\ \mathbf{O2} & \mathbf{0.25} & \mathbf{1} & \mathbf{5} & \mathbf{5} \\ \mathbf{O3} & \mathbf{0.14} & \mathbf{0.2} & \mathbf{1} & \mathbf{0.5} \\ \mathbf{O4} & \mathbf{0.17} & \mathbf{0.2} & \mathbf{2} & \mathbf{1} \end{array}\right)\left(\begin{array}{c} \mathbf{Weights\ (Eigen\,Vector)} \\ \mathbf{0.58} \\ \mathbf{0.27} \\ \mathbf{0.059} \\ \mathbf{0.089} \end{array}\right)$$

CR= 0.080

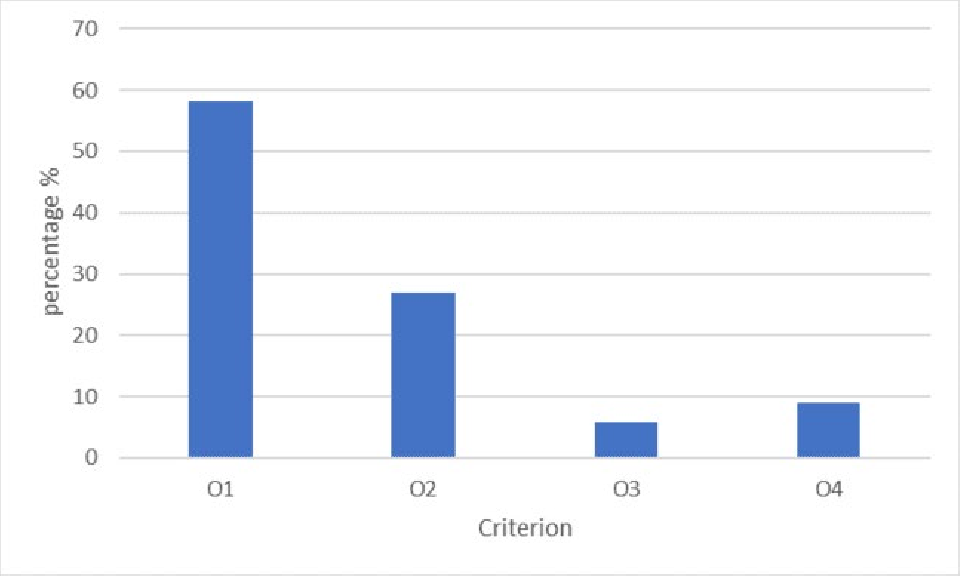

Figure 6.3: Relative priorities for various landfill criteria under opportunities

Threat

The threat of the landfill practice entails those factors that have the potential to stop the landfilling operation. The factor (T5) and (T1) were ranked the first and second by the respondents with recorded weight of 44 % and 26 %, respectively (Figure 6.4). According to the results, the CR is 0.097, this is an indication that the judgments of the consulted respondents are consistent and reliable. The factor (T3) was ranked the lowest with a recorded weight of 4.7 %. The respondents believed landfill can contribute to potential fire outbreak, however, there seemed not to be a lot of recorded fire outbreaks in the visited landfill. Table 6.6 shows the pairwise comparison matrix for the threats associated with landfill practice.

Table 6.6: Pair wise comparison matrix for threats associated with landfill practice.

$$\begin{pmatrix} \boldsymbol{Criteria} & \boldsymbol{T1} & \boldsymbol{T2} & \boldsymbol{T3} & \boldsymbol{T4} & \boldsymbol{T5} \\ \boldsymbol{T1} & \mathbf{1} & \mathbf{3} & \mathbf{6} & \mathbf{3} & \mathbf{0.33} \\ \boldsymbol{T2} & \mathbf{0.33} & \mathbf{1} & \mathbf{4} & \mathbf{3} & \mathbf{0.25} \\ \boldsymbol{T3} & \mathbf{0.17} & \mathbf{0.25} & \mathbf{1} & \mathbf{0.25} & \mathbf{0.2} \\ \boldsymbol{T4} & \mathbf{0.33} & \mathbf{0.33} & \mathbf{4} & \mathbf{1} & \mathbf{0.25} \\ \boldsymbol{T5} & \mathbf{3} & \mathbf{4} & \mathbf{5} & \mathbf{4} & \mathbf{1} \end{pmatrix} \begin{pmatrix} \boldsymbol{Weights\ (Eigen\ Vector)} \\ \mathbf{0.26} \\ \mathbf{0.16} \\ \mathbf{0.047} \\ \mathbf{0.104} \\ \mathbf{0.44} \end{pmatrix}$$

Consistency ratio CR= 0.097

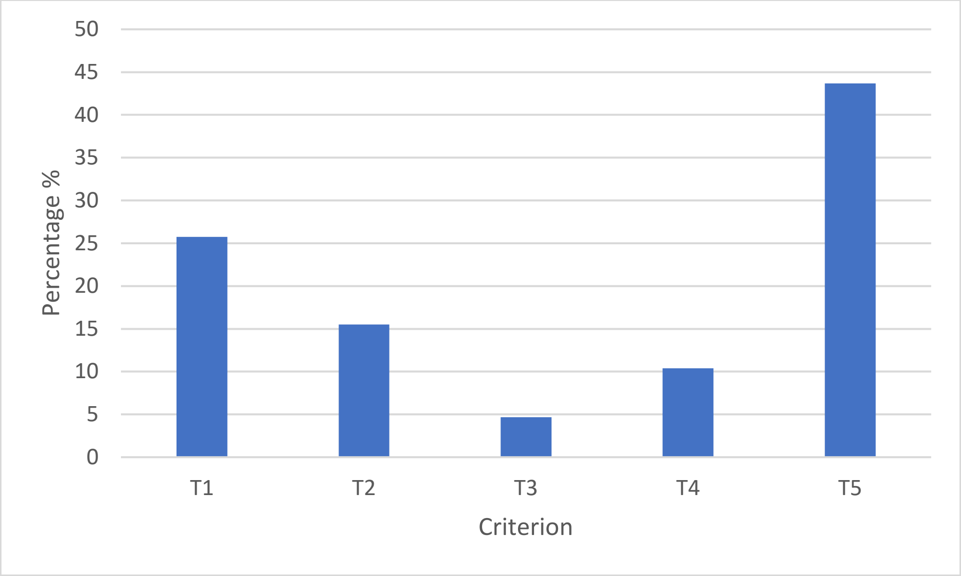

Figure 6.4: Relative priorities for various landfill criteria under threats

6.5 Conclusion

Landfilling has been the major source of MSW management in South Africa. This needs to be revisited as this management system is becoming outdated and it prevents the harnessing of resource found in MSW generation. There is an urgent call for the country to focus more on other alternative management systems, like recycling, biogas production, bio fertilizer, composting and even incineration. This will in turn help boost the economy of South Africa in the aspects of energy, agriculture and transportation. Drawing inspiration from developed nations that have successfully minimised their landfill waste to approximately 0.4% over time, it is evident that adopting effective waste reduction and management strategies can lead to significant environmental achievements.

This chapter thus evaluated the country's landfilling practices using a combination of SWOT analysis and the AHP tool. The findings show that the major strengths of landfills practice are that landfill has controled and managed most of South Africa's waste for over several decades. Similarly, the associated weakness that was identified mostly by the respondent was that the place is a breeding ground for insects, flies, rodents and bad odour. This is as a result of poor management practice, however, steps have been introduced to curb the menace, although, municipalities tend to get them wrong and not adhere to the standard given by the government. The opportunities to have a better landfill management practice focused on the ability for landfills to convert the waste to energy and other resources, particularly, because of the ability of waste to produce methane gases that can be used for energy generation. The main associated threat to landfilling is the continuous increase in waste generation, however, this can be improved if there is a drastic increase in encouragement of recycling, and reuse culture in the country.

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CHAPTER SEVEN: Developing a conceptual framework for an Integrated Solid Waste Management System (ISWMS)

Preamble

The results of the identified weaknesses and failures of the disposal technique (landfill) in effectively managing and harnessing the full potential of waste were focused upon in **Chapter Six** of this study. Thohoyandou landfill, a prominent rural-based South African landfill in Thulamela Municipality faces a waste management crisis marked by challenges such as illegal dumping, inadequate recycling infrastructure, and limited resources. Inspired by the success of Sweden's Boras model, this study aims to develop a relevant ISWMS framework for Thulamela Municipality. The framework, shaped through literature review, data analysis, and expert input, seeks to address waste challenges, promote resource recovery, and establish a sustainable model for broader implementation in South Africa. The goal is to transform waste into valuable resources through innovation, community engagement, and a holistic approach. This chapter develops a novel comprehensive framework for achieving zero waste, drawing inspiration from successful strategies employed in Boras, Sweden.

