Contribution of waste burning to ambient PM2.5: A case study of Sharpeville, South Africa

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Dissertation accepted in fulfilment of the requirements for the degree *Master of Science in Geography and Environmental Management* at the North-West University

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PHOTO GALLERY

PREFACE

This dissertation is presented in an article format with chapters (Chapter 3 and 4) written as article manuscripts. These manuscripts are prepared according to the Faculty of Natural and Agricultural Science's Quality Manual. It is required that one of the article manuscripts presented in the dissertation be submitted to an accredited journal. The section below provides the chapter division for this dissertation.

Chapter 1: Introduction and Overview

The introductory and literature review chapter explores global waste generation and its relation to population growth and describes the drivers behind open waste burning. This chapter also emphasises different literature on waste collection services, informal waste disposal, Monte Carlo simulation, and AERMOD dispersion modelling. It clearly describes the problem statement, aims and objectives, significance, and a broad overview of limitations associated with the study.

Chapter 2: Study Area

This chapter describes Sharpeville, Sedibeng district, and the Emfuleni Local Municipality, including demographic statistics and maps. The chapter discusses the significance of the study area, focusing on waste management and air quality. This dissertation has no methodology chapter, as each article manuscript, Article Manuscript I (Chapter 3), and Article Manuscript II (Chapter 4) explore the applicable methods used in detail.

Chapter 3: Waste Burning Emission Quantification (Article Manuscript I)

This chapter focuses on how a Monte Carlo approach can address uncertainties associated with waste burning emissions in Sharpeville. This chapter also used characterised waste for waste burning calculation using a Monte Carlo simulation and literature.

Chapter 4: Modelling Waste Burning Emissions (Article Manuscript II)

This chapter aims to model all the identified waste disposal sites in Sharpeville using AERMOD dispersion modelling and different emission rate scenarios.

Chapter 5: Summary and Conclusion

This chapter summarises the study, considers any unconsidered limitations, and recommends further research.

Bibliography

The references of all the chapters are merged into a single consolidated bibliography after the conclusion of this dissertation. Article Manuscripts I were prepared in agreement with the Journal of Total Science and Environment (Annexure A) guidelines the references were inserted and changed into the correct format according to the NWU Harvard references style.

Annexures

The annexures contain additional materials that offer further details.

The student served as the primary author for both article manuscripts, receiving guidance from Dr. B Language (supervisor), Prof. C Roos, and Prof. R.P. Burger (co-supervisors) collaborated on two article manuscripts as co-authors. The signed permission letters from all co-authors to use the article manuscripts in MSc are given in the Annexure.

Ethical consideration

The Faculty of Natural and Agricultural Science Ethics Committee approved the study under the ethics number NWU-01332-22-A9, as it had minimal risk; all survey data were gathered from a secondary source. In addition, the online ethics course (TREES) training was completed.

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ABSTRACT

Insufficient waste management is becoming a significant environmental problem in South Africa, with 12.7 million tonnes of waste not being collected. Due to poor waste management services, informal waste disposal and burning have become the alternative methods. However, this poses significant environmental and health challenges, especially in low-income settlements like Sharpeville, where there is limited data to quantify waste burning emissions and assess their contribution to ambient air quality. South Africa does not have sufficient emission inventories for local sources such as informal waste burning. To address this issue, a study was conducted to estimate $PM_{2.5}$ emissions from informal waste burning in Sharpeville and assess the contribution to ambient air quality. The study used a comprehensive methodology to estimate the contribution of each waste type by focusing on waste composition data collected in Sharpeville and combustible percentages from the literature. A Monte Carlo simulation was developed to account for uncertainties in waste burning calculations, providing variability in $PM_{2.5}$ emissions ranging from 154g to 711g of the total waste sampled collected. The study found that organic waste was the dominant contributor to $PM_{2.5}$ emissions. The results of the Monte Carlo simulation revealed a wide range of values for the amount of waste burned, with an average of 6 kg/day. The simulated emissions factor was used to estimate the total $PM_{2.5}$ emissions, which ranged from 1318g/day to 34622g/day. AERMOD modelling was used to assess the distribution of $PM_{2.5}$ concentration across Sharpeville, providing insights into spatial variability and potential exposure risk. The modelling applied different emission rates, ranging from $1.52x10^{-5}$- to $400x10^{-5}$ $g.s^{-1}$, and compared the predicted results with measured $PM_{2.5}$ concentrations from Sharpeville's AQMS. The Model runs illustrated notable variability, with the hourly highest concentration ranging from 9.38- to 2441µg/m^3 and 0.5- to 400µg/m^3 for the daily highest concentration. Despite limitations from data and modelling assumptions, the results offer valuable insights into the dynamics of $PM_{2.5}$ emissions from informal waste burning. The study highlights the complex variations between waste generation, the population that burns waste, and the amount of waste that burns. Waste burning is a significant problem in informal settlements in South Africa, and the contribution to ambient air quality is unclear. However, the findings emphasise the importance of incorporating uncertainty considerations in modelling, establishing target mitigation strategies, and refining policy interventions to address this growing environmental issue.

Key terms: $PM_{2.5}$ emissions, waste management, informal waste burning, Monte Carlo simulation, AERMOD modelling, uncertainty analysis, air quality

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

AERMOD	:	American Meteorological Environmental Protection Agency Regulatory Model
AERMET	:	American Meteorological Environmental Protection Agency Regulatory Model terrain pre-processor
AERMAP	:	American Meteorological Environmental Protection Agency Regulatory Model Meteorological pre-processor
CALPUFF	:	Californian Puff Model
HPA	:	Highveld Priority Area
NEMA	:	National Environmental Management Act
NEMAQA	:	National Environmental Management Air Quality Act
NOVA	:	Navorsing en Ontwikkeling vir die Voorkoming van Armoede Afrikaans acronym for: Research and Development for the Prevention of Poverty
SAAQIS	:	South Africa Air Quality Information System
US EPA	:	United States Environmental Protection Agency
VTAPA	:	Vaal Triangle Airshed Priority Area

ABBREVIATIONS

AR	:	Active Rate
AQMP	:	Air Quality Management Plan
AQMS	:	Air Quality Management Station
ATSM	:	American Society for Testing and Materials
Bfrac	:	Burned Fraction
CF	:	Combustible Fraction
CO	:	Carbon Monoxide
CMB	:	Chemical Mass Balance
DEA	:	Department of Environmental Affairs
Dr	:	Doctor
DM	:	District Municipality
ER	:	Emission Rate
EF	:	Emission Factor
GHG	:	Green House Gases
GVA	:	Gross Value Added
IDP	:	Integrated Development Plan
IPCC	:	Intergovernmental Panel on Climate Change
LM	:	Local Municipality
MM	:	Metropolitan Municipality
MSW	:	Municipal Solid Waste
MSWg	:	Municipal Solid Waste generation
NAAQS	:	National Ambient Air Quality Standard
NGO	:	Non-Profitable Organisation
NOx	:	Nitrogen Oxide
NWU	:	North-West University
O_3	:	Ozone
PAHs	:	polycyclic aromatic hydrocarbons
PCDDs	:	polychlorinated dibenzo-p-dioxins
PCDF	:	polychlorinated dibenzofurans
PF	:	Population Fraction
PM	:	Particulate Matter
PM_{10}	:	Particulate Matter with aerodynamic diameter $\leq$ 10 µm

$PM_{2.5}$	:	Particulate Matter with aerodynamic diameter $\leq$ 2.5 µm
PMF	:	Positive Matrix Factor
Prof	:	Professor
SA	:	South Africa
SANWMS	:	South Africa National Waste Management Strategies
SAWS	:	South Africa Weather Services
SASW	:	South Africa State of Waste
SO_2	:	Sulfur Dioxide
TREE	:	Training and Resources in Research Ethics Evaluation
UTM	:	Universal Transverse Mercator
UNEP	:	United Nations Environment Programme
VOCs	:	Volatile Organic Compounds
WMS	:	Waste Management services
$g.s^{-1}$	:	Gram per second
$g/s/m^2$	:	Gram per second per square meter
g/kg	:	Gram per kilogram
g/day	:	Gram per day
kg/day	:	Kilogram per day
$\mu g/m^3$	:	Microgram per cubic meter

KEY DEFINITION

Waste management services	:	Action that facilitates the removal and collection of waste by a company or organisation
Municipal Solid Waste	:	Waste that is generated daily by the community, which is discarded
Municipal Solid Waste generation	:	The amount of municipal solid waste that is generated per day per household or person
Emissions Rate	:	A product of the active rate and emission factor in waste burning calculation
Emission Factor	:	Representative value of the quantity of emission emitted into the atmosphere
Combustible Fraction	:	The Percentage to which the waste type combusted and burns
Waste burned	:	The total estimated amount of waste burned by the community at informal disposal sites
Monte Carlo Simulation	:	A Statistical approach that uses a probability distribution to determine a range of values when there is uncertified in emission quantification

CHAPTER 1: OVERVIEW

This chapter presents an overview of the study, highlighting its significance and scope. It also includes a detailed literature review that explains the connection between waste management and air quality. The study focuses on $PM_{2.5}$ emissions from waste burning, waste management in South Africa, waste composition, and the approaches to address uncertainties associated with open waste burning.

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1.1. Introduction

Waste generation rates are diverse across countries and correlate with a country's income and economic growth (Rana et al., 2015). As populations grow, waste generation is also increasing rapidly, especially in developing countries, representing ~70% of the global population (Filho et al., 2016). It is predicted that within this century, Africa's waste generation (total volume in tonnes) will surpass Asia and other high-income countries (UNEP, 2015). Unfortunately, this waste generation rate causes strain on management services (Nwokedi, 2011), especially in lower-income countries. According to recent reports by Hoornweg & Bhada-Tata (2012) and Kwenda et al. (2022), the cost of managing the increased levels of waste will probably double over the next two decades.

The Global Waste Management Outlook highlights that low- and middle-income countries still lack access to waste collection services, and this problem is expected to worsen as the population doubles in the next 20 years (UNEP, 2024). Developing countries in Africa, such as South Africa, face challenges in solid waste management due to increased waste generation and a lack of municipal services in informal settlements (Ampofo et al., 2016). The Africa Waste Management Outlook (UNEP, 2018) and the South African National Waste Management Strategy (SANWMS) (DEA, 2011) also identify this as a major problem.

Due to a strain placed on waste management services (WMS), people in developing countries often litter and informally dispose of their waste (Cogut, 2016). It is important to differentiate between these terms in the context of the research discipline, as it determines how these concepts are framed (Du et al., 2021). “Littering” has been clearly defined as the careless and improper disposal of small quantities of waste, which results in non-natural elements accumulating in the environment (Al-Khatib, 2009). In most cases, “illegal dumping” activities or practices are defined as waste disposal that involves the deliberate and unlawful abandonment of waste in non-permitted areas (Liu et al., 2017; Lu, 2019). This means that the former concerns smaller quantities of waste than the latter. This study focuses on “informal disposal”, which refers to large quantities of Municipal Solid Waste (MSW) disposed of in open public spaces and backyards of dwellings or household properties of communities. The term “informal disposal” will be used rather than “illegal dumping” as the conceptuality of the term remains unchanged.

While there is not much evidence to suggest that a lack of waste facilities causes an increase in informal disposal, there is evidence that communities move the MSW to open space. Therefore, a direct link between waste collection services and informal disposal can be noted (Ferrara, 2011; Ichinose & Yamamoto, 2011; Sotamenou et al., 2019). Thus, it can be assumed that there is a direct link between informal waste disposal and the increase in open waste burning (Cogut, 2016).

Informal waste disposal sites can be unpleasant to look at, so people in the community will burn the disposed waste sites due to odours or as a source of heat (Wiedinmyer et al ., 2014). However, communities are not always aware of the negative consequences of waste burning. Therefore, all factors contributing to informal waste disposal and informal waste burning must be explored. There are underlying uncertainties when quantifying waste and methods to address these uncertainties are explained in detail.

A recent review by Grobler et al . (2022) extensively explores waste management, littering, and dumping. It covers various aspects, such as the causes and consequences of these issues, stakeholders involved, challenges faced, and strategies for mitigation. This provides a good overview of all aspects to consider when investigating the abovementioned issues.

The following section of this chapter will focus on the challenges and consequences of inefficient waste management in developing countries, waste burning, and the resulting air pollution. Firstly, it will review the rates of global waste generation and those specific to Africa and South Africa (SA) and how they have changed over time. Secondly, it will examine the informal waste disposal methods commonly used in communities and how much they contribute to ambient $PM_{2.5}$ emissions from waste burning.

1.2. Literature review

1.2.1. Increased waste generation rates

On an international scale, it is emphasised that MSW generation will increase from 1.3 billion tonnes in 2012 to 2.2 billion tonnes by 2025 (Hoornweg & Bhada-Tata, 2012), while in 2016 it was estimated that the municipal waste generation rate was 2 million tonnes per year and would increase to 3.4 million tonnes by the year 2050 (Khandelwal et al., 2019). According to the Global Waste Management Outlook (UNEP, 2024), the Global North has a sufficient WMS, where waste management is essential in modern life. North America generates approximately 2 kg/capita/day (Mozo-Reyes et al., 2016). In countries such as Indonesia, with Medan being the third largest city, residents were estimated to generate 0.222 kg/capita/day (Khair et al., 2019). In other Asian countries such as China, Turkey, and Thailand, residents were estimated to generate between 0.25 and 1.20 kg/capita/day of MSW (Guerrero et al., 2013). Other parts of Asia, such as Eastern- and South-Central Asia, produce less than 0.5 kg/capita/day (Agamuthu & Babel, 2023). Table 1.1 shows estimated waste generation in different countries globally.

The Global South experiences the effect of inefficient WMS (Gutberlet et al., 2017). Places in South America have a diverse waste generation rate between countries. Table 1.1 indicates a 0.63 kg/day difference between the two countries in South America, with available data from the two countries. Countries in Africa, such as Uganda, Kenya, and Tanzania, estimated the waste generation to be 0.84, 1.145, and 1.938 kg/capita/day (Aryampa et al., 2019). Nigeria estimated that the waste generation for Ogbomoso was 0.5 kg/capita/day (Abel, 2007).

The annual waste generation in South Africa in 2011 was estimated to be 108 million tonnes. The average waste generation per capita per day in South Africa can range between 0.41 and 1.3 kg/capita/day, depending on the income group of informal disposal.(Nkosi et al., 2013; Rodseth et al., 2020). The South African State of Waste (SASW) Report indicated that the generation rate is approximately 1.3 kg/capita/day (DEA, 2018).

Provinces such as Limpopo produce a range of 0.32 to 0.7 kg/capita/day (Rodseth et al., 2020). Forty-two million tonnes of waste are produced in the Gauteng Province alone (Muzenda, 2014). Studies in 2009 (Guerrero et al., 2013) indicate that cities such as Pretoria, Langeberg, and Districts Muncipality (DM) such as Emfuleni generate between 0.6-0.65 kg of waste per capita per day. The Johannesburg area is estimated to generate between 0.38 and 0.99 kg/capita/day.

There are drivers behind this exponential waste increase on a global, national, and local level. It is essential to understand the factors that influence the waste generation rate.

Table 1.1 Waste generation rate of different countries.

Continent	Country	Cities	Year of Study	Rate [kg/capita/day]	Reference
North America	--	--	2016	2.0	(Mozo-Reyes et al., 2016b)
Asia	China	Beijing	2010	0.80	(Guerrero et al., 2013)
	Thailand	Bangkok	2010	1.10	
	Turkey	Kutahya	2010	0.60	
	Turkey	Bitlis	2010	0.90	
	Turkey	Amasya	2010	1.20	
Eastern Asia-	-	--	2018	0.37	(Agamuthu & Babel, 2023)
South-Central Asia	--	--	2018	0.21	
South America	Costa Rica	Cartago	2011	1.10	(Guerrero et al., 2013)
	Peru	Canete	2010	0.47	
Africa	South Africa	Pretoria	2009	0.65	(Guerrero et al., 2013)
	South Africa	Langeberg	2009	0.65	
	South Africa	Emfuleni	2009	0.60	
	South Africa	--	2020	0.41-1.29	(Rodseth et al., 2020)
	South Africa	--	2018	0.57	(DEA, 2018)
	Uganda	Kampala	2019	0.84	(Aryampa et al., 2019)
	Kenya	Nairobi	2019	1.145	
	Tanzania	Dar es Salaam	2019	1.938	
	Nigeria	Ogbomoso	2007	0.5	(Abel, 2007)

1.2.1.1. Drivers of increased waste generation

Many factors cause or may cause the increase in waste generation, such as the urbanisation of cities, rapid population growth, and lifestyle changes (Abu Qdais, 2007; Ayininuola & Muibi, 2008; Guerrero et al., 2013; Khair et al., 2019). Thus, the increase in waste generation could possible result in insufficient waste management, not only on a global scale but a significant amount in developing countries such as South Africa (Ghanimeh et al., 2019; Minghua et al., 2009).