Abstract

In South Africa, MSW management is a major concern due to a substantial amount of waste ending up in landfills, while only a small fraction gets diverted for alternative disposal methods. This study aims to create a holistic framework to move South Africa towards a zero-waste approach. The case study focuses on the Thulamela Municipality, drawing inspiration from the successful waste management model implemented in Boras, Sweden.

A qualitative approach was utilised to investigate the waste management process in Thulamela Municipality, South Africa. Firstly, a comprehensive analysis and overview of the existing boras model was conducted from pre-existing literatures, to gain insights into waste management practices in Boras city, Sweden. Also, 44 participants from the Thulamela Municipality were interviewed to understand its waste management practices, then the results were compared to the current Thulamela Municipality waste management strategy. An initial waste management framework was developed which was then validated by expert and various stakeholders. To validate the framework, 18 participants, including waste management experts and various stakeholders participated in the process. From the inputs of the validation process, a more comprehensive zero-waste framework for Thulamela Municipality was developed.

The resulting framework incorporates strategies to reduce waste, promote recycling, and maximise resource recovery. Key actions involve - stakeholder engagement, feasibility studies, and tailored waste management plans So that Thulamela can enhance waste sorting, recycling infrastructure, and explore innovative technologies. Compliance, monitoring, and sustainable practices were identified as essential for environmental sustainability and the journey towards a zero-waste model.

Key factor found in the development of the model were - the implementation of sorting and separation, composting and biogas production, development of recycling infrastructure, and handling hazardous waste. Thulamela Municipality can also explore innovative technologies, promote public-private partnerships, and align waste services with sustainable development objectives. Strengthening compliance and enforcement, promoting sustainable waste reduction strategies, and monitoring waste management practices are crucial for achieving environmental sustainability. These actions can lead to a culture of compliance, reduced pollution, proper waste disposal, and a cleaner environment. By implementing these findings, Thulamela Municipality can work towards a sustainable waste management system and achieve the zero-waste model.

Keywords: Boras Swedish model; Recycling infrastructure; Waste management; Zero-waste model,

7.1 Introduction

The world is currently grappling with a waste management crisis, and the situation is no different in Thulamela Municipality, South Africa. In 2011 the National Waste Management Strategy (NWMS) was put into effect, since then waste collection and disposal services have improved significantly, thanks in part to a successful effort to license landfills. Even though some urban regions have started separation at-source programs, there are still large backlogs in the provision of waste services. These backlogs frequently reflect historical disparities and are particularly severe in peri-urban and rural areas, as well as in informal settlements (Godfrey and Oelofse, 2017). According to DEFF (Department of Environment, Forestry, and Fisheries) in South Africa (Thobejane, 2022), MSW management faces multiple challenges. These include - littering, illegal dumping, poor source separation, inadequate recycling infrastructure, absence of a recycling culture, service delivery backlogs, inconsistent waste collection, permit non-compliance, landfill burning, limited support for waste service providers, as well as an education and awareness gaps in specific districts.

Most municipalities are presently struggling to simply sustain basic service levels due to challenges like - the absence of clear distinctions between responsibilities and powers among government levels, lack of well-defined roles and responsibilities for municipal waste staff, coupled with insufficient experience. Additional causes stem from - discrepancies between job specifications and the qualifications of managerial staff; relatively little technical or financial capacity outside the municipalities to leverage service delivery to support the beneficiation of waste (Fakoya, 2014). In the absence of provincial and national intervention, it is usually problematic for smaller and more rural municipalities to unlock value within the waste streams for which they are responsible (Serge and Simatele, 2020). Thulamela Municipality currently collects waste from residential and commercial areas; these waste-collection systems cover a significant portion of the Municipality which provides waste management services for approximately 618,462 people (Stats SA, 2022). In a study by Mudau and Ruhiiga (2017) and surveys conducted in Thulamela Municipality, approximately 100% of the waste generated and collected by the Municipality are taken to the landfill site, unless, in the deep rural areas where their waste is either buried in their backyard or burnt (Kone and Gumbo, 2023). Thulamela Municipality faces challenges with waste management, due to - limited financial resources, inadequate infrastructure, lack of expertise, low public awareness, the non-use of modern landfill technology and insufficient stakeholder engagement. These challenges highlight the need for improved waste management practices and the development of sustainable solutions. According to Njoku et al. (2022), residents living near landfills are susceptible to airborne pollution and related health issues and landfills also contribute to global warming in South Africa and expose workers to health risks. Diverse scholars have identified significant issues related to the landfill and the environment in the Thulamela Municipality (Edokpayi et al., 2018; Njoku et al., 2019)

These challenges, however, also present opportunities for improvement. By employing innovative waste management strategies, promoting recycling initiatives, landfill gas utilisation, creating job opportunities and enhancing public education and awareness campaigns, Thulamela Municipality and other local municipalities in South Africa can strive towards achieving a more sustainable waste management system (Mudau and Ruhiiga, 2017). Studies on the waste composition analyses conducted in Thulamela Municipality, revealed that the waste streams consist predominantly of - organic waste, followed by recyclable materials such as paper, plastic, glass, and metals (Mathako, 2019). These wastes are valuable resources that can be harnessed if properly managed and utilised, hence, there is a crucial need for enhanced ISWMS to effectively address the prevalent challenges in waste management, within Thulamela Municipality. Implementing such refined ISWMS will not only addresses local issues in Thulamela but also has the potential to extend the positive impact to benefit South Africa as a whole.

An ISWMS aims to incorporate various waste management components, such as waste minimisation, recycling, composting, and proper disposal, into a comprehensive and efficient framework. The Swedish city of Boras was one of the first to install a sustainable ISWMS administration system, where more than 90% of the city's waste was landfilled, before 1980. This was acknowledged as a problem in 1986, the same year that an investigation into the implementation of an integrated waste management system started. This gave birth to the Boras model, anchored on a holistic approach to waste management that prioritises source separation, recycling, resource recovery, community engagement, and continuous infrastructure development. In 1987, the city created its first waste management strategy, with the minimisation of waste to landfill as its main objective. The strategy involved adding or improving biological and thermal waste treatment facilities in addition to waste separation at the source (Rajendran et al., 2013). More than 40% of waste was landfilled in Sweden in 1996, however, the amount of waste being dumped in landfills was substantially decreased to 10% after the adoption of new, integrated, and creative technologies for waste fractionation, biological treatment, and thermal treatment. The Boras model focuses on sustainability, environmental responsibility, and economic efficiency, all of which contributed to its success in achieving zero-waste or close to zero-waste in the city (Rajendran et al., 2013). The Boras model has achieved significant results over the years. Between 1975 and 2016, the volume of waste going to landfills decreased from 62% to less than 1%. Recycling rates increased from 6% to 35%, and biological treatment increased from 2% to 16%.

Energy recovery through incineration also increased from 30% to 48%. Sweden's waste management system, including the Boras model, is now considered a global leader in sustainable waste management (Rousta, 2018).

This study aimed to develop a conceptual framework for an ISWMS in Thulamela Municipality, using the Boras model as a benchmark. The objective was to address the waste management challenges within the Municipality, promote resource recovery, and work toward a more sustainable waste management system that could serve as a model for broader implementation in South Africa.

7.2 Methodology

7.2.1 Data Collection

The methodology begins with a thorough literature review. Data was collected from a wide range of sources, including academic journals, government reports, industry publications, and relevant books. The purpose of this literature review was to gather existing knowledge, best practices, and key concepts related to waste management, hence, during the process, relevant data points, statistical information, case studies, and theoretical frameworks were extracted. The Boras model was adopted for this study to develop a zero-waste framework for the study area. A detailed procedural methodology and the development of the Boras Model were conducted in (Rousta, 2018).

This study adopted a qualitative approach, data collection from Thulamela Municipality employed a purposive sampling technique, facilitating this study's selection of 44 participants. This sample size was deemed adequate as data saturation became evident during the participant interviews, indicating a comprehensive coverage of relevant perspectives. The participants perform diverse roles– waste experts, landfill managers, municipal managers, and various stakeholders - ensuring a comprehensive representation of insights and expertise within the waste management area.

7.2.2 Data Analysis

A thematic content analysis was used for this study. Firstly, the collected data from the literature review underwent thorough examination and synthesis. This involved identifying key themes, best practices, and theoretical frameworks relevant to waste management. The Boras model served as a foundational framework, guiding the subsequent analysis and development process.

Next, data collected from the 44 participants were analysed. This involved transcribing and coding the interview data to identify recurring patterns, emerging themes, and critical insights regarding waste management practices, challenges, and opportunities in the study area. The data analysis process also included a comparative analysis between the existing waste management practices in Thulamela Municipality and the Boras model. This allowed for the identification of gaps, areas for improvement, and potential strategies for adaptation and implementation in the local context.

7.2.3 Validation of the Framework

The validation of the waste management framework involved the participation of 18 selected experts renowned for their extensive experience in the field. These experts were tasked with evaluating the developed framework in terms of its completeness, accuracy, and practical relevance. Upon receiving the framework, the experts engaged in a thorough review process, examining each aspect to assess its efficacy in addressing waste management challenges. Their feedback was instrumental in identifying strengths, weaknesses, and areas for improvement of the framework.

The systematic analysis of the experts' feedback enabled the research team to gain valuable insights into the framework's effectiveness. Key considerations for scrutiny included, the clarity of objectives, feasibility of implementation, and alignment with industry standards and best practices.

Recommendations provided by the experts were carefully reviewed and incorporated into the framework, enhancing its comprehensiveness and practicality. Additionally, any identified gaps or inconsistencies were promptly addressed to ensure the framework's robustness. Figure 7.1, show a flow diagram of how the Zero waste framework was developed.

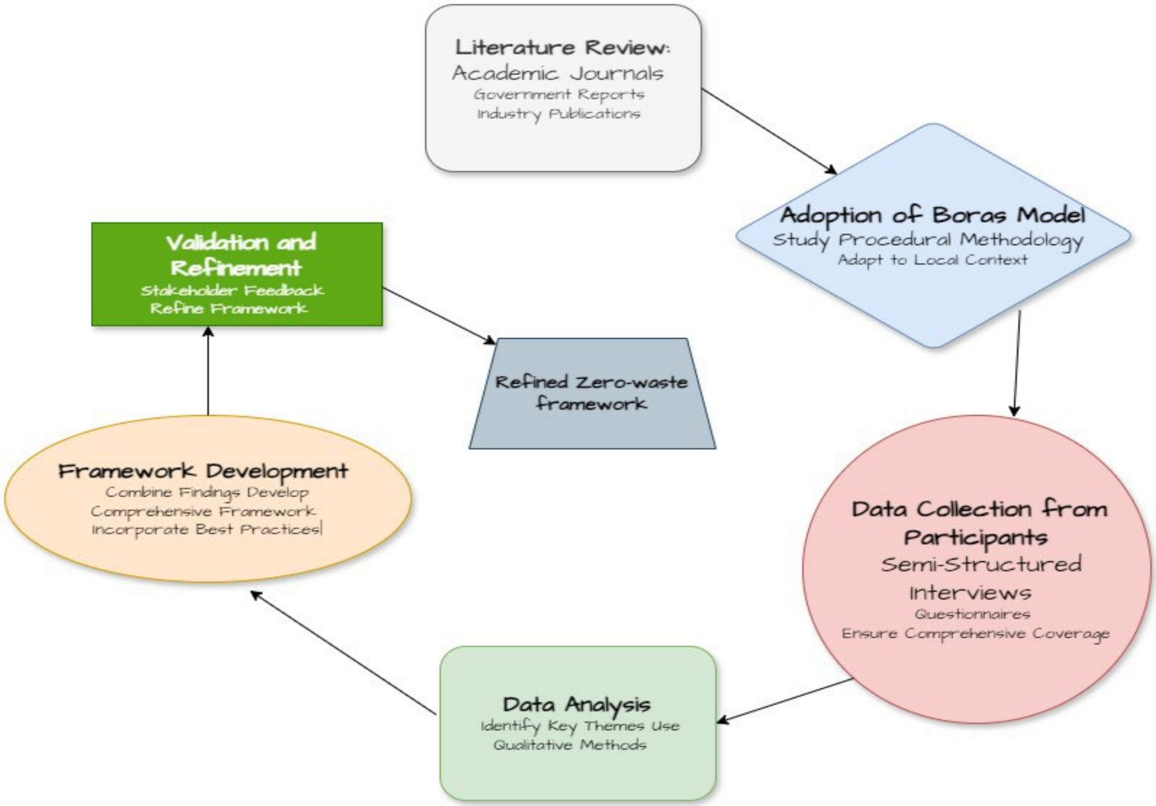

Figure 7.1: A flow diagram of how the Zero waste framework was developed

7.3 Results and Discussion

Tchobanoglous et al. (1993) introduced a pivotal model focusing on the interrelationship of solid waste management components that became integral to the Boras model, (Figure 7.2).

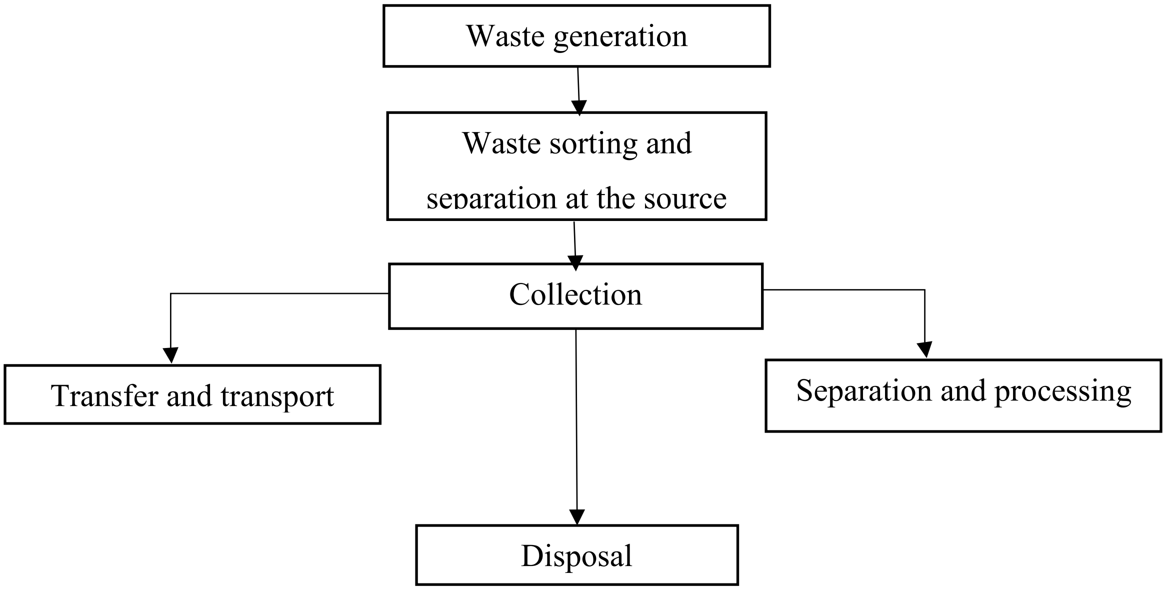

Figure 7.2: The six activities in the model by Tchobanoglous et al. (1993) for managing municipal solid waste

The Tchobanoglous model comprehensively addresses various stages of waste management, including - waste generation, waste handling and separation at source, collection (transport and processing) and disposal. By delineating the interdependencies among different facets of waste management, Tchobanoglous et al.'s model served as a valuable guide for understanding the Boras model and the Thulamela waste management process. For a better understanding of the Boras model and the Thulamela waste management, the Tchobanoglous et al.'s model, therefore, was used as a guide.