Population growth is the main factor for waste generation in any economy (Iyamu et al., 2020). Within the next 50 years, solid waste generation is expected to increase beyond control, with the highest generation in high-population areas (Nwokedi, 2011). This directly links human population growth and waste generation (Nwokedi, 2011).

Urbanisation of cities created challenges in Africa for the last 30 years, with migration increasing the population in the metropolitan areas (Collinson et al., 2007). Gauteng province has an economic position within the country; thus, migration and urbanisation are encouraged (Landau & Gindrey, 2008). Therefore, increased consumption due to population growth causes strain on WMS. The world's future is becoming urbanised and less simple (Rabaji, 2019).

An increase in socio-economic activities can increase waste generation (Nwokedi, 2011). Approximately 0.5% of a developing country's gross per capita is contributed to effective WMS (Devi et al., 2016). A trend where high-income households produce a greater volume of waste compared to low-income households where observed. Due to various demographic factors, including household size, educational attainment of household members, and socio-economic status, which influence waste generation patterns (Babayemi & Dauda, 2010; Guerrero et al., 2013; Sujauddin et al., 2008).

Other factors such as gender, land size, location of the households that generate the waste, and number of members can explain waste behaviour (Babayemi & Dauda, 2010; Ekere et al., 2009). Human activities continue creating products to fulfill the need for a human lifestyle, in which the production and consumption of resources lead to problems such as waste creation, storage, and management (Mamady, 2016; Zurbrügg, 2003).

Insufficient waste management in SA can cause environmental problems such as water-; air, and land pollution, which threatens the health of humans and the environment (Ghanimeh et al., 2019; Nwokedi, 2011). It is not only an environmental issue, as it can have negative social and economic impacts (Lohri et al., 2014).

1.2.2. Municipal waste service provision

Safely storing, collecting, and disposing waste is crucial for maintaining human and environmental health (Mamady, 2016). Effective WMS contributes significantly to ensuring a safe environment for communities. However, a strain on these systems often results in inadequate waste disposal practices in South Africa (Nahman & Godfrey, 2010). Schedule 5 of the South African Constitution (1996) stated that municipalities are responsible for refuse removal, refuse dumps, and solid waste disposal in a city or town. Other local government duties include making certain provisions for the local communities, promoting development, and ensuring a safe and healthy environment. The public places the responsibility for MSW removal on the municipality (Grobler et al., 2022)

The SASW Report indicated that 34% of the country dispose of their waste informally and 5% deal with it through other means (DEA, 2018). A study done in 2020 indicated that 69% of South African households receive WMS, which indicates that 31% do not receive any formal waste services (Rodseth et al., 2020).The percentage of waste collected by municipalities from different provinces in South Africa (Grangxabe et al., 2023).

Table 1.2 Waste collected by municipalities in different provinces across South Africa (Grangxabe et al., 2023).

Provinces	**Percentage [%]**
KwaZulu-Natal	65%
Limpopo	12%
Western Cape	76%
Mpumalanga	37%
North-West	56%
Free State	64%
Eastern Cape	41%
Northern Cape	38%
Gauteng	51%
South Africa	**51%**

The Eastern Cape has one of the lowest levels of waste collection services (Mngomezulu et al., 2023). Komani in the Eastern Cape has a population of 61% living in poverty (Ngalo & Thondhlana, 2023). The study suggested that 36% of the population does not have proper WMS. Several (120) informal waste disposal sites were identified in the town.

The Western Cape province has the best WMS, with 76% of waste collected (Grangxabe et al., 2023). Joe Slovo Park in Cape Town, Western Cape, consists of 6124 households and a population of around 15,000 identified 21 informal disposal sites in 2022 (Jakeni et al., 2024). The local government installed skip/bins to address this problem. 43.18% of the community does not have efficient waste management collection services. Approximately 94% of respondents indicated not having waste disposal bins at home (Jakeni et al., 2024).

There are 452,581 informal households in the Gauteng province, with 51% of waste collected (Grangxabe et al., 2023). This indicates that 49% of waste is not collected in the Gauteng province. Low-income households in Gauteng have around 5763 tonnes of waste not collected by WMS (Haywood et al., 2021).

Municipalities face significant challenges in managing waste as several factors impact waste collection, disposal services, waste transport, and disposal services. These factors include limited road access due to poor infrastructure, inadequate route planning, financial constraints, and waste generation (Niyobuhungiro & Schenck, 2022). The high population density in settlements and lack of knowledge about waste collection dates exacerbates these issues as residents remain unaware of when the waste collection services will occur (Hazra & Goel, 2009; Moghadam et al., 2009; Rodseth et al., 2020). There are different challenges for different local governments, where larger metropolitan areas have more effective services than smaller municipalities (more rural municipalities) (Rodseth et al., 2020).

There is no effective system for sufficient waste management service due to low revenue collection (Hettiarachchi et al., 2018). This refers to the removal of waste is paid by members of a community through taxes and low income community do not necessary pay or are able to pay for waste collection services. Waste management enforcement and service does not have adequate finances in South Africa (Nahman & Godfrey, 2010). Local government cannot adapt to the development of migration and increased population of low-income settlements (Boadi & Kuitunen, 2003).Oelofse and Godfrey, (2006) indicate, as cited by (the Municipal Demarcation Board, 2008), that 48% of the 231 municipalities assessed could not perform waste management or sanitation functions. 12.7 million (29%) tonnes of South Africa’s domestic waste generated are not collected by WMS (Rodseth et al., 2020). The provincial government does not invest in waste management disposal technologies due to inadequate funds (Mmereki et al., 2016).

Being a developing country, South Africa does not have enough resources to withhold the high WMS standards of developed countries (Aparcana, 2017). Lack of collection equipment, such as waste containers, waste bins, treatment facilities, and landfill sites, as well as the inability to apply technologies, contribute to poor waste management (Filho et al., 2016).

Outdated and unmaintained infrastructure relates to insufficient waste management (Grobler et al., 2022a). Informal settlements in developing countries do not necessarily have paved roads wide enough for waste collection vehicles. The vehicles could struggle with access to the community. Some communities use drop-off points for the waste vehicles to collect the waste, where there are not enough collection points for the demand (Yukalang et al., 2017). This causes residents of low-income areas to outsource and pay more for waste collection services (Grobler *et al.*, 2022a). This results in communities finding different methods to deal with uncollected waste (Wiedinmyer et al., 2014).

1.2.3. Informal waste disposal

The UNEP (2024) estimated that almost 3 billion people do not have the necessary MSW services on a global scale. A lack of formal WMS results in informal waste management activities (Rodseth et al., 2020). When the waste collection and disposal services fail to function appropriately, informal waste disposal occurs. This is the primary reason for informal waste disposal. The waste generator may choose not to take responsibility and dispose of the waste informally. This is not legal according to legislation or regulations. Informal waste disposal areas may include roads, water sources, and nearby land.

When the municipality lacks the necessary waste disposal and treatment, there is a financial strain to supply the necessary facilities (Guerrero et al., 2013), which increases waste disposal costs (Ichinose & Yamamoto, 2011). This cost increase will ultimately lead people in communities of developed and developing countries to dispose of their waste informally. For example, Korea and Japan are developed countries that use an upstream policy where households pay for the generated waste which needs disposal. The waste generator does not want to pay for waste collection services if the cost or cost increases (Park et al., 2013). This indicates that it is not just developing countries with waste management issues (Ichinose & Yamamoto, 2011). If there is an increase in informal disposal in a specific area, it is a result of an increase in insufficient waste disposal services (Yang et al., 2017).

Informal waste disposal sites cause informal recyclers or waste pickers to contribute to recycling as part of the informal sectors (Yang et al., 2017). The techniques used are rather primitive, and secondary pollution that is not managed can increase pollution in the water, air, and soil (Yang et al., 2017).

1.2.3.1. Informal waste disposal in South Africa informal settlements

The waste management problem causes the need for alternative ways to dispose of waste, leading to communities informally burning the waste to dispose of it (Ghanimeh et al., 2019; Wilson & Webster, 2018). The burning of the waste can cause air pollution, and the waste can end up in water streams, resulting in floods, the spread of diseases through rodents, and pollution (Zurbrügg, 2003).

Approximately 3.9% of these households in informal settlements in Gauteng use an on-site or in-the-yard disposal site. Figure 1.1 shows waste burning events in informal settlements in South Africa namely Oranjeville (Top) and Zamdela (Bottom). There will mainly be a focus on informal waste burning and its contribution to $PM_{2.5}$ because of waste management service issues for this research.

Figure 1.1 Waste burning in South Africa, informal settlements within VTAPA, namely Oranjeville (Top left and top right) and Zamdela (bottom) Photo: Aneska Richter.

Sharpeville has been struggling with service delivery for years. An article published in 2021 stated that the local municipality's financial state caused a complete collapse of the services delivery sector, which includes WMS (Dlamini, 2021). Tsoka (2019) indicated that these sites were large and “stretch for miles”. The effectiveness of clean-up campaigns resides in the community’s education regarding waste disposal, reuse, and recycling (Tsoka, 2019). The community's negative attitude results in the informal disposal of waste. Some community members took it upon themselves to address this environmental problem.

It is also vital to encourage communities to minimise waste generation (Oelofse & Strydom, 2010; Strydom et al., 2009). South Africa's waste management hierarchy focuses on waste avoidance and reduction. Re-use and recycling are popular amongst waste pickers. Along with the waste management hierarchy, the waste management strategy of South Africa has goals in place that focus on promoting re-use, recycling and specific goals that set waste minimisation and disposal services (DEA, 2011). Due to a lack of adequate waste disposal service; it is challenging to enforce or apply these strategies.

Areas not receiving the appropriate waste management service result in people burning the waste dumped informally (Wiedinmyer *et al.*, 2014). Waste can also be burned due to cost avoidance or the inability to transport the waste to the nearest landfill. When burned, waste can be a concern for public health and environmental impacts such as air pollution (Lemieux, 1998). It can be challenging to monitor informal waste-burning activities. There is a difference between controlled waste burning and uncontrolled waste burning.

1.2.4. Informal waste burning

Controlled burning can refer to waste being burned under regulation to manage pollution and waste, where harmful pollution could emitted from MSW combustions into the ambient environment (Guttikunda & Kopakka, 2014). Open burning includes forest fires, biomass burning, emissions during fireworks shows, which is not always intentional, and waste burning. Uncontrolled waste combustion usually occurs at lower temperatures, resulting in increased emissions (Tai et al., 2010), which can result in higher levels of atmospheric pollution (Lemieux, 1998; Wevers et al., 2004). Open burning usually occurs outside, where waste is dumped near the home, often in piles or on public grounds (Zhang et al., 2011). Limited solutions have been found to reduce the health impact uncontrolled burning has and solve environmental issues (Reyna-Bensusan et al., 2018).

Open- and uncontrolled burning of domestic waste releases toxic pollutants in the air, such as polychlorinated dibenzofurans (PCDFs), polychlorinated dibenzo-p-dioxins (PCDDs), volatile organic compounds (VOCs), polycyclic aromatic hydrocarbons (PAHs), and particular matter (PM) (Carriero et al., 2018; Gullett et al., 2010; Rabaji, 2019a; Wiedinmyer et al., 2014). Pollutants emitted from waste burning depend on the types of waste being burned and how effectively the combustion takes place (Cogut, 2016). Uncontrolled burning is still a management solid waste issue in developing countries (Rabaji, 2019; Sharma et al., 2019). This research focuses on the informal burning of informal waste disposal sites. Uncontrolled burning is still a management solid waste issue in developing countries (Rabaji, 2019a; Sharma et al., 2019). This research focuses on the informal burning of informal waste disposal sites.

1.2.3.2. Waste burning on a global, national, and local level.

Approximately 40% to 50 %of the waste generated globally undergoes uncontrolled burning as a disposal method (Wiedinmyer et al., 2014). In addition, the 2010 global anthropogenic $PM_{2.5}$ emission estimated was 29% of open waste combustion (Wiedinmyer et al., 2014). Factors such as temperature, moisture and windspeed influence the condition of combustions. For instance, while paper typically combusts at lower temperatures compared to plastic, plastic may burn at a higher temperature and consequently emit a higher concentration of PM (Lemieux, 1998; Wevers et al., 2004). Pollutants such as PM are released at ground level when informal waste is burned. However, the composition of the waste being burned can be diverse and happens in places that struggle to monitor the burning activities; this makes it difficult to get reliable environmental samples to estimate the waste's emission, combustibles and non-combustibles (Lemieux et al., 2004).

Unlike controlled waste burning, informal waste burning does not undergo complicated combustion due to temperature differences (Mihai et al., 2019). This incomplete combustion of waste causes an increase in PM emissions. Food waste emits a higher amount of $PM_{2.5}$ emissions due to the high fuel load and incomplete combustions (Zhu et al., 2018). Glass is estimated to have no significant contribution to $PM_{2.5}$ emissions due to the temperature not reaching high enough for the glass to combust (Wang et al., 2023; Zhu et al., 2018)

1.2.5. Health impacts associated with particulate pollution

Air pollutants are emitted naturally or anthropogenic. Some natural sources include volcanic eruptions and forest fires (Muthige, 2013). Anthropogenic sources refer to any pollutant emitted from human-induced activities such as industrial sources, domestic fuel burning, biomass burning, traffic emissions, and waste burning. The most abundant and commonly monitored pollutants emitted in SA are sulphur dioxide (SO_2), nitrogen oxides (NO_x), Ozone (O_3), and Particulate Matter (Zunckel et al., 2006). Atmospheric aerosols are suspended particles, either liquid or solid, emitted into the atmosphere (Piketh et al., 1999; Tyson et al., 1996).

PM is characterised by the size property and classified into different size fractions (Seinfeld & Pandis, 2006). The coarse fraction, or PM_{10}, refers to particles with an aerodynamic diameter of 10 micrometres (µm) or less, while the fine fraction, or $PM_{2.5}$, refers to particles with a diameter of 2.5 µm or less (Li *et al.*, 2017; World Health Organization (WHO), 2006). PM can be emitted from primary or secondary sources, while $PM_{2.5}$ is often a result of secondary pollutants (WHO, 2013).

The Global Burden of Disease (Abbafati et al., 2020) estimated that air pollution ranks 4th among global risk factors for estimated premature deaths. The death rate for women reaches over 2 million people per year, while for men, the estimated death rate is approximately 4 million deaths. Most of the deaths are related to preventable respiratory diseases for both men and women (Abbafati et al., 2020).

There is a strong direct link between $PM_{2.5}$ and respiratory diseases and people who are hospitalised for cardiovascular disease and infant mortality (Gu et al., 2018; Hauck et al., 2004; Tecer et al., 2008). According to a risk modelling study (Kodros et al., 2016), the mortality rate caused by respiratory exposure to open burning pollution is 270,000 premature adult mortalities. A study in China (Gu et al., 2018).declared that the mortality rate caused by $PM_{2.5}$ pollution is 76.3% of the air pollution moralities, while the rest was due to O_3 pollution.