Review of the waste management in Boras city

7.3.1 Waste generation

A review of waste generation must also focus on the types of waste, so as to understand the kinds of waste generated from the Boras. From literatures, a recurrent theme across various studies was the significance of household waste in the Boras city. This included everyday items such as food waste, packaging materials, plastics, paper, and miscellaneous household items (Rajendran et al., 2013 and Rousta, 2018). Also, other literatures suggested that there is substantial contribution of commercial and industrial activities to the overall waste composition in the city (Rajendran et al., 2013; Model, 2018). Urban development and ongoing construction projects significantly influence Boras's waste profile, according to the reviewed literature. Construction and demolition waste included concrete, wood, metal, and debris, showing the interrelationship between urban growth and waste generation (Miliute-Plepiene, 2020; Rousta and Bolton, 2019). Insights drawn from various articles also shed light on the substantial contribution of green waste, originating from gardens and yards to the city's waste stream. Grass clippings, leaves, branches, and organic materials also collectively contributed to the ecological footprint of waste in Boras city (Rousta and Bolton, 2019). Distinct waste categories, such as electronic waste (e-waste), hazardous waste, and medical waste, however, demand specialised attention due to their unique environmental and health risks (Rousta and Bolton, 2019; Model, 2018).

7.3.2 Waste handling, separation at source

At the core of the Boras model system is the active involvement of citizens in sorting waste at the source (Rousta, 2018). To understand the waste handling and source separation practices in the city, it was essential to examine the implemented strategies aimed at fostering a culture of waste separation among the residents. From the literatures, themes were identified, like educational initiatives, community engagement, technological innovation, policy framework, convenient infrastructure and social and environmental awareness. Table 7.1 gives a summary of the key factor that have played a pivotal role in the successful adoption of waste separation practices in Boras city.

Table 7.1: summary of key elements for waste handling and separation initiatives in Boras city

Factors driving waste separation in Borås city	Key components	Implications	References
Educational Initiatives	School programs for early education on waste sorting,	Builds a foundation for lifelong waste management habits	Rousta, 2018; Bolton and Rousta, 2019; Rajendran et al., 2013; Tsuyama, 2020
	Booklet distribution and comprehensive information on waste handling and sorting	Enhances awareness and knowledge among residents	
	University research programs on waste-to-value innovation	It brings about ongoing improvements in waste management technologies	
Community engagement	Citizen involvement and cooperation which brings about strong community commitment	Higher efficiency in waste sorting and disposal	Bolton et al., 2016; Bolton et al. 2018; Rajendran et al., 2013
	Regular social activities and events for awareness	Fosters a sense of responsibility in waste management practices	
Technological innovation	Deposit system ("Pant"), incentives for recycling	Tangible rewards for responsible recycling behavior	Sweden EPA, 2005
Policy frameworks	Continuous review of waste-related policies to better assist in easy waste handling and separation at source	Provides structured approaches to waste management	Rajendran et al., 2013).
	Financial incentives, tax benefits for sorting	Motivates residents to actively participate in waste management	
Convenient infrastructure	Recycling containers for strategically placed for easy access	Facilitates widespread and convenient waste disposal	Rousta, 2018; Rajendran et al., 2013;
Social and environmental awareness	Wider environmental awareness for understanding the positive impact of separating waste at source	Strengthening community commitment to sustainability	Bolton et al., 2018; Rousta and Ekström, 2013;

Educational Initiatives

Educational initiatives play a pivotal role in shaping waste separation habits in Boras, particularly through school programs designed to instill responsible waste behavior from an early age, thereby, according to Rousta (2018) kindergarten students were motivated to actively engage in learning how to sort and separate waste. This early education established a foundational understanding of waste management, fostering a culture of responsibility toward waste from the formative years (Rajendran et al., 2013). The curriculum integrated waste management as a distinct subject, similar to subjects like, physical education or mathematics. Notably, children were taught practical applications, such as creating garden compost from food waste like potato peels (Bolton and Rousta, 2019).

Continuous research initiatives and development have been driving forces enhancing waste separation in Boras city (Tsuyama, 2020). Ongoing research programs conducted by the University of Borås suggest the city's commitment to staying at the forefront of waste management advancements. These initiatives focus on exploring novel ways to repurpose and extract value from various waste streams. The emphasis is not only on effective waste disposal but also on harnessing the potential of waste as a resource (Rousta, 2018).

The significance of continuous development in waste utilisation practices is highlighted through these research programs. By constantly seeking innovative solutions, Boras ensures that its waste management strategies align with the latest technological and environmental advancements. Furthermore, the City takes a proactive role in educating citizens by distributing informative booklets to each household. These materials, numbering approximately 130, comprehensively detail the handling of various waste materials (Bolton and Rousta, 2019), for instance, colored and white glass bottles are clearly distinguished in the sorting process, as are fluorescent, halogen, LED bulbs, and other energy-saving lamps. This booklet-distribution strategy ensured widespread access to valuable information, ensuring a common understanding and adherence to the waste separation process. Through these educational efforts, residents were well-informed about the proper techniques for separating different types of waste.

Community Engagement

Community Engagement has been a basis for successful waste handling and separation initiatives in Boras city, particularly through active citizen cooperation (Bolton et al., 2016). The success of waste handling and separation can, hence, also be attributed to the commitment and engagement of the community, resulting in a high level of participation in waste sorting practices. Bolton et al. (2018) suggests that the community's dedication to waste sorting, reflects a collective sense of responsibility towards environmental sustainability.

In addition to citizen cooperation, regular sports and social activities were conducted to raise awareness among adults in the city. This strategic approach of social engagement served as a platform for fostering a enhanced sense of responsibility towards waste management practices. These activities not only created awareness but also actively involved residents in discussions and actions related to waste separation, contributing to the overall success of the city's waste management initiatives (Rajendran et al., 2013). The active involvement of citizens and the incorporation of social activities into waste management awareness campaigns exemplified a community-oriented approach. This approach ensured that waste separation practices were not just adopted but become ingrained in the community's values and behaviours.

Technological Innovations

In the context of sustainable waste management and the pursuit of zero-waste to landfill objectives, the exploration of innovative approaches is crucial, with the Swedish 'Pant' deposit scheme standing out as a successful and intriguing method (Swedish EPA, 2005). This scheme, widely adopted in Sweden, introduces collection devices in supermarkets to facilitate the recycling of Polyethylene Terephthalate (PET), aluminum, and specific glass bottles. The Swedish 'Pant' deposit scheme operates by charging customers an additional cost of 1 to 4 SEK each time they purchase a PET or aluminum bottle. This deposit fee is later reimbursed when customers return the original bottle to designated collection machines. The result of this incentive-based system has been remarkable, with PET and aluminum bottle recycling achieving a rate of more than 90% in Sweden (Sweden EPA, 2005). In the realm of waste management literature, the success of the Swedish 'Pant' deposit scheme serves as a notable example of how innovative approaches, coupled with incentives, can significantly impact recycling rates and contribute to broader sustainability goals.

Convenient Infrastructure

Convenient Infrastructure, particularly the strategic placement of recycling containers within walking distances from households, plays a pivotal role in facilitating efficient waste disposal and encouraging active participation in waste separation by Boras residents (Rousta, 2018). This approach to waste management aligns with the city's commitment to creating a user-friendly and accessible system. Rousta, (2018) highlights the significance of convenient infrastructure, such as strategically positioned recycling containers in recycling centers, in fostering a waste separation culture. By making recycling containers easily reachable from households, Boras ensured that residents encounter minimal barriers to participating in waste separation initiatives; in the recycling centers, the waste containers are labelled clearly and visibly for the resident to know where they can drop their waste.

Furthermore, the distribution of designated white and black bags to each family, as highlighted by Rajendran et al. (2013), is a complementary initiative that adds to the convenient infrastructure. Black bags are specifically designated for food waste, which includes kitchen scraps and organic materials, while white bags are used for other combustible waste deemed suitable for incineration. This serves as a practical tool for encouraging proper waste disposal practices. The integration of biological treatment procedures focusing on black bags and organic materials, resulted in the generation of over 3,000,000 m^3 of biogas annually, showing the effectiveness of the policy initiatives and convenient infrastructure in Boras (Rajendran et al., 2013). This comprehensive waste management strategy not only promoted waste separation but also contributed to renewable energy generation through biogas production.

Social and Environmental Awareness

Social and Environmental Awareness emerges also as a crucial factor of waste separation initiatives in Boras (Bolton et al., 2018). The residents' understanding of the positive impact of waste separation on environmental sustainability serves as a catalyst for increased adherence to waste management practices. The literature suggests that this heightened awareness is cultivated through active advertising campaigns and billboards strategically placed within the community (Rousta and Ekström, 2013). By showcasing the direct connection between waste separation efforts and positive environmental outcomes, Boras actively engaged in shaping a community that values and participates in sustainable waste management practices.

Policy frameworks

Policy incentives, specifically financial incentives, have proven to be influential factors in promoting waste separation in Boras. Policies implementing approaches like the "pay less tax for higher sorting rates" have emerged as effective tools in encouraging active citizen participation and contributing significantly to the success of waste separation initiatives. The literature suggests that the financial benefits tied to higher sorting rates play a crucial role in motivating residents to actively engage in waste management efforts. The "pay less tax for higher sorting rates" approach creates a direct link between responsible waste behavior and financial incentives (Rajendran et al., 2013).

7.3.3 Collection (transport, separation, processing and transformation of solid waste)

The transformation of waste into energy in Borås is a systematic process involving various stages. The waste management process in Borås begins with the citizens segregating waste into primary streams: food and residual waste, packaging materials, and bulky waste, hazardous waste, white goods, and electronics. The use of designated black and white plastic bags aids in this separation (Taherzadeh and Richards, 2018).

The inclusion of designated drop-off points for specific waste materials further enhanced the overall effectiveness of the waste management system in Borås. The way waste is handled in residential sources varies depending on the type of buildings, the local population, and the collection technique. In low-density locations, it is traditional for residents to collect their waste at home and place it in the nearest general waste containers. The frequency of collection of waste for these areas varies from every 7 to 14 days, however, in high-rise buildings, it is more common to use the chute opening, which can collect the waste of one or more units; vacuum is an option for this system. In contrast, commercial and industrial sources often use a few containers close to the location where waste is generated, depending on the wastes' categories and amount. They are moved into larger containers that are utilised to move the waste to the disposal facilities. There are 32 trucks operating in total for the purpose of collecting household waste. About 11 of the trucks are involved in the gathering of the black and white plastics and there is a particular truck that is created specifically for transferring hazardous wastes (Rousta, 2018).

Borås employs a waste management system with three streams. In the first stream, food and residuals waste, like nappies and tissues, are sorted into black and white plastic bags by residents. The second stream deals with packaging materials such as paper, cardboards, plastic, metal, glass, and newspapers, which are collected at over 80 recycling stations. These materials are then transferred to recycling industries, adhering to producer responsibility laws. The third stream manages bulky waste, hazardous items, white goods, and electronic waste, among others (Model, 2018). There are five recycling centers, each equipped with specific containers for various waste types. Residents receive on-site assistance for proper sorting, and the materials are transported to the Material Recovery/Transfer Facility (MR/TF) for further distribution or treatment. Additionally, medicinal wastes are separately sorted by residents and collected in pharmacies, while a deposition system addresses PET, aluminum, and glass bottle recycling in the city (Rousta, 2018). This reduction in waste going into the landfill was achieved, despite increasing waste generation during these years. The average proportions of different waste treatments in the city of Borås, in 2009 are illustrated in Figure 7.3.

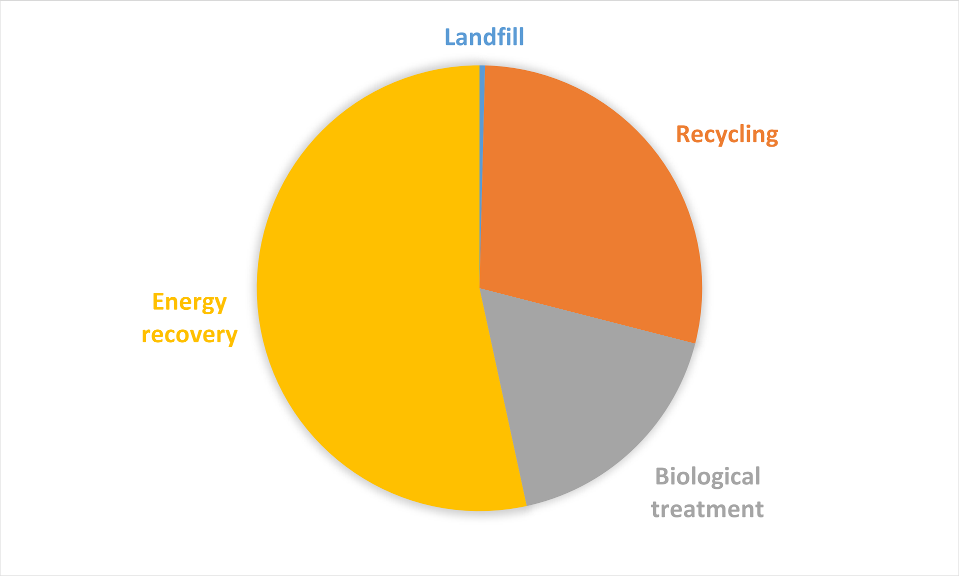

Figure 7.3: The proportion of different waste treatment methods in the municipality of Borås in 2009 (Source from Taherzadeh and Richards, 2018).

Review of the waste management in Thulamela municipality

7.4.1 Waste generation

In Thulamela Municipality, similar waste as that from Boras city is generated in Thulamela Municipality. One of the interviewees explained,

> *"…. We generate waste like waste from kitchen … for example food waste, papers, things we don't use again, like broken bottles, plastics, and so on……"*

7.4.2 Waste handling, separation at source

There is also no form of separation center in the city.

> *"There is no form of waste separation at source currently happening. All waste generated is put together and taken to the landfill, from the houses, where the municipal trucks come and take the waste to the landfill."*

The residents of Thulamela Municipality currently put all their waste together, which is then collective by the municipal trucks and transported to the landfill. This absence of any form of sorting or separation of waste at home poses challenge to implementing effective waste management practices, hindering the potential for recycling and resource recovery.

When asked if there are there any form of incentives for waste separation in the municipality,

an interviewee said,

> "*There are only people who move around and pick aluminum cans that are thrown on the ground. They take them to recycling centers for exchange of money…. the money is not worth it. The aluminum can are not bought expensively so it is not worth t picking up aluminum cans…. I was given very little amount of money for the aluminum cans I have been collecting for the whole year*".

Incentives for waste separation in Thulamela are not worthwhile. The responses from the interviewees showed that individuals collect aluminum cans and plastic bottles from the ground for some incentives at recycling centers, however, the financial returns from this endeavor were consistently inadequate, with one participant citing an example of receiving very little amount of money for a year's worth of collected aluminum cans. This shows a limitation in the current incentive structure as the monetary rewards are not compelling enough to encourage active participation in waste separation.

An interviewee expressed his support for waste reclaimers in the landfill,

> *"…We also have people in the landfill …they help us recycle…. they collect plastics and aluminum from the waste piles and sell to waste companies…"*

This informal sector of waste reclamation has played a crucial role in diverting recyclable materials from the landfill, contributing to the reduction of the overall waste volume disposed. The reliance on informal waste reclaimers suggests gaps in the formal waste management system. The fact that individual's resort to scavenging in landfills indicates potential inefficiencies in the collection, sorting, and recycling processes within the official waste management framework in Thulamela.

When asked whether they are aware of the importance of waste separation, one interviewee said,

> "*Not really… I have never done any separation before, so I won't know if there is any need for separating waste*".

From the responses of the interviewees, the importance of waste separation is not known among the citizens. There is, therefore, a knowledge gap in environmental education and community outreach efforts concerning waste separation.

7.4.3 Collection (transportation, Separation, processing transformation of solid waste)

The waste collected in Thulamela Municipality is directly transported to the Thohoyandou landfill. Unfortunately, the landfill lacks any waste utilisation technology, leading to the direct dumping of all collected waste from residential households into the landfill. The only semblance of waste reduction within the landfill involves waste reclaimers who wait for the truckloads. Once the waste is dumped on the ground, these reclaimers immediately sort through the piles, focusing on scrap metals, aluminum, and plastic materials. The reclaimed materials are then gathered and sold to recycling companies in bulk.

This system has inherent inefficiencies and risks, especially for the waste reclaimers, also, only a small fraction of the waste is recycled through this process. Ultimately, most of the generated waste still ends up being buried in the landfill. This highlights the limitations of the current waste management system, stressing the need for more effective and sustainable waste utilisation methods to minimise landfill contributions and enhance resource recovery.