The results show that the emission causes a mortality of 1 143 000 premature mortalities (Gu et al., 2018). The world is growing concerned about the environmental problems pollution brings; therefore, the relationship between ambient air pollution and human health has become more important. Even though there is an increased concern for human health in exposure to air pollution, there is a limited research focus on the damages caused to public health, which ignores these health consequences of uncontrolled burning and focuses more on the issues related to inappropriate WMS (Cogut, 2016). The composition and the time humans are exposed to the pollutant can lead to different human health issues (Kampa & Castanas, 2008). This study focuses explicitly on $PM_{2.5}$ because of its potential to contribute to respiratory diseases that can cause mortalities (Kampa & Castanas, 2008; Tecer et al., 2008).

1.2.6. Relation between waste composition and PM $_{2.5}$ emissions

Despite the well-characterised impacts of domestic burning on air quality, there is a limited understanding of the broader population-scale effects of open waste burning emissions (Hersey *et al.*, 2015). While studies quantifying informal waste burning in developing countries are limited

(Rabaji, 2019a; Sharma et al., 2019), studies conducted in Africa have focused on charaterising waste and estimating waste composition (Al-Khatib et al., 2010; Bernache-Pérez et al., 2001; Dahlén & Lagerkvist, 2008; Miezah et al., 2015; Ogwueleka, 2009; Sharma et al., 2019).Tabel 1.3 gives an overview of the different waste type categories used in this study. The organic waste excludes 'fodd waste' , 'paper and cardboard' .

Table 1.3. Description of the different waste categories (Rabaji, 2019)

Waste Type	**Description**
Paper and cardboard	Office paper, computer paper, magazine, glossy paper, waxed paper, newsprint, corrugated and cardboard
All plastics and polystyrene	Dense and plastic film
Food waste	All food waste except bones
Other organics (not food)	Yard waste (Branches, twigs, leaves, grass and other plant material), wood, textiles, rubber, leather and other primarily combustible materials not included in the above component category
Metals	Ferrous (Iron, steel, tin cans and bi-metal cans), aluminum and non-ferrous non-aluminum metals (copper, brass)
Glass	All glass materials
Other	Rock, sand, dirt, ceramics, plasterboard, bricks, cement, concrete, building rubble and bones

1.2.6.1. Waste composition

According to Karak et al. (2012), studies in some European countries in the Global North indicate that the dominant waste type is 'organic waste'(yard waste), including food waste. The waste type contributes between 20-50% of all the categories. Countries like Finland produce more paper and cardboard than organic material (Sokka et al., 2007). Italy and Sweden had two domain waste types ('organic material', 'paper, and paperboard'). 'Textiles and others' contribute more to countries such as Denmark (Karak et al., 2012) and Germany, Berlin (Zhang et al., 2010). The Global North has effective WMS (Cogut, 2016).

In various Asian countries, such as China, Indonesia, and the Philippines, organic waste is estimated to contribute to more than 45 % of the waste type. India and South Korea's main waste type was textile, with others comprising more than 40% of the waste composition (Idris et al., 2004; Karak et al., 2012). In developing Asian countries, local municipalities do not have sufficient recovery and recycling capacity. In African countries such as Nigeria, Ghana, Namibia, and Botswana, the highest amount of waste generators is organic waste (Karak et al., 2012). All the neighbouring countries of SA produced primarily organic waste. At the same time, Zimbabwe is the only neighbouring country where paper, cardboard and plastic are the dominant waste types of waste composition (Karak et al., 2012). Table 1.4 indicates all the waste types of waste composition. The waste composition was placed in different categories, 'Organic waste', Paper and Cardboard', Plastic, 'Glass', 'Metal', and 'Textile other'.

Table 1.3 Waste composition from different countries in the global North and Africa in weighted percentage (Idris et al., 2004; Karak et al., 2012).

Continent	**Country**	**Organic Waste**	**Paper and Cardboard**	**Plastic**	**Glass**	**Metal**	**Textile and Other**
Europe	Finland	33	40	10	5	5	7
	Italy	29	28	5	13	2	2.2
	Sweden	39	40	6.8	6.2	4.9	3.1
	Denmark	29	27	0.8	5	6	32.2
	Germany	15	20	23	7	2	33
Asia	China	67.3	8.8	13.5	5.2	0.7	4.5
	Indonesia	70.2	10.9	8.7	1.7	1.8	6.2
	Philippines	24.9	19	17	-	6	9
	India	41.8	5.7	3..9	21	1.9	44.6
	South Korea	32.8	23.8	-	2.8	-	4.6
Africa	Sudan			-	-	-	
	Nigeria	57.5	7.1	7.9	11.3	2.6	13.6
	Ghana	73.1	6.6	3.3	1.5	2.1	13.4
	Namibia	36	20	16	13	5	10
	Botswana	59.3	0.6	0.6	0.2	1.5	37.8

In 2018, the SASW Report indicated a breakdown of SA's waste composition for 2017. The dominant waste type was organic waste (34%), followed by paper and paperboard contributing (4%) and plastic (2%) (DEA, 2018). Non-recycled material is one of the highest contributors to the waste composition (Nkosi *et al.*, 2013). Figure 1.2 shows SA's waste composition for the different streams.

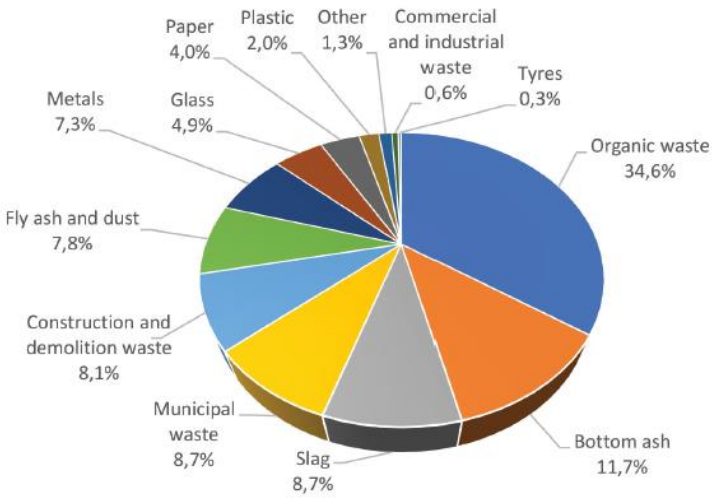

Figure 1.2 Waste composition of the different waste types in South Africa 2017 (DEA, 2018).

According to the South African waste classification report of Cape Town, 53% of household waste is composed of organic waste and 13% of paper and cardboard (APWC, 2020). The overall waste composition of the different provinces was estimated by Oelofse (2015), which indicated that the dominant waste type for most of the provinces was organic waste. Northern Cape was the only province where organic waste was in the minority. Organic waste. 36% of the waste profile in the Gauteng province is organic material, as shown in the table below (Table 1.4). Glass and metal have the lowest weight of waste in all provinces (Oelofse, 2015). The Gauteng province only has a percentage of 3 for Metal and 5% for Glass. This indicates that informal waste pickers recycle the waste at dumping sites with a low weight for the recyclable materials (Sharma *et al.*, 2019).

Table 1.4 South African waste composition of each province in weighted percentage (Oelofse, 2015).

Province	**Paper and cardboard**	**Plastic**	**Glass**	**Metal**	**Organic waste**	**Other waste**
Western Cape	24	22	9	8	22	16
Northern Cape	21	18	10	3	10	9
Free State	14	12	8	6	42	19
North-West	11	9	6	2	58	14

Gauteng	17	10	5	3	36	30

Establishing the waste composition is crucial for providing vital data and efforts to quantify waste charateristion for waste burning emissions (Gidarakos et al., 2006; McCauley-Bell et al., 1997) PM emissions from burned waste can avry depending on the waste composition in the region.(Cogut, 2016; Wevers et al., 2004). The data generated from the waste composition could be used in further studies to estimate air emission calculation more accurately.

MSW includes various household waste types. This waste can contribute to producing ~ 65% of the total $PM_{2.5}$. The general composition of waste is characterised by food waste, organic waste, plastic, glass, metal and others (Muzenda, 2014). Paper is included in the waste composition due to its synthetic materials, including labels laminated with vinyl (Park et al., 2013).

1.2.6.2. Quantifying $PM_{2.5}$ emissions from informal waste burning

One method to quantify waste burning emissions is through emission inventories (Jonas *et al.*, 2019). PM emissions can be quantified through ambient air quality monitoring gravimetric weighing and air quality dispersion models (Merkisz & Pielecha, 2015). Studies attempted to quantify waste burning on a global scale (Wiedinmyer et al., 2014). The IPCC developed calculations to estimate emissions to address uncertainties associated with waste burning (IPCC, 2006).

The total emissions are calculated using the active rate and the emission factor (Wiedinmyer et al., 2014). The active rate is a product of the population, people that burn waste, the percentage of waste that burns, and the waste generated. Some of these variables in the equation create uncertainty when calculating waste-burning emissions in areas that lack this variable information. Das et al. (2018) and Reyna-Bensusan et al. (2018) addressed some of these uncertainties by conducting household surveys and experiments to determine the waste burned.

On an international level, studies conducted in various countries such as Nepal (Das et al., 2018), India (Nagpure et al., 2015), Thailand (Pansuk et al., 2018; Ramadan, Rachman & Matsumoto, 2022), and Mexico (Reyna-Bensusan et al., 2018) used the equations to estimate the waste burning emissions. In SA, the equation was used in master's dissertations (Bosman, 2018; Chidhindi, 2022) and conference papers (Richter et al., 2021). The second generation of the VTAPA AQMP Draft Baseline Assessment Report (DEA, 2019) attempted to use the equations and factors from Wiedinmyer et al. (2014) to determine PM emissions' contribution to the region.

This indicated the need for waste burning emission inventories (Elston et al., 2017). These studies used emission factors from the literature, and some difficulties and costly factors are associated with measuring emission factors (Nkosi et al., 2013b). Other studies (Lemieux, 1998; Park et al., 2013; Wiedinmyer et al., 2014) used the equations to estimate the waste burning emissions and developed emissions factors for $PM_{2.5.}$ In South Africa, emission factors from open inform waste burning were measured Wang et al. (2023).

Different literature reported emission factors running between 2 to 17g/kg for $PM_{2.5,}$ with some reports being from 1994, approximately 20 years ago. The emission factors are useable in a SA context but not sufficient due to the variation in waste composition and combustion of MSW in SA. Although Wang et al. (2023) reported emission factors for MSW and the different waste types, the study did not measure the emission factor for Metal and Glass due to open waste burning temperature being too low for combustion (Wang et al., 2023). Table 1.5 shows the different waste burning emission factors for $PM_{2.5}$ from the literature for studies conducted in different countries.

Table 1.5 Comparison of emission factors from different studies in the literature.

Study Reference	**Country of study**	**$PM_{2.5}$ Emission Factor [g.kg]**
(U.S. EPA, 1995)	USA	8
(Lemieux, 1998)	USA	14.8
(U.S. EPA, 2020)	USA	17
(Park et al., 2013)	South Korea	2.3
(Wiedinmyer *et al.*, 2014)	Global	9.8
(Wang *et al.*, 2023)	South Africa	6.86

Some emission inventories consider waste burning emissions, while open waste burning is excluded from inventories mainly due to the uncertainties associated with waste burning. These uncertainties include i) emissions factors, ii) the fraction of the population that burns waste, and ii) the fraction of waste that burns, including the combustible fractions (Das et al., 2018; Nagpure et al., 2015).

1.2.7. Monte Carlo Approach for estimating $PM_{2.5}$ emissions from waste burning.

Uncertainty in emissions refers to measurement errors and systematic errors. Variability refers to the differences in composition, time, and pressure (Tan et al., 2014). Understanding the variability in emissions sources can characterise the uncertainty, whereas statistical approaches can quantify uncertainties. The Monte Carlo approach can be described as a statistical tool for addressing uncertainty (Aderibigbe, 2014). Using a computer, the simulation selects random values of the activity rate (AR) and emission factors (EF), which are repeated multiple times to build the overall estimated emission probability (IPCC, 2006). The Monte Carlo simulation is an approach that uses probability distributions of data inputs (McVoy, 1979). Sources of uncertainties are all the assumptions associated with the emissions data inputs, e.g. AR and EF (McMurray et al., 2017). The results or estimates of the simulation runs are applied to equations to determine the emissions. Figure 1.3 illustrates the Monte Carlo approach by inserting different variables for a final distribution.

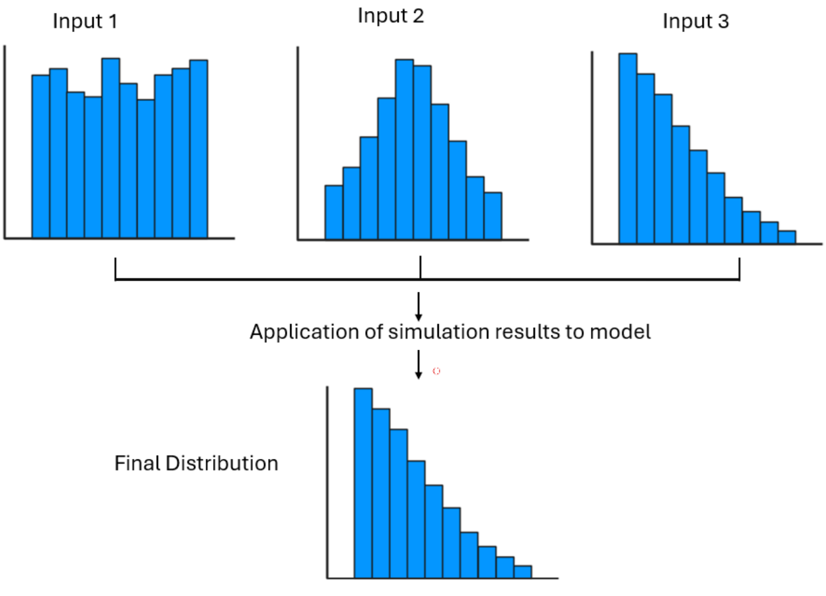

Figure 1.3 Illustration of the Monte Carlo approach inserting different variables into the simulation (adatped from McMurray et al., 2017).

To estimate the contribution of $PM_{2.5}$ from waste burning, the AR is determined. The AR for waste burning is calculated using the community population (U.S. EPA, 1995). The number of people in the community who burn waste is mainly collected using surveys and interviews (Wiedinmyer et al., 2014). The interview results mainly focused on the participants' honesty regarding waste-burning-related questions. The survey used a sample population to represent the specific community, which could over- or under-represent the community. The burning fraction of waste depends on the composition of the waste, burning temperature, and combustion of the waste. This creates uncertainties that are not fully addressed in a South African context.

When running a Monte Carlo simulation, determining the appropriate distribution suited for each variable is crucial, as shown in Figure 1.4. These variables are used as inputs in the Monte Carlo simulation, where data is lacking (IPCC, 2006). This results in assumptions made based on literature. A uniform distribution was suited due to the variables having an equal likelihood of obtaining any value within the range. Variables such as the population that burns waste and the municipal solid waste generation had a uniform distribution (IPCC, 2006).

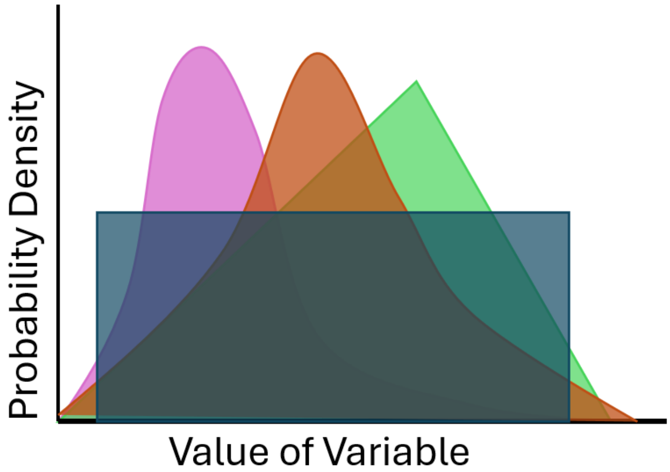

Figure 1.4 Different types of probability distribution can be used in the Monte Carlo simulation.