7.5 Lessons learnt from the Boras model

Boras and Thulamela Municipality use different waste management strategies, which demonstrate diverse challenges and approaches to sustainability in urban environments. Boras has established a comprehensive waste management system that prioritises reducing landfill use, fostering community engagement, and leveraging advanced waste utilisation technologies. Thulamela Municipality, however, faces challenges characterised by limited waste management infrastructure and community awareness, leading to a predominant reliance on landfills for waste disposal. Table 7.2 provides a summary of the key aspects in waste management of Boras and Thulamela Municipality. The differences in - waste strategies, community engagement, infrastructure, technology utilisation, policy incentives, and incentivised recycling schemes - are highlighted, offering insights into lessons learned from these distinct approaches.

Table 7.2: Comparison of Boras and Thulamela waste management strategies with some lessons learnt

Aspects	Boras city	Thulamela	Lessons learnt from Boras and Thulamela
Waste generation	The city implements a comprehensive waste generation strategy focusing on minimising waste to landfill. Focus is on source separation, encouraging residents to separate waste at home or source. The main sources of waste are food, plastic packs, bottles, papers, mostly residential waste.	The Municipality relies mainly on landfill disposal, with limited emphasis on formal source separation programs. Waste generation primarily occurs without a structured approach, leading to challenges in recycling and resource recovery.	Importance of a well-defined and strategic waste management plan to achieve sustainability goals. The two communities generate similar waste types.
Waste handling,	Boras city actively encourages and facilitates source separation through	Thulamela Municipality lacks formal source separation initiatives	Significance of convenient infrastructure and

separation at source	convenient infrastructure such as designated recycling containers and distributed bags. Educational programs further enhance residents' understanding of waste categorisation and its environmental impact.	and infrastructure, resulting in a significant portion of waste being disposed of without prior separation. This absence hinders recycling efforts and resource recovery.	educational programs for source separation.
Collection (transportation, Separation, processing transformation of solid waste)	Boras utilises efficient waste collection methods, including designated white and black bags and recycling centers. It implements advanced waste processing technologies, such as energy recovery through biogas, energy, and heat production. This comprehensive approach minimises the volume of waste sent to landfills.	Thulamela Municipality faces challenges in waste collection, with a predominant reliance on landfill disposal. Limited separation during collection and the absence of advanced processing technologies contribute to inefficiencies in waste management.	Technological disparities in waste collection and processing. Importance of efficient collection methods and utilisation technologies.
Disposal	Boras prioritises minimising waste to landfill to approximately 100%. The emphasis has been on recycling, composting, and energy recovery. The comprehensive waste disposal strategy aligns with environmental sustainability goals and contributes to reduced greenhouse gas emissions.	Thulamela Municipality relies heavily on landfill disposal, lacking advanced methods such as recycling, composting, or energy recovery. This approach poses environmental challenges, including increased methane emissions and limited resource utilisation.	The significance of minimising landfill dependence for sustainable waste management.

7.8 Developing a conceptual framework for zero-waste management system for Thohoyandou Municipality incorporating the Swedish Boras model approach

Thulamela Municipality has encountered significant challenges in the management of its solid waste, impeding its ability to effectively harness the potential of waste as a valuable resource. Boras, however, has successfully achieved a zero-waste approach, which provides valuable insights and strategies that will be incorporated in the Thulamela Municipality waste management system. This will address its existing challenges and move towards a more sustainable waste management system.

One notable aspect of Boras' waste management approach was the strong focus placed on waste separation at source and recycling. This involved educating and engaging residents on the benefits and methods of waste separation, such as through community workshops, awareness campaigns, and clear guidelines. Boras' strong commitment to building an effective recycling infrastructure and providing easily accessible recycling facilities and collection centers has significantly increased recycling rates while reducing landfill waste. Thulamela Municipality aims to emulate this success by improving its recycling infrastructure, by ensuring that these facilities are easily available to residents throughout the municipality. Strategic collaborations with local businesses, industries, and waste management entities are expected to play a crucial role in establishing a resilient recycling system. This collaboration will efficiently process and transform recyclable materials into new products, contributing not only to advancements in waste management but also fostering job creation and economic opportunities within the growing recycling sector.

The framework developed for Thulamela municipality draws inspiration from the successful zero-waste to landfill model implemented in Boras (Figure 7.3). This involves strategically adapting the key elements of the Boras model to guide Thulamela Municipality towards achieving zero-waste to landfill. The process, therefore, entails a purposeful and systematic flow, incorporating the best practices and lessons learned from Boras' successful zero-waste strategy into the waste management approach of Thulamela Municipality.

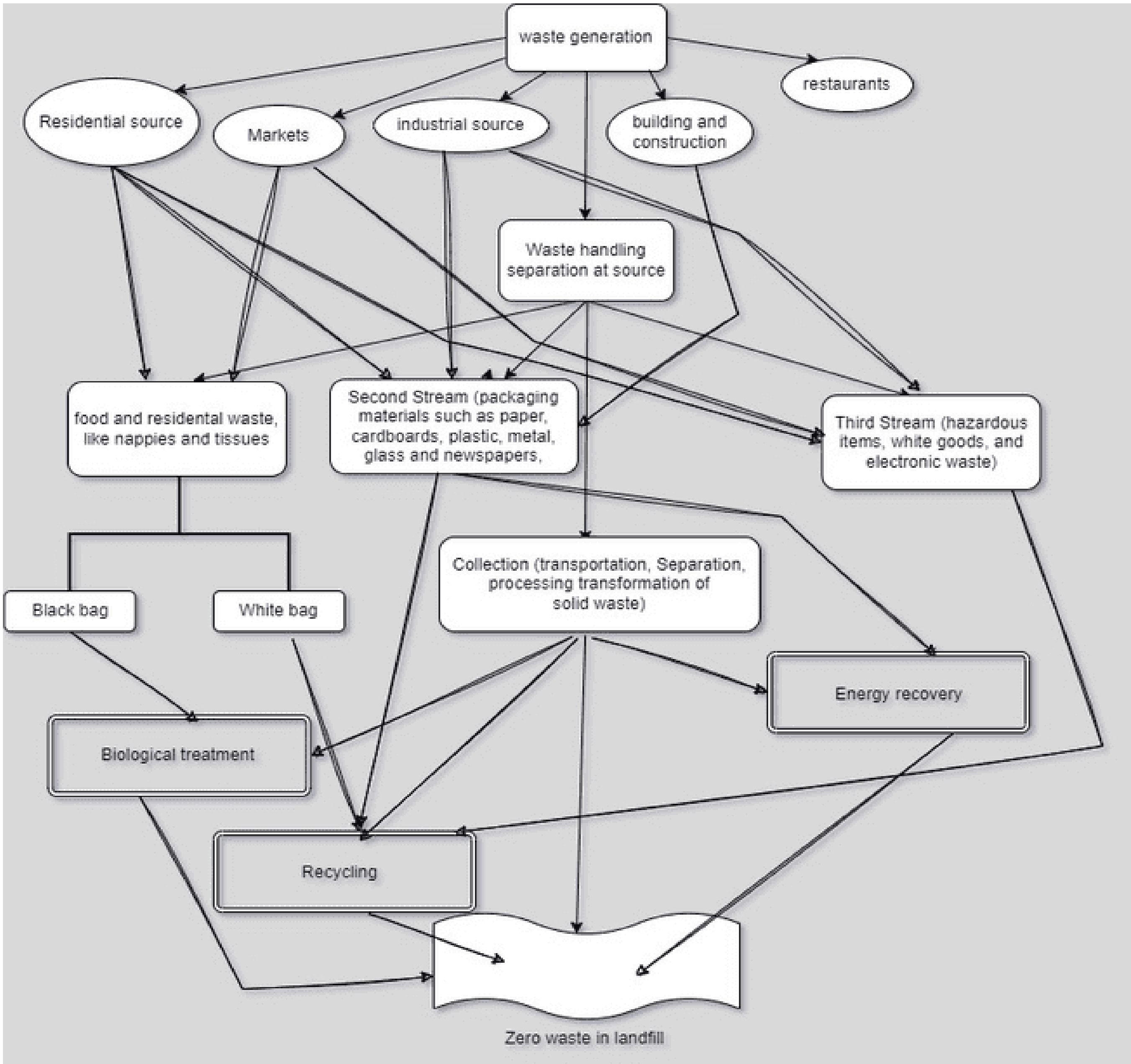

Figure 7.4: Self-made conceptual framework for the Thulamela Municipality

7.9 Validating of the framework

Based on the comprehensive study conducted in Thulamela Municipality and the feedback received from participants, the waste management framework developed for Thulamela Municipality shows promising potential for addressing the current waste management challenges and achieving the goal of zero-waste. The framework focuses on several key areas and incorporates strategies inspired by the successful case of Boras. A waste expert advised that by incorporating the feedback and insights from the participants, the waste management framework for Thulamela Municipality could be designed to tackle the existing waste management challenges effectively. The expert, however, was concerned with the structure of the conceptual framework diagram as it was too scattered and needed to be drawn in a more systematic way for easy understanding.

Another participant raised a concern that while the waste management framework has its merits, it overlooks the social and economic aspects of waste management. The focus on infrastructure development and compliance may neglect the needs and capabilities of vulnerable communities. It is essential to consider the socio-economic impact of waste management initiatives and ensure that vulnerable communities are inclusive in the plans and treated equitably. The framework should prioritise community engagement and empowerment to truly address the waste management challenges. This was an important concern regarding the social and economic aspects of waste management. The researcher acknowledges that waste management initiatives cannot overlook the needs and capabilities of vulnerable communities. In response to this concern, the framework was enhanced by incorporating a strong focus on community engagement and empowerment. Additionally, conducting thorough socio-economic assessments and providing targeted support to vulnerable communities will help address the social and economic dimensions of waste management.

Another participant had reservations about the framework's reliance on the Boras case as a blueprint for Thulamela Municipality. He noted that every context is unique, and what works in one city may not necessarily work in another, hence, it is crucial to tailor the framework to the specific challenges and resources of Thulamela; the proposed framework should place work with local data and insights rather than solely relying on an external model. A more context-specific approach would ensure the framework's relevance and effectiveness. The participants rightly pointed out that every context is unique, and a one-size-fits-all approach may not be appropriate. In response to this, while the framework drew inspiration from Boras, the researcher made sure the data for the framework was drawn from the Thulamela waste management records. The Boras model only helped achieved the set objective of this study as the researcher acknowledged the importance of local data and insights in shaping the Thulamela framework's design. to ensure its relevance and effectiveness.

The conceptual framework proposed for Thulamela Municipality, reflects a commendable effort to address the existing challenges and move towards a more sustainable waste management system. The validation of this framework involved a holistic assessment of its key components, aligning them with the unique context of Thulamela and drawing insights from the Boras model. Focusing on waste separation at the source, an essential element in Boras' success, was appropriately integrated into the Thulamela framework. Paying attention to community education and engagement, as witnessed in Boras through workshops and awareness campaigns, was essential for fostering behavioral change and ensuring effective waste separation practices. This point aligns with the proposed framework's intent to improve recycling infrastructure and make recycling facilities easily accessible to Thulamela residents.

Strategic collaborations with local businesses, industries, and waste management entities, as suggested in the framework, resonate well with the Boras' model. The integration of such collaborations not only supports the efficient processing and transformation of recyclable materials but also aligns with the framework's goal of job creation and economic opportunities. This collaborative approach ensures a more resilient recycling system, promoting sustainability beyond waste management.

The self-made conceptual framework, shown in Figure 7.4, visually illustrates the proposed waste management system, facilitating comprehension of its key components and interrelationships. Participants suggested the incorporation of a detailed risk analysis, accounting for potential challenges and mitigation strategies and to develop a phased implementation plan with clear milestones and performance indicators that would provide a roadmap for effective execution. Continuous stakeholder engagement throughout the implementation phases should also be prioritised to ensure ongoing support and adaptability.

Other participants had concerns about infrastructure limitations posing another potential challenge. Also, financial constraints pose a critical challenge that Thulamela Municipality might encounter during the implementation of the proposed waste management model. The costs associated with infrastructure development, technology implementation, and ongoing operations could surpass the available financial resources. The researcher, in response, suggested municipal collaboration, as well as external sourcing for funds from government, recycling companies and private companies, which will go along way in achieving the zero-waste goal.

After a careful examination of the inputs from the participants, Figure 7.5 gives a revised holistic conceptual framework for zero-waste for Thulamela Municipality.

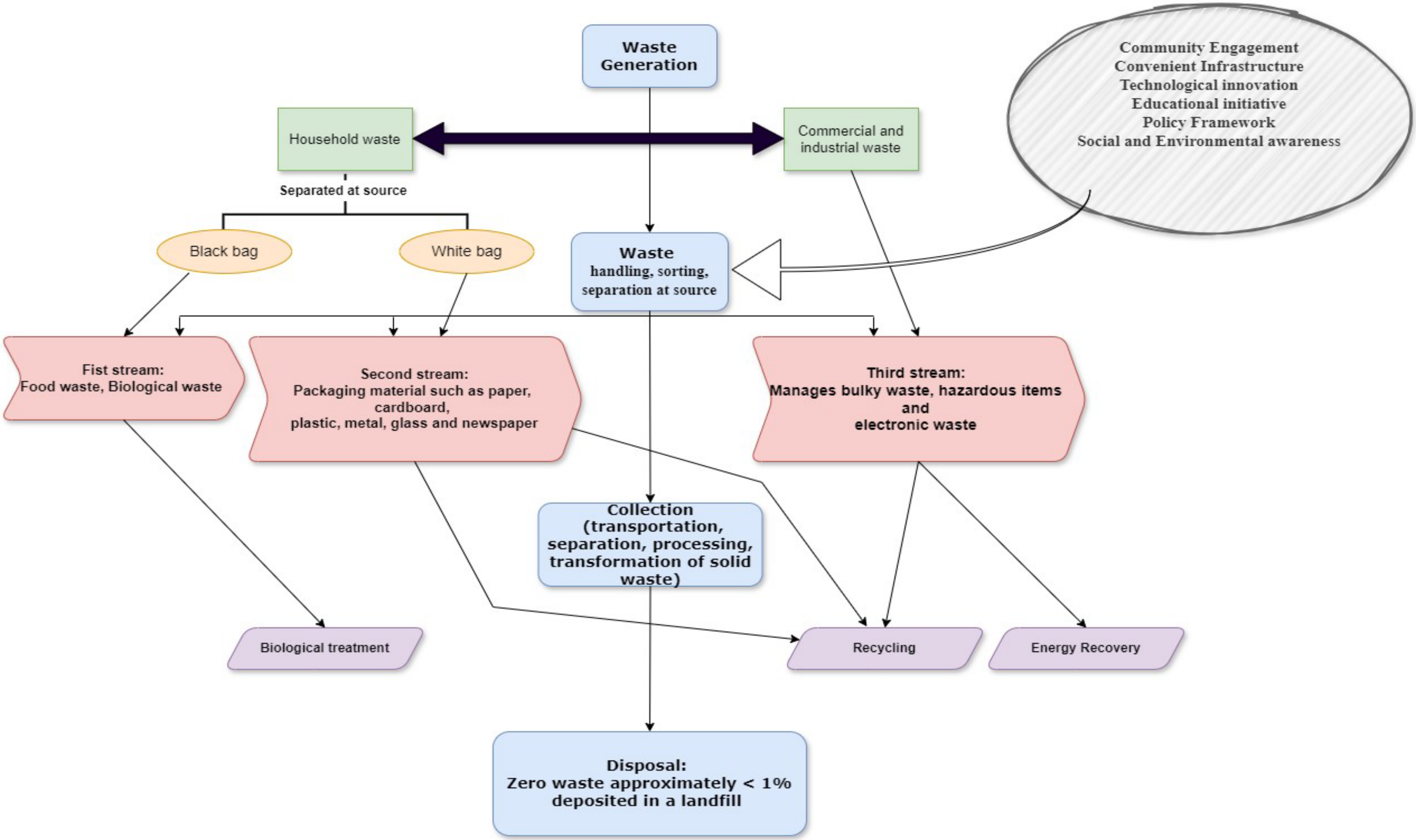

Figure 7.5: Revised zero-waste conceptual framework for Thulamela municipality

7.10 Value preposition of framework

The waste management framework developed for Thulamela Municipality holds a strong value proposition that addresses the pressing challenges faced in waste management and offers a pathway towards adopting a zero-waste model. This framework encompasses a range of essential elements that contribute to its overall value. The Thulamela framework unearths the nature of an integrated solid waste management system drawing from the inference of the Boras Swedish model. From the point of view of Rajendran et al., (2019), the Boras model highlights the technological aspects of successful integrated waste management, however, inputs from respondents identified significant exogenous factors that can be incorporated to the Boras model for an effective integrated solid management system for Thulamela. Having an appropriate integrated waste management system is critical to improve recycling, reuse, and especially diverting of waste from landfills. The continuous dependence of landfilling in South Africa is not sustainable in the long run. Landfills contribute significantly to the greenhouse gas emissions. Furthermore, once waste is buried in landfills it is deemed worthless, however, waste generated is a significant resource which can be useful for various purposes.