After the type of distribution is determined, the input range and standard deviation are inserted as inputs in the simulation. The simulation has multiple runs, where the user chooses the number of runs. McMurray et al. (2017) suggest that the rule of thumb is to use ~10,000 simulation runs, as this can result in a stable outcome in the simulation. The estimated total emission of the simulation is stored in a data file. These files can be used in dispersion modelling to see the transportation and dispersion of the estimated emissions (Aderibigbe, 2014). Figure 1.5 gives an overview summary of a Monte Carlo simulation process.

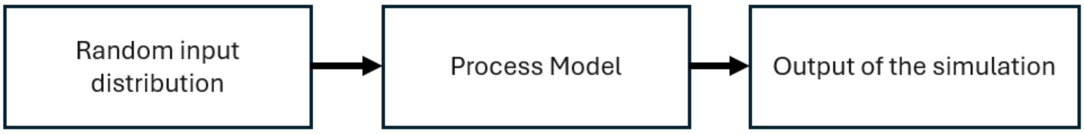

Figure 1.5 Monte Carlo simulation process (Aderibigbe, 2014).

1.2.8. Managing ambient $PM_{2.5}$ concentration in South Africa

The following section discusses the regulatory tools, methods, and instruments used to manage and address air quality, specifically $PM_{2.5,}$ in South Africa. The legislation regarding air quality will be described with regulatory tools such as air quality monitoring, air dispersion modelling, and AERMOD modelling.

1.2.3.3. Legislation

Section 24 of the SA Constitution (1996) states that everyone has the right to (a) an environment that is not harmful to their health or well-being. As indicated in section 1.2.4.1) there is difficulty managing, controlling, and regulating policies for open, uncontrolled waste burning. The National Environmental Management Act (NEMA) shifted the focus of Air Quality Management from regulating sources to evaluating the effect on receptors. NEMAQA assesses compliance with ambient air quality by using air quality monitoring as a regulation tool. The NEMAQA attempts to regulate the acceptable concentration through the National Ambient Air Quality Standards (NAAQS). These standards are developed to control the air quality in SA (DEA, 2012). There is a daily standard of a 24-hour concentration level of criteria pollutants. Table 1.6 shows the NAAQs for PM_{10} and $PM_{2.5}$.

Table 1.6 South Africa's NAAQS for PM_{10} and $PM_{2.5}$ (DEA, 2009a, 2012)

Pollutants	Period	Concentration [µg/m^3]	Exceedance Frequency
PM_{10}	24-hours	75	4
	1 Year	40	0
$PM_{2.5}$	24-hours	40	4
	1 Year	20	0

Various areas of the country are not adhering to the standards and contribute to poor air quality. There are no standards for informal waste burning; therefore, the NAAQS is used to assess air quality in the selected location.

1.2.3.4. Air Quality Monitoring

Air quality monitoring is crucial to evaluate the long-term air quality levels of pollutants, but it is insufficient. Instruments with specific principles of operation, methods, and techniques are used to measure the pollutant's concentration based on the pollutant's complexity (Venter et al., 2012). Different types of monitoring can be used. SA uses fixed monitoring to provide data over a long-term period. The continuous monitoring stations are in proximity to different sources. There are 132 monitoring stations in SA, most of which are in the Gauteng province (Cairncross, 2015). With 30 stations in the Gauteng provinces, only five have been reported to meet the data requirements (Cairncross, 2015).

Fixed monitoring stations are primarily managed and owned by different levels of government (Cairncross, 2015). The country has three priority areas, namely the Highveld Priority Area (HPA), Vaal Triangle Priority Area (VTAPA), and Waterberg Priority Area, which are managed at a national level. The Western Cape is the only province that manages monitoring stations at a provincial level (Cairncross, 2015). The local municipality controls the rest. There are ~70 privately owned monitoring stations. The priority areas are the only stations that measured both PM_{10} and $PM_{2.5}$ in 2012 (Cairncross, 2015).

To create air quality management plans, policymakers need to consider monitoring to establish the region's air quality state and develop short/long-term policies to improve air quality. SAAQIS website provides the database platform for air quality data and state air quality reports and can report poor air quality incidents. This tool can be used to report waste-burning incidents (DEA, 2019a).

1.2.3.5. Air dispersion modelling

Air dispersion models are mathematical equations that predict and forecast pollutants emitted into the atmosphere (Wernecke et al., 2015). The dispersion model is a scientific, standardised method to assess pollutant impact from different sources (Cora & Hung, 2003). The concentration level is estimated depending on the spatial and temporal scale. Modelling the dispersion of pollutants is one of the most frequently used tools for air quality management. Source Apportionment, risk analysis, and control policies can benefit from dispersion models. Air dispersion models are used to address compliance with emissions from sources. For pollutants that are difficult or expensive to measure, air dispersion models are used to estimate pollutant concentration. The US EPA developed Models with different methods that consider distances, terrain, and complexities of chemical and atmospheric processes, modified for exceptional dispersion cases (Bosman, 2019; Tan et al., 2014). Several modelling techniques have been developed, which include box, Lagrangian, and Gaussian models (Haq &Schwela, 2021)

The box model is a rectangular box that covers a city, where the air pollution concentration is estimated with this box. The emission factor is independent of space and time in the model (Haq et al., 2019). The box assumes no pollutants leave the top or sides parallel to the wind direction. There is a uniform 'mixing' of pollutants produced by turbulence, where pollutants enter the box from the upwind sides of the model. The wind moves with a constant velocity. Some assumptions are unrealistic and are not configured for many small sources. In the Lagrangian model, pollutants are dispersed by discrete air volumes labelled by their trajectories. An emitted pollutant is distributed over an area or line of volume sources (Haq &Schwela, 2021)

Other models, such as the Gaussian model, are a solution to the basic equation for the transport of pollutants and are widely used for dispersion modelling (Aggarwal & Jain, 2015). The Gaussian model is a statistical model that uses a normal distribution (Rood, 2014). The model estimates the emission movement in a downwind direction at a specific height of the sources (Haq &Schwela, 2021). Figure 1.6 shows the plume of a Gaussian dispersion model. Gaussian models assume that the meteorological conditions are a steady state with three-dimensional continuous emissions, where under specific atmospheric conditions, the plume distributes in vertical and horizontal directions (Rzeszutek & Szulecka, 2021).

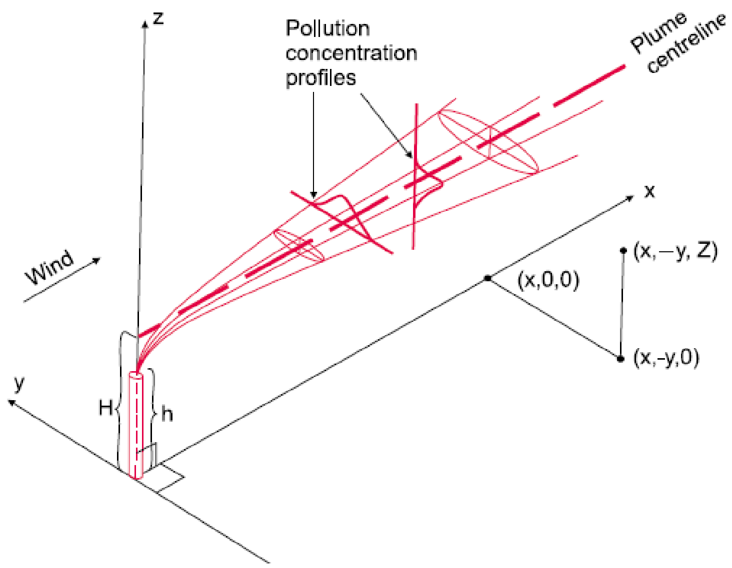

Figure 1.6 Schematic of a Gaussian dispersion model plume (Haq &Schwela, 2021).

For a model to effectively predict the physical-chemical system, it simulates the anticipated response to expect. Creating an accurate model replicating actual atmospheric processes is crucial (Dennis et al., 1996). The models do not support dispersion under low wind conditions or site sources closer than 100m. However, it is best suited for short ranges within 50km (Caputo et al., 2003). Thus, the Gaussian dispersion overestimated the concentration, which is reassuring for modelling the contribution of low-level sources (Chidhindi, 2022).

Different ranges of models are available based on the users' needs. The assessment level should be determined by technical factors relevant to the model. These include geophysical characteristics, emission factors, and meteorological conditions (DEA, 2014).

Level one assessment estimates the worst-case scenario, such as Screen 3. Screen 3 is a one-dimensional model that calculates screening-level impacts using simple terrain analysis and single-source modelling. Californian Puff Model (CALPUFF) is used for more complex pollutants over a great distance (Ridzuan et al., 2020). CALPUFF is a level 3 assessment that uses a multi-layered Lagrangian puff-dispersion model to predict the efforts of different meteorological conditions on the transportation of concentrations (Hersey et al., 2015). It also considered different terrain aspects and coastal regions (Daly & Zannetti, 2007). CALPUFF has options that allow vertical wind shear effects and estimate horizontal plumes from turbulence-based dispersion (Rood, 2014). The American Meteorological Environmental Protection Agency Regulatory Model (AERMOD) is a Gaussian model suited to model the waste burning concentration (U.S. EPA, 2018).

1.2.3.6. AERMOD modelling

US EPA provides guidelines on the regulatory applicability of air quality dispersion models (U.S. EPA, 2018). AERMOD software from Lakes Environmental is a close source of Gaussian dispersion. AERMOD is a level 2 regulatory model and one of the preferred dispersions to model intra-urban air pollution (Kesarkar et al., 2007). AERMOD has a model extend of 50 km radius or less. The model can simulate rural or urban environments with flat or complex terrain (Perry et al., 2005) All sources are sensitive to surface roughness (Faulkner et al., 2008). AERMOD considers flow over rough terrain, although the Gaussian model struggles to simulate concentration across excessively elevated terrain (Holmes & Morawska, 2006). Table 1.7 shows the different outcomes from the AERMOD model depending on the requirement of the model needs.

Table 1.7 AERMOD modelling selected outcomes (U.S. EPA, 2018)

Capability	**AERMOD options**
Application	<50km
Source Type	Point, line, area, volume
Source release	Near-surface, surface, elevated
Source location	Urban/rural
Concentration distribution	Gaussian plume model
Plume rise	Briggs empirical expression
Boundary layer structure	LMO Scaling
Plume deposition	Dry or wet deposition
Terrain type	Simple/complex
Building effects	PRIME downwash algorithms

The guidelines need to outline the selected model and input data requirements (U.S. EPA, 2018) Inputs such as meteorology, topography, and emissions sources are considered when using AERMOD modelling (Ridzuan *et al.*, 2020). One of the primary inputs is the control file with the source location and emissions data (U.S. EPA, 2018). AERMOD consists of two pre-processors, namely AERMET and AERMAP. Along with these two pre-processors, information from the source is required for reliable outputs (Idris *et al.*, 2020).

Different types of source inputs are used in the model for air quality assessments. For instance, point sources are stationary sources like industrial stacks or chimneys. Area sources, on the other hand, are sources that are too numerous to be considered as a point source. Waste burning can be modelled as a point or combined to form an area source (DEA, 2014). Area sources are used to model low-level emissions and can be represented as any polygon shape. Sources such as automobiles, including trucks, cars, and motorcycles, are considered line sources, which are non-stationary sources, while on- or off-the-road line sources include boats and aircraft (Macêdo & Ramos, 2020).

The quantification of emissions is a vital component for modelling air pollution. There are methods for calculating the necessary emissions. To quantify point sources, information such as industrial activity, combustion conditions, fuel type, and stack height is required as input data (U.S. EPA, 2004). Area sources the accumulation of all these sources, which results in significant air quality emissions. The equation to quantify the area source is the sum of the total emissions calculated by the AR multiplied by the EF. The following sections provide an overview of the AERMOD dispersion model and pre-processor.

AERMET is the meteorological data pre-processor in AERMOD. Meteorological data such as i) surface data, which includes temperature, rainfall, cloud cover, relative humidity, wind speed, and wind direction, and ii) upper air data are required to process AERMET outputs. AERMET calculates friction velocity, Monin-Obukhov length, and mixing height. These data can be requested from the station or the SAWS. Some areas do not have these datasets available, so that the nearest stations can be used as an alternative. If missing data values are present, AERMET merges the surface and upper air datasets to create surface profile file output for AERMOD (Stein et al., 2007).

AERMAP software processes terrain and elevation data to determine the relation between air features and pollutant dispersion (Croner et al., 1996). Simulating the flow of air over a flat and elevated area. Therefore, geographical information systems (GIS) are a vital component used to represent a study area's topography. Terrain data can be downloaded from the AERMAP database, and specific terrain files can be uploaded. Figure 1.7 illustrates a schematic to visually represent how the input and pre-processors work to run AERMOD.

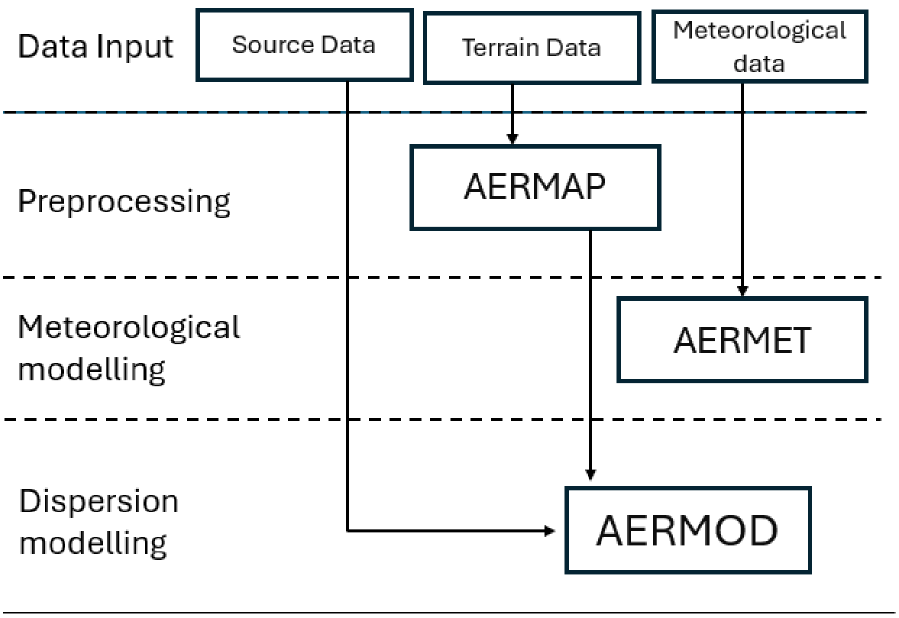

Figure 1.7 Schematic of AERMOD dispersion modelling processes (U.S. EPA, 2018).

1.3. Problem statement

Countries struggle to provide WMS for their citizens (UNEP, 2024). With the intensive migration, the increase in population growth, urbanisation, and economic position results in an unmanageable increase in waste generated. Ampofo et al. (2016) noted that in developing countries, such as South Africa, local municipalities do not provide the essential services for waste disposal.

Due to insufficient solid waste management, communities resort to other methods, such as informal disposal (Grobler et al., 2022a). Unwanted waste generated by the community is discarded in open public spaces or the backyard of their dwelling/household. The SAWS Report (DEA, 2018) highlights the contribution of poor waste service delivery to the uncontrolled dumping and burning of waste; it further acknowledges the potential negative impacts of poor waste management practices on air quality.

The effects of air pollution on public health are inexcusable (Cogut, 2016), whether informal burning occurs as controlled-, uncontrolled burning, or open burning when it is due unintentionally (forest fires). Due to insufficient waste management regulation and implementation, it has environmental and health impact globally. WMS were so poorly that some community members of Sharpeville started clean-up projects to manage this environmental problem internally (Tsoka, 2019).

PM emissions from waste burning vary based on the source size waste composition, meteorological conditions, and activity rate. The activity rate for open waste burning has uncertainties, such as the combustion percentage to which waste burns (Wiedinmyer et al., 2014). It is important to address these underlying uncertainties to assess the potential contribution of informal waste burning to ambient $PM_{2.5}$ concentrations.

Although many studies focus on waste characterisation and quantify the waste composition at a global level, only a few quantify the waste composition on a national or local scale. Some studies take a step further, quantifying waste burning emissions using waste characterisation data and attempting to create inventories for SA. Uncontrolled and open informal waste burning is excluded from inventories due to its complexity in the composition and associated uncertainties (Wiedinmyer et al., 2014).

1.4. Aim and objectives

This study aims to determine the contribution of waste burning to $PM_{2.5}$ (Particulate Matter) concentrations in a low-income settlement, namely Sharpeville, located in the Highveld region of South Africa. More specifically, the objective of the study is to:

i. Calculate the emissions of $PM_{2.5}$ resulting from informal waste burning in Sharpeville using available waste composition data and emissions factors.

ii. Utilise a Monte Carlo simulation distribution model to estimate the uncertainties associated with the $PM_{2.5}$ emissions from informal waste burning in Sharpeville.

iii. Model the ambient $PM_{2.5}$ concentrations in Sharpeville from informal waste burning using AERMOD.

1.5. Study scope

The dissertation was a case study that aimed to connect real-world scenarios to specific environmental issues by focusing on a particular area in SA. The study was conducted in a low-income settlement in the Gauteng province, to understand the role of waste burning in Sharpeville in contributing to $PM_{2.5}$ concentration. Sharpeville was selected as the study site due to its location and vulnerability to poor air quality.

The study focused solely on $PM_{2.5}$, a pollutant released during informal waste burning due to incomplete combustion, according to Mihai et al. (2019). The research relied on existing data on waste composition and surveys from a study conducted in Sharpeville (Rabaji, 2019a). However, Rabaji's research only covered informal disposal/burning in open public spaces and did not consider backyard burning in dwellings/households. The waste composition was only examined at one informal disposal site and characterised over a day (Rabaji, 2019a). These data were then used to estimate the waste burned through Monte Carlo simulation and to calculate waste-burning emissions using different emission factors, which were used for dispersion modelling.

During dispersion modelling, the study only focused on hourly and daily concentrations during 2017, when waste disposal sites were identified and characterised. The modelling included uniform and discrete receptors but did not account for seasonal variability, as the timing of waste-burning events and the hours waste sites burned were undetermined.

The study utilised a Monte Carlo approach and dispersion modelling to address waste-burning-related uncertainties in depicting the distribution and transportation of $PM_{2.5}$ concentrations. AERMOD was used for close area sources, and AQMS data was employed to compare the model results with measured concentrations to establish the contribution of the ambient atmosphere.

1.6. Significance of the study

Rabaji (2019) conducted a waste composition study, where the results can ultimately be used for further waste burning calculations, as it is important to quantify the $PM_{2.5}$ emission. It is crucial, to conduct studies at a local level to address uncertainties of waste burning calculations. Furthermore, it is vital to identify factors contributing to the quantification of waste burning, such as lack of reliable data, cost of conducting emission factor research, difficulties with community engagement, and labour intensity. This study emphasises the need for waste burning emission inventories and characterisation for informal settlements in developing countries. The result revealed a reliable indication of the $PM_{2.5}$ contribution of informal waste burning through useable model inputs and addressed uncertainty with waste burning quantification. Furthermore, policymakers can use this to establish the potential contribution of this source to the environment, and to raise awareness among the public about the consequences of informal waste burning. To be used a method to create updated AQMP that does not significantly under-or overestimate the contribution of informal waste burning. The results can ultimately be used to develop innovative strategies in waste management and air quality control. The study intends to create results can that contribute to creating interventions.

1.7. Limitations of the study

The limitations are divided into two categories, namely, the i) scope of study- and ii) methodological limitations. The scope of study limitation refers to the limitations associated with the scope defined in Section 1.5. In contrast, the methodological limitations are linked to the methods used in the study, including the ATSM, Monte Carlo Simulation, and AERMOD.

1.7.1. Scope of study limitation

- The study relied on secondary data from previous studies.
- The waste identification and the size of waste disposal sites were estimated and used for AERMOD.
- There were data limitations for the input of the Monte Carlo, and studies were conducted using the same approach for waste burning specifically.
- Additionally, there are spatial and temporal limitations due to seasonal variations and the community's behaviour regarding waste burning activities. This includes how often they burn waste, the times they burn waste, and how long the waste site burns. So there were

assumptions made that the participant burned the whole day and conducted the model with no seasonal variations.

- The ambient air quality monitoring station dataset had a lot of data gaps, with 43% missing data for the year. This made it difficult to fully explore the contribution of informal waste burning to the ambient $PM_{2.5}$ concentration in Sharpeville during 2017. Data cleaning was employed to overcome this challenge.

1.7.2. Methodological limitation

- The ATSM methods used are American, which may not be sufficient for a South African context. Using South African waste composition methods that address the variation in waste types could improve the reliability of the data.
- There were uncertainties associated with waste burning emissions factors due to the combustible fraction, so simulated emission factors were used instead.
- Both the Monte Carlo and AERMOD dispersion modelling took some time to simulate. A lab computer was used for most of the study period to run AERMOD. However, South Africa, a developing country with excessive load-shedding, created challenges in modelling before the electricity shut off, which resulted in data loss. To address this issue, a UPS was used to have a moment to save data. Another solution was to use a virtual computer to run the model.

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The research is based on a literature review that examines the relationship between waste management services, practices, and air quality. The study focuses on waste composition analysis and methods to reduce uncertainties associated with informal waste burning and $PM_{2.5}$ emissions from waste burning by a statistical approach and model. The next chapter describes the study's study area.

CHAPTER 2: STUDY AREA DESCRIPTION

This chapter explores the study's geographical and contextual setting. It comprehensively overviews the study area's environment, population, and relevant characteristics such as air quality and source emissions. This chapter does not include the methods, as these are fully described in Article Manuscripts in Chapter 3 and Chapter 4.

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2.1. Introduction

This chapter introduces Sharpeville, a township in the Gauteng province's Emfuleni Local Municipality and Sedibeng District, as the study area. The region faces inadequate WMS and poor air quality, as stated in the Gauteng Air Quality Management Plan (AQMP) (Hurt & Borman, 2009). Gauteng is relevant when focusing on waste burning and air quality on a provincial level. Informal settlements in high-density areas like Gauteng are more prone to air pollution due to the concentration of pollutants. Gauteng is the smallest province in South Africa, yet it has the highest population density (Hurt & Borman, 2009). The Gauteng AQMP outlines three Metropolitan Municipalities (MM), which are the City of Johannesburg, Tshwane, and Ekurhuleni, and two District Municipalities (DM), namely, the West Rand and Sedibeng. The subsequent sections explore the significance of the Vaal Triangle Air Quality Priority Area (VTAPA) and reflect on various demographics and air quality characteristics of the area.

2.2. The Vaal Triangle Priority Area

In 2006, the Department of Environmental Affairs and Tourism Minister declared the Vaal Triangle a priority area under section 16 of NEMAQA (DEAT, 2006). As such, it has its own priority area plan. The VTAPA is South Africa's oldest and largest priority area, which suggests that the region struggles to comply with air quality regulations. Due to poor WMS, sources of air pollution in the region are caused by human activities, including industries, domestic fuel burning, biomass burning, mining activities, and open waste burning. In 2011, the population of the VTAPA region was 2.8 million people (DEA, 2019). By 2016, it had grown to 3.1 million, indicating a 10% increase in population over five years (DEA, 2019). The VTAPA region encompasses municipalities such as the City of Johannesburg MM, Fezile Dabi DM (Free State Province), and Sedibeng DM. The following elaborates on the demographics of the Sedibeng DM, Emfuleni LM, and, more specifically, the community of Sharpeville. Table 2.1 summarises the demographic characteristics of Sharpeville, municipalities, and priority areas.

Table 2.1 Summary of the study area's demographic characteristics and waste services (DEA, 2019b; Statis SA, 2020; Vaal & City, 2023).

Characteristics	**VTAPA**	**Sedibeng DM**	**Emfuleni LM**	**Sharpeville**
Aera (km^2)	4 900	4 185	968	5
Population	3.1 million	1190688	733 444	37500
Population Density(km^2)	633	285	758	7 536
Households	--	376 971	297910	12 170
Unemployment	--	36.7%	56.2%	--
Sesotho speaking residents		47%	53%	76%
Education	--	21%	3.8%	--
Services	--	91%	90%	--

2.2.1. Sedibeng District Municipality

Mpumalanga, the Free State, and North-West surround the Sedibeng DM. The Sedibeng DM is divided into three Local Municipalities (LM), including (i) Midvaal LM, (ii) Lesedi LM, and iii) Emfuleni LM (Emfuleni LM, 2023).

The Sedibeng DM has the second largest population size in the VTAPA region after the City of Johannesburg. The district's population is approximately one million (DEA, 2019).Figure 2.1 shows the annual growth rate for Sedibeng DM, which increased to 1.7% in 2023 from 1.2% in 2021. The decrease in population in 2021 was due to COVID-19-related deaths. The growth rate is the highest amongst the population group over the age of 65. The leading cause of death in the Sedibeng districts in males between 15 and 24 and females between 35 and 64 are lower respiratory diseases such as Tuberculosis (Elston et al., 2017). Therefore, Sedibeng residents are vulnerable to health problems related to poor air quality.

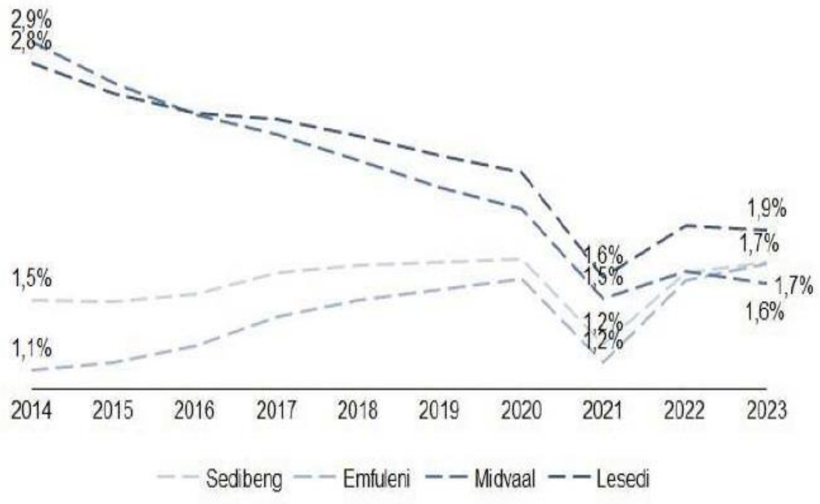

Figure 2.1 The annual population growth, in percentage, of the Sedibeng DM and the LM within the districts between 2014 and 2023 (Sedibeng DM, 2023).

The Sedibeng district has diverse land uses, including industrial, mining, and agriculture. According to Table 2.2, the annual growth of the different economic sectors in the district varies. The manufacturing sector significantly contributes to the total Gross Value Added (GVA), accounting for 23.4%. However, this reliance on manufacturing makes the district vulnerable to electricity supply and domestic demand issues (Elston et al., 2017). While the other sectors experienced an increase in annual growth, manufacturing decreased by 1%. Unfortunately, unemployment in the Sedibeng district has increased due to a decline in the steel industry (Elston et al., 2017).

Table 2.2 Annual growth, in percentage, of the economic sectors in Sedibeng DM (Elston et al., 2017).

Sector	**2008**	**2013**	**2018**	**Average Annual**
Agriculture	0.38	0.39	0.41	0.82
Mining	0.62	0.67	0.62	0.04
Manufacturing	11.38	10.58	10.33	-0.97
Electricity	1.51	1.75	1.71	1.23
Construction	1.16	1.48	1.57	3.06
Trade	3.75	4.46	4.79	2.50
Transport	2.53	2.83	3.07	1.95
Finance	7.81	8.56	9.35	1.81
Community Services	7.07	8.41	8.90	2.33
Total Industries	**36.21**	**39.12**	**40.75**	**1.19**

This ultimately resulted in the unemployment rate reaching over 35% (Emfuleni LM, 2023). There is a positive correlation between the unemployment rate and education level in Sedibeng. Approximately 42% of the district population is functionally illiterate, with 21% having no schooling (Emfuleni LM, 2023). Only 20% of the district's population graduated with a matric, and 9% had an undergraduate qualification.

The Sedibeng DM Integrated Development Plan (IDP) included summary comments addressed from community/stakeholder inputs. One of these comments addresses illegal dumping in the DM, especially in the Vereeniging Region (Emfuleni LM, 2023). There is reported to be a decrease in refuse removal in Sedibeng over the years, with 25800 households not receiving waste collection services. Figure 2.2 indicates the decrease in waste collection in the district (Elston et al., 2017).

Figure 2.2 The annual refuse removal between 2008 and 2018, in the Sedibeng DM (Elston et al., 2017).

2.2.2. Emfuleni Local Municipality

The Emfuleni Local Municipality (LM) is situated on the border between the Free State and North-West provinces, with the Vaal River dividing the two provinces. The Emfuleni LM is located on the west side of the Sedibeng DM. The municipality has a population of nearly one million, with 297910 households residing within the LM. The primary sectors in Emfuleni are agriculture and mining (Municipalities of South Africa, 2023). The unemployment rate in the LM is estimated to be more than 55% of the population, with 3.8% having no formal education (Municipalities of South Africa, 2023). Emfuleni has a high black population residing in townships (Elston et al., 2017). Waste collection services are estimated to be accessible only to 90% of Emfuleni's population. The township Sharpeville, situated between Vereeniging and Vanderbijlpark, is one of the significant townships in the LM.

2.2.3. Sharpeville Community

Sharpeville, a town that covers a total area of 5 km^2 and has around 40,000 residents (Statistics South Africa, 2020). The population density is ~7,536 people/km^2, with 12,170 households with an average of 3 people per household. The majority of the community is between 20 and 29 years old (Statistics South Africa, 2020). Sesotho is the most commonly spoken language in the area, accounting for 76% of the population, followed by Xhosa which is spoken by 7%.

Sharpeville was chosen due to the increased failure of WMS, and it resides in the largest priority area in South Africa. Figure 2.3 illustrates the VTAPA region, Emfuleni Municipality and Sharpeville in South Africa. Sharpeville is in the Vaal triangle, which is declared an air shed priority area. The Vaal

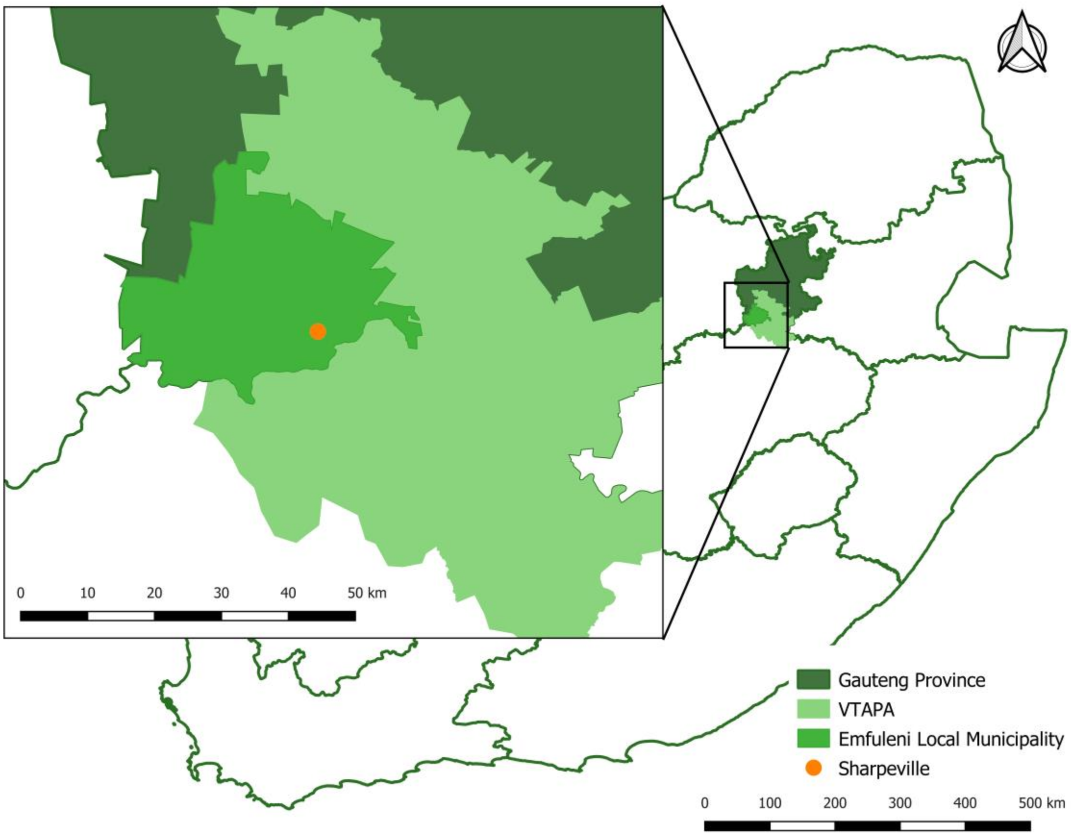

Figure 2.3 The VTAPA region and all the associated municipalities and study area in the Gauteng Province.