First and foremost, the framework takes a comprehensive approach to waste management, recognising the need to tackle the issue from various angles. By incorporating waste reduction strategies, recycling initiatives, infrastructure development, public awareness campaigns, and enforcement measures, the framework ensures that all critical aspects of waste management are considered. This comprehensive approach enhances the effectiveness of the framework in dealing with the complex and multifaceted nature of waste management challenges. In Thulamela.

A notable aspect of the framework is its reliance on data-driven decision-making. Through waste audits, surveys, and feasibility studies, the framework collects and analyses crucial data related to waste generation, disposal methods, infrastructure, and public participation. This data-driven approach enables evidence-based decision-making, ensuring that strategies and initiatives are tailored to the specific needs and characteristics of Thulamela Municipality. By leveraging data, the framework enhances the accuracy, relevance, and effectiveness of waste management practices.

The framework's focus on stakeholder engagement is another valuable aspect. By involving residents, waste experts, and industry representatives in the development and implementation of waste management strategies, the framework fosters collaboration, knowledge-sharing, and a sense of ownership among stakeholders. This participatory approach not only enriches the framework with diverse perspectives and expertise but also increases the likelihood of successful implementation and long-term sustainability.

Sustainability lies at the core of the framework's value proposition. By exploring innovative waste management technologies, encouraging public-private partnerships, and emphasising sustainable development, the framework ensures that waste management practices align with environmental goals and principles. This focus on sustainability minimises the environmental impact of waste management activities, conserves resources, and contributes to the transition towards a circular economy. The framework's sustainability orientation enhances its long-term viability and supports the overall well-being of Thulamela Municipality.

Lastly, the framework places significant importance on compliance and enforcement. By strengthening waste management regulations, establishing monitoring mechanisms, and implementing enforcement measures, the framework aims to foster a culture of compliance among residents, businesses, and other stakeholders. This commitment to compliance ensures that waste management practices are followed consistently, reducing pollution, littering, and unlawful waste disposal. The framework's attention to compliance further reinforces its effectiveness and anticipated achievement of waste management goals.

7.11 Contributions of the proposed framework to knowledge

The significance of this study is determined by its influence on society. The suggested model will contribute to practice and knowledge creation in this area - both elements are crucial to managing solid waste in South Africa and elsewhere. The study has calculated the factors that ought to be backed up to improve South Africa's solid waste management. Taking these factors seriously, therefore, can contribute significantly and creatively to improving waste reuse, recycling, energy production from waste, and ultimately zero-waste to landfills.

The model pinpoints the current requirement for a strategy that can direct appropriate integrated solid waste management. It offers a thorough examination of the existing waste management scenarios in South Africa and a thorough analysis of the Boras model in accordance with Bolton and Rousta, (2019). Given that this has not been done in the setting of South Africa, it stands out as a significant, original, and innovative contribution. The scholarship of discovery is that which stands out as distinctive and essential to the development of ideas, methods, and policy changes.

First, the suggested model adds to human knowledge and the intellectual environment by helping to inform curricula regarding solid waste management, particularly zero-waste to landfill. It is distinct. Given that the literature has constantly outlined such a knowledge vacuum in Africa, it was imperative to propose a holistic solid waste management model in South Africa that is centered on its indigenous qualities. The current model thus makes a significant contribution to the body of knowledge.

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Chapter Eight: Conclusion, recommendation, contribution to knowledge and novelty of the study

8.1 Conclusion of the study

Through a comprehensive investigation spanning the years 2019 to 2022, this study has provided comprehensive analysis of LFG emissions from the Thohoyandou landfill site. Firstly, the deployment of LFG monitoring probes over a two-year period validated the migration of LFG along the sub-surface of the landfill, with CH_4 concentrations varying significantly across different areas. The study identified areas closer to the current waste dumping sites as exhibiting the highest CH_4 concentrations, exceeding South African emission limits and CO_2 concentrations surpassed South African emission limits throughout the study duration.

Meteorological factors were found to significantly influence CH_4 and CO_2 generation and emission, with wind patterns playing a pivotal role in pollutant dispersion. Prevailing winds from the southeast, along with occasional winds from the northwest, were identified as key influencers of emission distribution, particularly impacting residential areas proximate to the landfill. A dispersion modelling using the AERMOD model provided critical insights into emission patterns, revealing the impact of wind direction on pollutant dispersion; despite a positive bias in model predictions compared to measurements from the TROPOMI satellite, the AERMOD model remains a reliable tool for regulatory compliance assessments and trend analyses.

The health risk assessments highlighted findings regarding non-cancer and cancer health risks associated with LFG emissions. While most non-cancer risks levels were deemed acceptable, specific compounds exceeded threshold levels, indicating potential health risks for nearby residents and workers. The study stressed the importance of mitigating LFG emissions to protect public health and promote environmental sustainability.

This study fulfils its objective of conducting a comprehensive analysis of LFG emissions from the Thohoyandou landfill site. By integrating meteorological analysis, dispersion modelling, and health risk assessment, this research provides valuable insights for landfill management and environmental impact assessment.

Furthermore, to apply remedial methods to reduce LFG emissions, this research investigated comprehensively into the critical area of solid waste management, focusing on the context of South Africa, with a specific reference to Thulamela Municipality. This study, therefore, provided a comprehensive framework for transitioning towards more integrated and sustainable approaches to solid waste management. The development of the ISWMS framework represented a significant contribution to both academic scholarship and practical application. Drawing inspiration from successful models such as the Boras model in Sweden, the framework was personalised to the specific challenges and opportunities present in Thulamela Municipality. By highlighting principles of resource recovery, community engagement, and innovation, the framework offers a roadmap for achieving the ambitious goal of zero waste.

This research did not only identify key challenges in current waste management practices but has also highlighted opportunities for improvement. From addressing illegal dumping to enhancing recycling infrastructure, there exist tangible avenues for progress that can lead to tangible benefits for both the environment and the community. This study has highlighted the importance of interdisciplinary collaboration and stakeholder engagement in addressing complex issues, such as solid waste management. By bringing together expertise from diverse fields, including environmental science, engineering, economics, and policy, this research has sought to develop holistic solutions that are both technically sound and socially equitable. The findings of this study have significant implications for policy, practice, and future research in the field of solid waste management. By advocating for a paradigm shift towards more sustainable and integrated approaches, this research aims to contribute to the broader goal of achieving environmental sustainability and social equity.

8.2 Recommendations

- The study recommends continuous monitoring of LFG emissions from the Thohoyandou landfill to mitigate the potential risks of fire hazards, environmental degradation, and health effects. Regular monitoring will help in early detection of any issues and enable timely intervention.
- Considering the variability of gas concentrations in different areas of the landfill, it is recommended to enhance the monitoring system by installing additional probes or immovable sensors in areas for hourly readings of the LFG emission.

- Given the identified health risks associated with LFG emissions, it is imperative to prioritise public health protection measures. This may include implementing buffer zones around the landfill, conducting health impact assessments on nearby residents and workers, and providing adequate healthcare resources and support services, Until a more appropriate way of reducing LFG emissions is implemented.
- The ISWMS framework developed in this study should be implemented and continuously refined to transition towards more sustainable waste management practices.
- Continued research and innovation in the field of solid waste management are essential for identifying emerging challenges, exploring new technologies and approaches, and adapting to evolving environmental and socioeconomic contexts.

8.3 Contribution to the body of knowledge and Novelty of the study

- For the first time ground truthing was conducted in a rural landfill to calibrate and validate the LandGEM model using on-site data, thus deriving input parameters for the LandGEM. These constants can be used for landfills in similar settings.
- Estimations of lateral and sub-surface migration of CH_4 and CO_2 were performed in a rural landfill in South Africa, which is very important to rural landfills in sub-Saharan Africa.
- A validated, comprehensive, integrated zero-waste framework for waste management was developed specifically for rural settings, offering potential applicability to other areas with similar settings.
- The findings from this study have practical implications for landfill operators, environmental agencies, and policymakers, providing them with evidence-based information to make informed decisions about landfill gas management and regulatory compliance.