2.2.4. State of ambient air quality

There are thirteen (13) fixed AQMS in VTAPA, where six (6) are managed by the national government, namely (i) Diepkloof, (ii) Kliprivier, (iii) Sebokeng, (iv) Sharpeville, (v) Three Rivers and (vi) Zamdela. Two belong to the Sedibeng DM (Meyerton and Vanderbijlpark), and three are owned by Industries, namely Sasol, Rand Water and Eskom. Figure 2.4 illustrates the location of government and private AMQS in VTAPA.

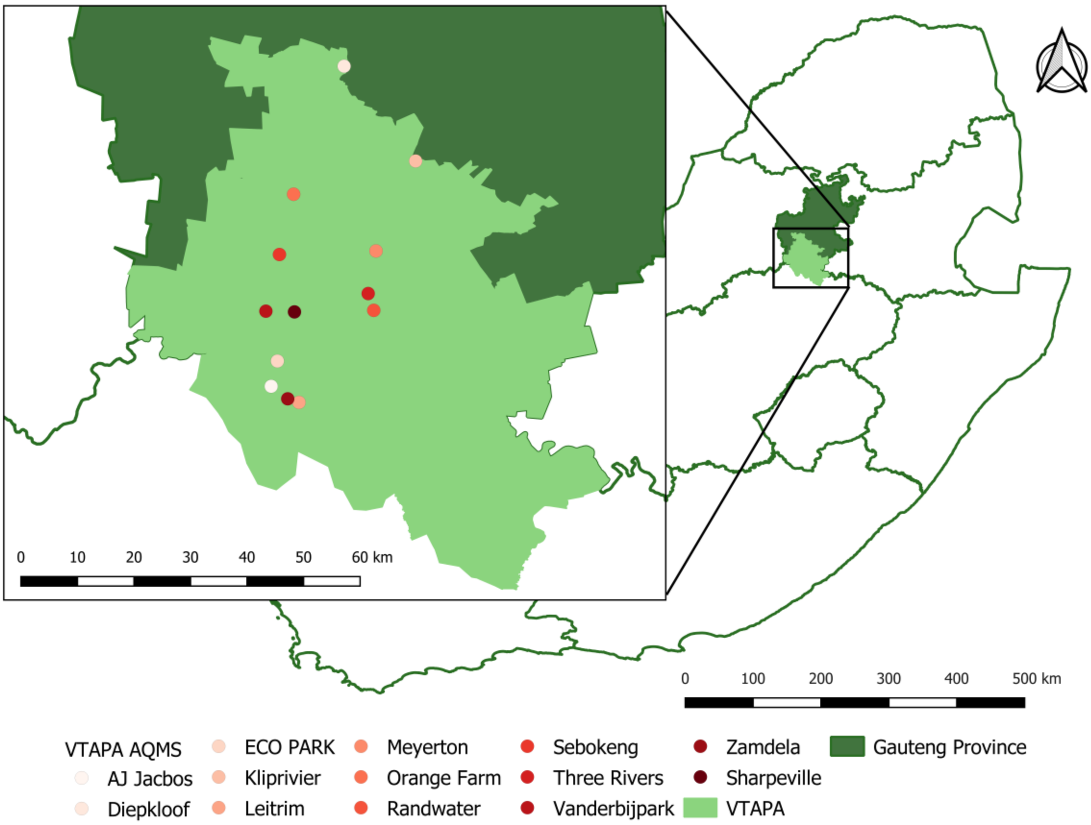

Figure 2.4 AQMS in the VTAPA region is managed by the government and the private sector.

The annual concentration of $PM_{2.5}$ exceeded the National Ambient Air Quality Standards (NAAQS) multiple times in Sharpeville between 2008 and 2010, 2012 and 2017, as well as in 2018 and 2022 (DEFF, 2020). Figure 2.5 depicts the $PM_{2.5}$ exceedances within the VTAPA region, encompassing Sharpeville. According to the 2018 State of Air Quality report, $PM_{2.5}$ exceeded the NAAQS for most of the decade, as shown in Figure 2.5. The study focuses on 2017 when waste composition and survey data were collected. Sharpeville had 96 $PM_{2.5}$ exceedances in 2017, most of which occurred during the winter months, as per the December VTAPA monthly report (SAWS, 2017).

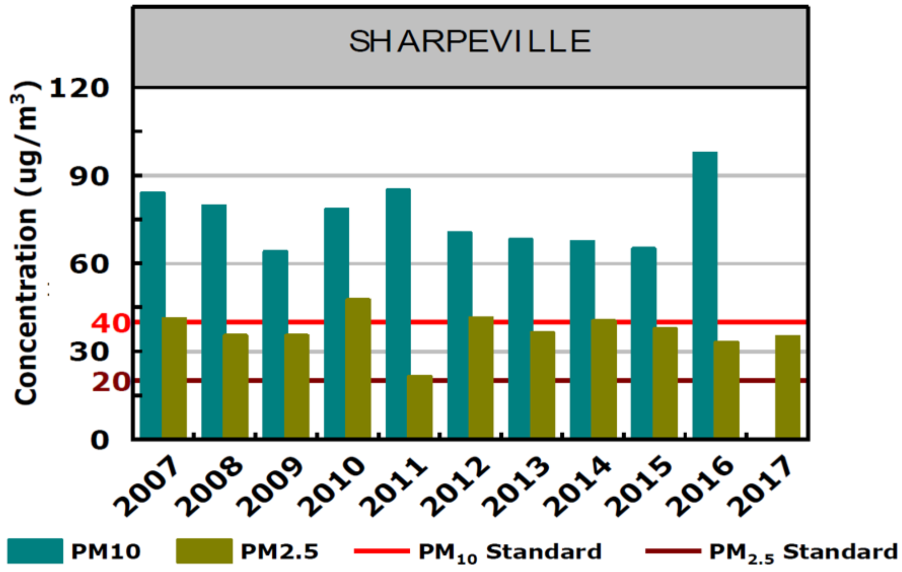

Figure 2.5 $PM_{2.5}$ and PM_{10} exceedances in Sharpeville, 2007 and 2017 (DEA, 2019a).

2.2.4.1. Sources of Emissions

An emission study in the Gauteng province shows that the highest emission sources are from biomass and informal settlements. In the townships of the Gauteng area, ambient concentrations of PM are higher by 78% in industrial areas and 51% in urban areas (Hersey *et al.*, 2015).

The VTAPA Air Quality Management Plan (AQMP) acknowledges waste burning as a source of air pollution. However, it fails to consider the potential contribution of open waste burning to the air pollution in the area (DEA, 2009a). The VTAPA AQMP did not try to measure waste burning emissions in the baseline because there is limited census data and information on the source and a lack of waste collection services (DEA, 2009a). In the second draft of the VTAPA baseline report (2019a), waste burning was acknowledged as a contributing source. The VTAPA assessed the Emfuleni LM and six other municipalities nationwide. The report quantifies open waste burning sources within these assessed LM. The data used to measure open waste burning emissions for $PM_{2.5}$ were based on literature (DEA, 2019a).

A source apportionment study in the VTAPA region shows that $PM_{2.5}$ from open waste burning is one of the lowest source contributors to ambient air quality (Muyemeki et al., 2021). However, waste burning was a contributing source of $PM_{2.5}$ emissions in the summer of Sharpeville. Figure

2.6 shows the results of the summer source apportionment for four VTAPA sites: Zamdela, Kliprivier, Sebokeng, and Sharpeville (Muyemeki et al., 2021).

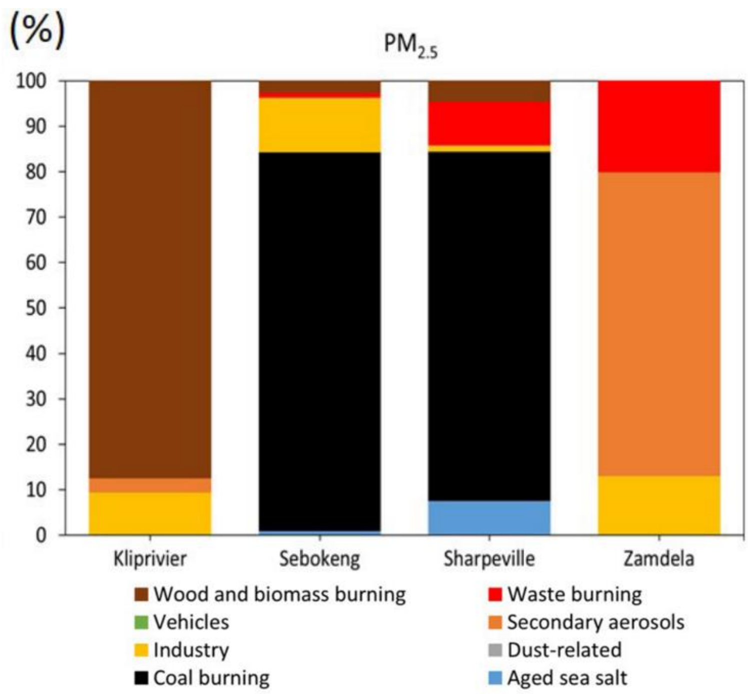

Figure 2.6 Illustration of the $PM_{2.5}$ contribution of different sources in the VTAPA (Muyemeki et al., 2021).

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This chapter focused on the challenges Sharpeville faces and the wider VTAPA located in Gauteng province. The primary challenges are related to air quality and service delivery. Despite its priority status, VTAPA still struggles to meet air quality standards due to various human activities. Socioeconomic factors like high unemployment and limited access to education worsen environmental concerns in Sharpeville. The Sedibeng DM has made limited progress in addressing these challenges. To ensure a sustainable future for Sharpeville and similar communities in the VTAPA, it is essential to develop comprehensive strategies that integrate environmental management, socio-economic development, and community engagement.

CHAPTER 3: WASTE BURNING $PM_{2.5}$ EMISSIONS CALCULATIONS AND UNCERTAINTIES

ARTICLE MANUSCRIPT I

Research Objective I: Calculate the emissions of $PM_{2.5}$ resulting from informal waste burning in Sharpeville using available waste composition data and emissions factors.

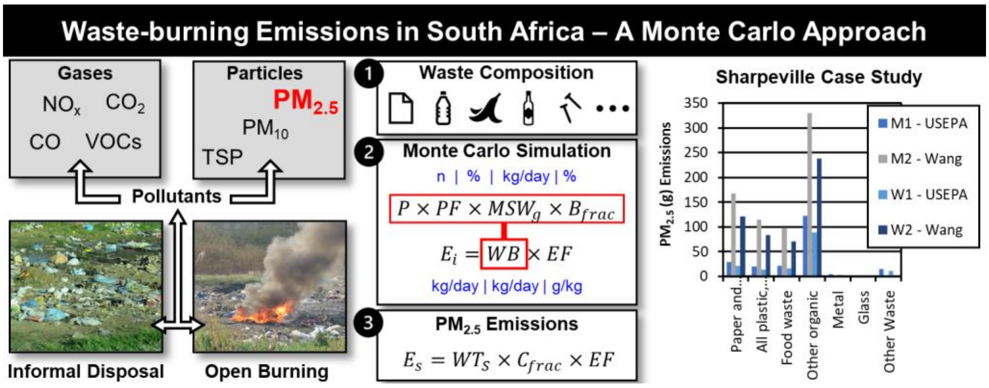
Research Objective II: Utilise a Monte Carlo simulation distribution model to estimate the uncertainties associated with the $PM_{2.5}$ emissions from informal waste burning in Sharpeville.

Abstract

Municipal waste removal services are either lacking or severely constrained in many of the dense, low-income settlements in South Africa. Many reports focus on waste management issues (such as the Global Waste Management Outlook, African Waste Management Outlook, South African State of Waste Report, and National Waste Management Strategy) and report that waste ends up being informally burned due to inappropriate/insufficient waste collection services. The geographic extent of waste burning, the waste composition, and the volumes involved are also poorly understood. Unregulated open waste burning is acknowledged for emitting airborne pollution such as polycyclic aromatic hydrocarbons, criteria pollutants namely, carbon monoxide, nitrogen oxide, volatile organic compounds, and particular matter (PM). The paper focuses on $PM_{2.5}$ due to its link to health-related issues such as lung cancer and asthma. This paper aimed to quantify $PM_{2.5}$ emissions from open informal waste burning through a Monte Carlo approach and waste burning calculation. A Monte Carlo simulation refined the uncertainties associated with waste burning emissions since a lack of data and information creates limits for waste burning calculations. Identified sites were observed with active/historical burning, where s total of 133.2kg of waste was collected for the waste characterisations in Sharpeville, which was used for waste burning calculations. The calculated waste burned from the Monte Carlo simulation ranges between 380 and 2300 kg/day for Sharpeville. The total emissions range between 1000 and 6000 g/day. The annual emissions would exceed 20 tonnes for $PM_{2.5}$. The United States Environmental Protection Agency (US EPA) combustible percentage indicated the amount of collected waste burned. This could contribute between 155 and 711 g of $PM_{2.5}$, assuming the collected waste

burned. The different methods used to estimate reliable waste burning emissions should be explored in South Africa as this can help governance address the waste management problems.

Graphical Abstract



Keywords

Domestic solid waste, Municipal solid waste, Waste burning, Air pollution, Monte Carlo, $PM_{2.5}$

3.1. Introduction

Rapid population growth and industrialisation, community awareness, and waste generation are crucial factors in waste management (Ramadan et al., 2022). Other aspects that are focused on in this paper are informal disposal and waste collection services. Global waste generation rates ranged from 1.3-2.4 billion tonnes a year between 2007-2019, with the generation rate increasing to 4,54 billion tonnes by 2050 (Maalouf & Mavropoulos, 2023). Inefficient WMS are a global environmental problem, especially in developing countries (Ferronato & Torretta, 2019).

According to the Africa Waste Management Outlook (UNEP, 2018), informal dumping of waste, with associated open burning is common in Africa. The report emphasises that the drivers for waste dumping and associated burning include the absence or infrequency of waste collection services, a lack of regulatory enforcement, and limited awareness of other disposal methods (UNEP, 2018).

In the foreword of the 2019 General Household Survey (Statistics South Africa, 2020), the Statistician-General Risenga Maluleke remarked: “It is striking that the percentage of households whose solid waste was removed weekly or less often declined from 66,4% in 2018 to 61,5% in 2019, the lowest this figure has been for more than a decade”. The national decline in access to solid waste services is even more striking when compared to the gradual improvements in living standards evidenced in the same report (e.g., increased access to clean water, sanitation, and electricity) (Statistics South Africa, 2020).

In 2019, it was estimated that one-third of the municipal solid waste (MSW) generated was disposed of uncontrolled (illegally dumped or informally disposed of) (Maalouf & Mavropoulos, 2023). The SAWS Report (DEA, 2018) highlights the contribution of poor waste service delivery to the uncontrolled dumping and burning of waste. Further, the report acknowledges the potential negative impacts of poor waste management practices on air quality. The 2020 National Waste Management Strategy prioritises the reduction of illegal dumping and associated waste burning as a focus area under Pillar 3, focusing on compliance, enforcement, and awareness (DEFF, 2020).

Although a common occurrence, there is a general lack of information on illegal/informal disposal in open spaces and waste burning in townships. Although there are a few scattered references, with international publications on domestic waste burning in China (Cheng et al., 2020), Mexico (Reyna-Bensusan et al., 2018), Korea (Park et al., 2013), and African countries (Cogut, 2016), there is a lack of research and scientific publications on this topic, specifically for South Africa. There is a study conducted and published in 2023 on waste burning emissions in a South African township (Zamdela) by Wang et al. (2023). There is a few unpublished research that characterised waste composition (Rabaji, 2019a), waste burning in townships (Bosman, 2018; Chidhindi, 2022).

Waste burning emissions calculations use waste characterisation; thus, obtaining data on the waste composition is critical (Gidarakos et al., 2006; McCauley-Bell et al., 1997). There is limited information available for open waste burning emissions in South Africa. The available literature focused more on burning emissions from incinerators in South Africa (Friedrich & Trois, 2011, 2016).

Many studies quantify waste types and estimate the waste composition globally and in developing countries such as Africa (Al-Khatib et al., 2010; Bernache-Pérez et al., 2001; Dahlén & Lagerkvist, 2008; Miezah et al., 2015; Ogwueleka, 2009; Sharma et al., 2019; Zhang et al., 2011), and a few studies (Das et al., 2018; Nagpure et al., 2015; Wiedinmyer et al., 2014) have attempted to estimate the impact that waste burning has on air quality.

The burning of disposed municipal solid waste (MSW) emits a substantial number of harmful substances in the environment (Guttikunda et al., 2013). These harmful substances include polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins (PCDDs), and other criteria pollutants such as volatile organic compounds (VOCs), Nitrogen Oxides (NOx), Carbon Monoxide (CO) and particular matter (PM) (Carriero et al., 2018; Rabaji, 2019a; Ramadan, Rachman, Ikhlas, et al., 2022; Wiedinmyer et al., 2014; Zhang et al., 2011). The waste composition and variability of waste type create the need for emission inventories and reliable data sets to determine the contribution of waste burning in developing countries (Nagpure et al., 2015; Zhang et al., 2011).

$PM_{2.5}$ from open waste burning contributed approximately 29% of the global anthropogenic $PM_{2.5}$ emissions (Wiedinmyer et al., 2014). $PM_{2.5}$ refers to fine particulate matter that directly impacts human health as the particle size can penetrate the lungs, leading to respiratory diseases such as asthma and lung cancer (Kampa & Castanas, 2008; McDonnell et al., 2016). This makes it essential to understand the source and effects of $PM_{2.5}$ from waste burning to ultimately develop mitigation strategies and minimise the $PM_{2.5}$ concentration and exposure.

This paper aims to quantify $PM_{2.5}$ emissions from open informal waste burning in a low-income settlement and attempt to address uncertainties through a Monte Carlo simulation, due to a lack of waste burning data. This paper also used waste composition data to estimate $PM_{2.5}$ emissions from identified sites in Sharpeville.

Sharpeville is considered a densely populated urban area. The low-income settlement is in Emfuleni Local Municipality between the towns of Vereeniging and Vanderbijlpark (Sedibeng DM, 2023).

According to Muyemeki et al. (2021), waste burning contributes to Sharpeville's $PM_{2.5}$ concentrations. The $PM_{2.5}$ concentrations in the VTAPA area are high in the central part, with concentrations above the national standard (Muyemeki et al., 2022). The Eskom Air Quality Offset Implementation Plan emphasises that waste burning in Sharpeville is an important local source of emissions (Matimolane, 2021). During a Community Source Survey in 2017 (NOVA, 2018a), participants were asked to identify sources of air pollution. Notably, the dumping and burning of waste ranked as the second-largest source of air pollution, following dust.

The VTAPA region is the first and largest priority area in South Africa with waste burning being one of the main contributing sources, waste burning lacks emissions inventories and mitigation strategies to minimise these emissions (IPCC, 2006). Wang et al. (2023) did introduce emission factors for some of the categories but not for non-combustible such as metal and glass. Thus, limited data is available for priority areas as many uncertainties arise with the lack of data (IPCC, 2006). The Air quality plan proposed compiling an emission inventory of waste-burning sources (IPCC, 2006).

There are approaches and models available for quantifying waste burning, such as system dynamics models, that can be used to understand waste burning over time (Coyle, 1997). The CFD (Computational Fluid Dynamics) can address combustion from waste burning using chemical reactions (Frank & Castaldi, 2014).

The Monte Carlo is a statistical tool to simulate a real-life system through a mathematical model, which repeats randomly sampled input to estimate the probability of the outcome (Holnicki & Nahorski, 2015). The simulation is a computer-based technique where the output is not an exact value but a range of values distributed (Ramírez-Soriano et al., 2008). The Monte Carlo approach is appropriate due to its ability to handle uncertainty, quantify risk, account for variability, and address data gaps and limitations (IPCC, 2006; McMurray et al., 2017). The Monte Carlo also allows for multiple model integration to provide a more usable representation of waste burning (McMurray et al., 2017). The Intergovernmental Panel on Climate Change (IPCC, 2006) suggests a Monte Carlo approach as a method to combine activity data and emission factor uncertainty from different emission sources such as open waste burning (IPCC, 2006). Some studies used the Monte Carlo simulation model to address the uncertainty of other air pollution sources, such as domestic fuel burning in South Africa; however, this has not been done for waste burning (Nkosi, 2018). The data available to estimate the waste burning emissions is accessed from available government census and research institutions that will be discussed.

It is crucial to acknowledge and address the uncertainties through quantification (Frey, 1998). This can improve data inputs for models (Frey & Zhao, 2004). These outputs can be used in air quality modelling to establish mitigation and strategies to reduce waste-burning emissions in low-income settlements (Cuvelier et al., 2007). The paper focuses on quantifying waste-burning emission calculations through a Monte Carlo simulation to address uncertainties related to data availability in South Africa.

3.2. Material and methods

3.2.1. Study area

The study area for this paper focuses on Sharpeville, a low-income settlement in the Gauteng Province of South Africa. The township is located in the Emfuleni Local Municipality. The population of the settlement is approximately 35000 people. The area lacked WMS and has evidence of waste burning (Rabaji, 2019a). Figure 3.1 shows the location of Sharpeville in the Gauteng province, with all the identified waste disposal sites.

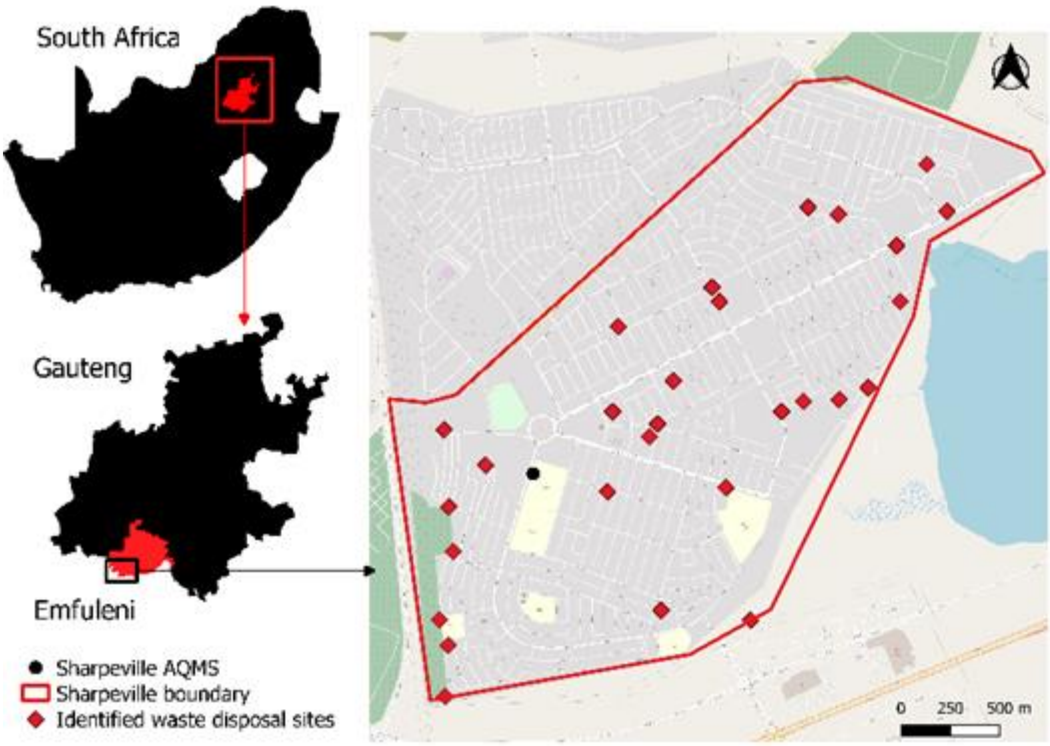


Figure 3.1 A map of all the identified waste disposal sites in Sharpeville.

3.2.2. Survey data

This was a secondary analysis of data collected by the NOVA Institute. The NOVA Institute is an NGO intending to improve resident's quality of life in South Africa (Rabaji, 2019). In 2017, the NOVA Institute conducted a general household survey to collect data about demographics, subjective well-being, education, living conditions, and access to solid waste collection services. Waste management-related questions focused on waste collection in the area and the number of the populations that burnt their solid waste. Out of the entire population of households in Sharpeville, a sample of 225 households was selected for the waste related question of the study. The survey was conducted from 22 June to 28 July 2017. A full account of how the survey was conducted is provided in a report (NOVA, 2018b).

The general survey revealed that 3% of the participating community members did not have access to waste collection services, and household waste was collected from outside their residences. In

Sharpeville, 97% of the responding households benefit from waste collection services. Among them, 29% face occasional service interruptions, 42% experience monthly service failures, and 29% have consistent waste collection.

This data emphasises the importance of addressing service reliability factors and extending services to the remaining 3% of households without access, ensuring a cleaner environment for the community. Table 3.1 summarises the survey results regarding waste collection services in Sharpeville during the 2017 survey period.

Table 3.1 Summary of waste collection services failure in Sharpeville during 2017.

Occurrences	**Percentage (%)**
>1 per month	29%
1 per month	42%
Rare waste collection failures	29%

The NOVA Institute conducted a detailed energy survey along with the general household survey that gathered information on Sharpeville's domestic energy usage patterns. Information was also collected on any factors that influenced emissions. The questionnaire contains 24 sections and 253 questions (NOVA, 2017). Not all the answered questions were used in this study.

The survey found 72 instances of waste burning activities in public areas and four burning activities in yards, potentially leading to 928 annual incidents, averaging 3 per day. This might be underestimated as they only surveyed public spaces and recorded observed incidents.

Other factors contributing to waste burning include households lacking bins and security concerns. The community often burns waste to decrease the waste volume in the surrounding area.

3.2.3. Waste characterisation and composition

In 2017, a study developed by North-west University (NWU) was conducted by the NOVA Institute to identify informal waste disposal sites in Sharpeville, revealing the presence of 33 such sites. This data was used in secondary data analysis. A total of 16 sites bore evidence of either historical or active waste burning at the time of the research. Historical waste burning refers to waste disposal sites that show evidence of waste burning (black spots and ash) but the site is not actively burning during the observation period. Actively burning refers to a waste disposal site that undergo’s burning during the site observation.

The research by Rabaji (2019) identified a total of 29 sites that were characterised in terms of their geographic location, size, waste-related activities (i.e. dumping only, dumping and sorting), the extent of the waste burning activities, and visual estimations of the waste composition. 4 of the sites that were identified by NOVA in 2017 were no longer used as disposal sites/cleaned up by the time Rabaji (2019) did the follow-up research.

The largest of the identified sites was then selected for an in-depth waste composition analysis using the ASTM method (ASTM D5231 – 92; 2003) to determine the composition of unprocessed municipal solid waste. Composite samples were gathered from the dumping area to assess the relative composition by weight, as provided by Rabaji. The analysis conducted by Rabaji (2019) was constructed on manual sorting over a grid where the waste site has been identified (Maystre & Viret, 1995; Rabaji, 2019a). Waste was collected by dividing the dumping site into a grid of approximately 3m x 3m quadrants and sampling waste from random quadrants. Only one site was characterised to represent the entire area (Dahlén & Lagerkvist, 2008).

Seven distinct samples were collected from the chosen waste site. The waste sample was categorised into the following groups: ‘paper and cardboard’, ‘dense and light plastics’, ‘food waste’, ‘other organics’ (not food), ‘metals’, ‘glass’, and ‘other waste’. The category of ‘other waste’ includes rock, sand, dirt, plasterboard, cement, rubble, bones, nappies, and other miscellaneous waste. The categorisation was undertaken with the recognition that various materials, when subjected to combustion, produce varying levels of PM emissions (Krecl et al., 2021; Lemieux, 1998; Wang et al., 2023; Wevers et al., 2004).

3.2.3.1. Waste Composition

At the chosen Sharpeville site, Rabaji (2019) collected approximately 132,9 kg of waste. Table 3.2. shows the total weight sampled, the average waste composition, and the standard deviation.

Based on the research on waste composition characterisation conducted by Rabaji, the bulk of the waste was categorised as ‘Other organics’ (39.4 kg), followed closely by ‘Other waste’ (35.2 kg).

Table 3.2 Composition of Waste at Sharpeville Site 16: Average Weight (kg) and Percentage (%).

Waste Type	Waste Sampled (kg)	Ave. Waste Sampled (kg)	± SD
Paper and cardboard	25.3 (19%)	3.6	1.30
All plastic, polystyrene	12.3 (9%)	1.8	0.65
Food waste	10.1 (7%)	1.4	1.20
Other organic	39.4 (29%)	5.6	4.14
Metal & glass	10.3 (8%)	1.5	0.91
Other waste	35.8 (27%)	5.1.	3.94
Total	133.2	19	--

‘Glass’ and ‘metal’ were the smallest categories, each weighing less than 6 kg, with metal consistently the smallest at just 0.8 kg across all sites. Categories like ‘other organics’ and ‘paper and cardboard’ were present in all the samples collected by Rabaji (2019).

3.2.4. Estimating atmospheric emission from waste burning using a Monte Carlo Approach

Various emissions can be calculated from waste burning, such as Black Carbon (BC), CO, CO2, SO2, NOx, and PM (Das et al., 2018). The method calculating the estimated $PM_{2.5}$ emission from informal waste burning was adapted from the Intergovernmental Panel on Climate Change (IPCC) guidelines for the national Greenhouse Gas (GHG) inventories (IPCC, 2006; Wiedinmyer et al., 2014). The estimated emission (Ei) is the product of the total waste burned (WB) and the relevant emission factor (EF) for the specific pollutant. The waste burned is calculated using different statistical data and literature.

$$E_i = WB \times EF$$

Equation 3.1 Estimated Emission

(Ei) refers to the estimated emissions (Equation 3.1) from the Sharpeville area, calculated by the activity rate to simulate burning waste. The emission factor (EF) considered in this study pertains to $PM_{2.5}$. The data inputs for this analysis were sourced from various literature references and integrated into the Monte Carlo simulation. The activity rate, a crucial parameter, represents the estimated quantity of waste burned (WB) and is calculated using the following Equation 3.2:

$$WB = P \times PF \times MWS_g \times B_{frac}$$

Equation 3.2 Waste Burned

Within the framework of the Monte Carlo simulation, the variable with the most significant level of uncertainty in the waste burning calculation was characterised by a range of values employed in the simulation. On the other hand, certain values, such as the population, even with uncertainty remained constant, as the population of Sharpeville could not have fallen below the figures reported in the 2011 census data.

The population (P) of Sharpeville is determined using data from the 2011 census. PF represents the portion of the Sharpeville population that engages in waste burning (Wiedinmyer et al., 2014). The estimation of PF was derived from an Eskom household energy survey, expressed in percentages (Das et al., 2018; NOVA, 2018b). MSWg is the total waste generated in Sharpeville (Rodseth et al., 2020). Bfrac signifies the percentage fraction of waste that is anticipated to be burned at a dumping site (IPCC, 2006; Wiedinmyer et al., 2014).

The fraction of the waste burned (Bfrac) was initially established at around 60% (IPCC, 2006; Wiedinmyer et al., 2014). However, while the IPCC provided a specific percentage, uncertainties existed due to variations in waste composition in South Africa (Ayeleru et al., 2018). To ensure a more robust and reliable outcome, the percentage of burned waste was given a range from 20% to 97%. To compute the concentration for each waste type, the combustible percentage for each waste category was obtained from the US EPA (2018) combustion with energy recovery results.

The Monte Carlo simulation incorporated various parameters related to waste burning, including the population engaging in waste burning, the quantity of waste generated, the fraction of waste that undergoes combustion, and the emissions factor. Diverse ranges of existing data associated with waste burning were employed to account for uncertainties. The input data for the Monte Carlo simulation comprised information collected from surveys and existing datasets.

The median values derived from the 10,000 iterations within the Monte Carlo simulation served as a key component in calculating the emission rate (Tan et al., 2014). These results hold significance for the current calculations and their applicability in other computational and air dispersion models. The subsequent section will comprehensively explain the range values incorporated into the Monte Carlo simulations.

3.2.5. Estimating emission from the collected waste characterised

The waste categories in Sharpeville play a crucial role in calculating the PM emissions from the sampled waste. Equation 3.3 provides an estimate of emissions when a portion of waste is collected at the dumping site:

$$E_{sample} = WT_{sample} \times C_{frac} \times EF$$

Equation 3.3 Estimated emissions based on waste collected

In this equation, Esample refers to the total estimated $PM_{2.5}$ emissions that would be released if the collected waste sample were to burn hypothetically. WTsample denotes the specific waste samples gathered in Sharpeville for the various waste types, and the cumulative waste sample was used to estimate the $PM_{2.5}$ emissions. Cfrac refers to the combustible percentage of each waste type. EF refers to the emission factor for $PM_{2.5}$. The total waste mass for the seven samples across different categories was combined to calculate this. For this estimation, the total waste sample was used in conjunction with a combustible percentage (Cfrac) and emission factor (EF) specifically tailored for the $PM_{2.5}$ particle gas (U.S. EPA, 1995). This approach facilitated the computation of the diverse contributions of waste emission. Therefore, the estimated $PM_{2.5}$ emissions could provide insights into the extent to which waste burning influences air quality in Sharpeville.

3.3. Results and discussion

3.3.1. Waste types and volumes

The waste generation rate is influenced by several factors, such as population growth, socioeconomic class, and climate (Miezah et al., 2015; Ogwueleka, 2009). There is a direct link between the waste generation rate, population growth, and population density, with the Gauteng province having the highest density in South Africa. This increase in population growth can cause strains on the waste management system in South Africa. South Africa generates approximately 2,7 million tonnes of waste each year (Cogut, 2016).

Quantifying and characterising waste are important for waste management strategies. There is a lack of data in developing countries (Karak et al., 2012). The major waste stream in developed countries such as Austria, Belgium, Denmark, France, Germany, and Greece are organic waste, followed by paper and cardboard (Karak et al., 2012). These countries have 100% waste collection services, whereas these developed countries have little waste disposal in open areas (Cogut, 2016).

Developing countries in South Asia generate more waste than developed countries. ‘Organic waste’ dominates the waste sector, followed by the ‘textile’ and ‘other waste’ categories, in some countries, namely, Singapore, Vietnam, Bangladesh, China, and India (Huang et al., 2006; Idris et al., 2004; Karak et al., 2012).

The composition in Africa consists mainly of ‘organic waste’ in countries such as Algeria, Botswana, Egypt, and Ghana (Asase et al., 2009; Miezah et al., 2015) and Mozambique (Couth & Trois, 2010). The efficiency of waste collection services decreased, where 85% of waste in North African countries is still collected (Cogut, 2016). The rest of Africa has the lowest waste collection efficiency, with 46% of waste being collected.

In South Africa, a study indicates that nationwide ‘plastic’ is the dominant waste type, while cities like Soweto had ‘textile and ‘other waste’ as the major waste type (Karak et al., 2012). A study at the Marie Louise Landfill site in Johannesburg, South Africa, found that ‘organic waste’ is the biggest contributor (Ayeleru et al., 2018).

The characterised site was chosen to represent Sharpeville’s waste characterisation. As referred to in Table 3.2, most categories, excluding ‘food waste’, ‘other organic’, and ‘other waste’ are recycled materials. The lowest waste categories were ‘metal’ and ‘glass’. The deficient waste sample can indicate waste pickers targeted these categories (Rabaji, 2019a). While other categories, such as “organic waste” and “other”, were not targeted by waste pickers due to a lack of incentive values. Other categories, such as ‘All plastic, polystyrene’, which were recycled material, had a lower weight. Only 36% of the waste sample at the characterised site can be recycled. Waste streams such as ‘organic waste can be recovered and used as composting (Ogwueleka, 2009).

Categories for other composition studies differ. Some studies included food waste with the organic waste category, while others combined textiles with building materials (Adeleke et al., 2021; Karak et al., 2012). This high amount of organic waste does not represent the diverse types of organic material. The ATSM adaptation excluded food waste from organic waste.

The overall composition of Rabaji (2019) waste characterisation shown in Table 3.2 indicates that ‘other organic’ (29%) and ‘other waste’ (27%) are dominant, with approximately 56% of the waste composition comprised of one or the other. Reflecting on the waste type, organic material dominated the waste profile with a total of 39.4 kg from the sample. Plastic was the third smallest waste fraction of the waste composition and had the third highest percentage of combustibility, indicating that the emissions released could have a high contribution. Waste characterisation showed that ‘other organic’ (29%) and ‘other waste’ (27%) are dominant, with approximately 56% of the waste composition comprised of one or the other.

The Gauteng province exhibits a trend of low glass collection rates similar to that observed in Sharpeville (Oelofse, 2015). Waste composition and categories change significantly with population growth and consumer choices (Palanivel & Sulaiman, 2014). It is important to establish a category system suited to the spatial area. It is important to establish a category system suited to the spatial area.

3.3.2. Number of households that burn waste

On an international level, developing countries have contributed the most to open waste burning. In Mexico, around 92% of rural households reported burning waste, and approximately 65% of the rural population and 10 % of the urban population dispose of their uncollected waste by waste burning (Reyna-Bensusan et al., 2018). A Study done in Thailand reported that 50% of domestic waste is burned (Nagpure et al., 2015).

In Africa, research done in Sudan by Makki et al. (2023) indicated that 28,5% of households have insufficient waste collection services. Approximately 74.5% of the participants were to burn household waste not collected by WMS (Makki et al., 2023).

According to Haywood et al. (2021), in the northern parts of South Africa (Gauteng, Limpopo, North-west, and Mpumalanga), 5161 Households burn waste inside their yard. It was reported that 10% of the households dispose of the waste in the streets of the community. In Gauteng, approximately 3,9% informally dispose of their waste (Haywood et al., 2021). Informal disposal in Sharpeville reported that 29% of domestic waste was not collected. The survey indicates that 6.2% of households burn waste.

During the research campaign, it became evident that the relatively low number of informal structures did not correlate with the significant volume of waste being burned. The waste disposal sites that underwent a composition analysis were situated in power line servitudes, road servitudes, or on the outskirts of the township, near community residences. Many of these sites have been used for several years (Rabaji, 2019).

A noticeable pattern of discipline was observed regarding waste disposal in the community. Residents consistently transported their waste to the nearest dumping site for proper disposal. There are health risks associated with waste burning practices by humans (Makki et al., 2023). Therefore, a lack of waste collection services could result in informal disposal sites. Schedule 5 of the South African Constitution (1996) mandates that municipalities are responsible for regulating waste collection. The lack of enforcement and financial strain creates challenges with WMS. A sustainable solution is required, such as awareness campaigns in the community and cost-effective systems. Households are not necessarily aware of the risks related to waste burning (Cogut, 2016; Haywood et al., 2021; Makki et al., 2023).

3.3.3. Estimated concentration through the Monte Carlo

3.3.3.1. Estimation of waste burned

When calculating emissions, it is crucial to quantify the uncertainty of the estimates (McMurray et al., 2017). The Monte Carlo method was employed to estimate various parameters in waste burning calculations, with the simulations executed using Python programming. There were five different parameters inserted in the simulation. The choices of the parameter's maximum likelihood can lead to varying estimates of uncertainty for a distribution (Frey, 1998).

A total of 10,000 iterations were performed within the Monte Carlo simulation to ensure robust estimates. Table 3.3 presents the described statistics for the variables involved in the simulation. Log-normal and uniform distribution were suited for the available data to estimate the total waste burned (Frey & Zhao, 2004).

Table 3.3 Descriptive statistics of the involved variables for the calculated Waste Burned (WB, kg/day) from the Monte Carlo simulation.

Parameter	P (people)	PF (%)	Bfrac (%)	MSWg (kg/day)	WB (kg/day)
min	35000	6.2	20	0.45	380.16
25%	35000	19.4	53	0.71	3451.11
Media	35000	32.8	60	0.97	5787.37
75%	35000	46.0	67	1.23	8949.41
Max	35000	60.0	97	1.49	23582.38
Mean	35000	32.9	60	0.97	6581.86

Note: P – Population, PF – Population Fraction, Bfrac – Burned Fraction, MSWg – Waste Generation, WB – Waste Burned

The population, a constant variable in the analysis, was generated using a uniform distribution based on the 2011 census data, indicating a population of 35000 residents in Sharpeville. The Population fraction (PF) exhibited a range from 6.2% to 60%, suggesting that the simulation projected ~33% of the population would engage in informal waste burning. The burned fraction (BF) ranged from 20% to 97%, with both the median and mean values at 60%. The waste generation (MSWg) ranged from 0.45kg to 1.49 kg, with a mean of 0.97kg per day. The mean for the population fraction and the waste generation were similar to the median. Regarding the actual waste burned, the mean was 6582 kg per day, ranging from a minimum of 380kg per day to a maximum of 23582 kg per day. However, the median (5787 kg per day) deviated from the mean.

Figure 3.2 illustrates the probability distribution of the waste burned in Sharpeville. The distribution shows a gradual increase in the waste burned, reaching a peak of approximately 5000 kg/day, followed by an exponential decline in waste burned. This pattern suggests the simulation predicts the highest likelihood of waste burned falling within the range of 3000 to 10,000 kg/day.

The values of these five variables created a product of total waste burned; after that, the total waste burned was used as a variable to estimate the $PM_{2.5}$ emissions in Sharpeville. In waste generation, the number of households that burn waste creates uncertainty and variability, and it is important to understand the implications that are associated with simulating environmental issues (Frey, 1998). Failure to consider these consequences generates an unusable representation, which leads to difficulties for policymakers (Frey & Zhao, 2004).

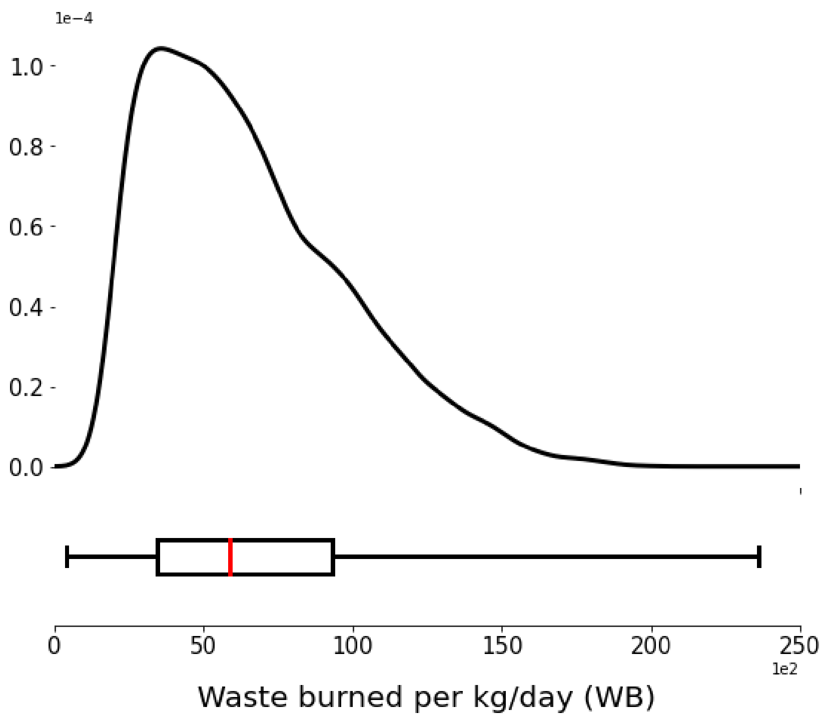


Figure 3.2 A simulation run of the waste burned in kg/day in Sharpeville, South Africa.

3.3.3.2. Estimation of the emission factor and total waste burned

Approximately 10 million tonnes of $PM_{2.5}$ is emitted per year globally. A study showed a direct link between $PM_{2.5}$ exposure and hospital admissions (Cogut, 2016). There were approximately 3.1 million deaths in 2010 due to $PM_{2.5}$ exposures (Cogut, 2016). Thus, there is significance in estimating the potential contribution of $PM_{2.5}$ from waste burning. Table 3.4 provides essential descriptive data for the variables used in the emissions estimation simulation. None of the variables in the table remained constant during the runs, illustrating their dynamic nature.

Table 3.4 Descriptive statistics of the involved variables for the calculated Total Emissions (ET, g/kg) from the Monte Carlo simulation outputs.

Parameter	**WB (kg/day)**	**EF (g/kg)**	**ET (g/day)**
min	380.16	2.30	1318
25%	3451.11	6.00	25882
50%	5787.37	9.57	52181
75%	8949.41	13.33	88110
Max	23582.38	16.99	346224
Mean	6581.86	9.64	64831

Note: WB – Waste Burned; **EF** – Emission Factor; **ET** – Total Emission

The waste burned was determined based on the values in Table 3.4. Emission factor input ranges were established through a literature review, referencing sources such as IPCC (2006), Wiedinmyer et al. (2014), U.S. EPA (1995), Wang et al. (2023), and Park et al. (2013). These sources indicated a minimum input of 2.30 g/kg and a maximum input of 17g/kg for $PM_{2.5}$. The simulation's estimation yielded a mean of 9.64g/kg and a median of 9.57 g/kg, respectively. This outcome is a typical result when employing a uniform distribution. To estimate total emissions, the waste burned was multiplied by a randomised emission factor.

The daily total emissions stemming from waste burned in Sharpeville exhibited a wide range, spanning from 1 318 g/day to 346 224 g/day, with an average of 64 831 g/day per day. When extrapolating these daily emissions to an annual cycle, it becomes evident that the total annual emissions would exceed 20 tonnes. The calculated minimum annual emissions fall below half a tonne (500 $kg.a^{-1}$), while the maximum annual emissions could reach as high as 126 tonnes of $PM_{2.5}$ emissions in Sharpeville's ambient atmosphere. There is a significant difference between the minimum and maximum annual $PM_{2.5}$ concentrations. $PM_{2.5}$ emissions have uncertainty associated with quantifying emissions from waste burning (Wiedinmyer et al., 2014).

Annual cycle, it becomes evident, that the total annual emissions would exceed 20 tonnes. The calculated minimum annual emissions fall below half a tonne (500 $kg.a^{-1}$), while the maximum annual emissions could reach as high as 126 tonnes of $PM_{2.5}$ emissions in Sharpeville's ambient atmosphere. There is a significant difference between the minimum and maximum annual $PM_{2.5}$ concentrations. $PM_{2.5}$ emissions have uncertainty associated with quantifying emissions from waste burning (Wiedinmyer et al., 2014).

Figure 3.3 displays the probability distribution of the total emissions in Sharpeville, using the simulated emission factor and waste burned data. The figure illustrates the estimated total emissions, showing a positive skew with the highest emissions between 2500 g and 5000 g per day. The red line on the box and whiskers plot represents the mean of the distribution. The results reveal that greater waste burning leads to higher $PM_{2.5}$ emissions, emphasising the direct relationship between waste burning and particulate matter emissions in Sharpeville.

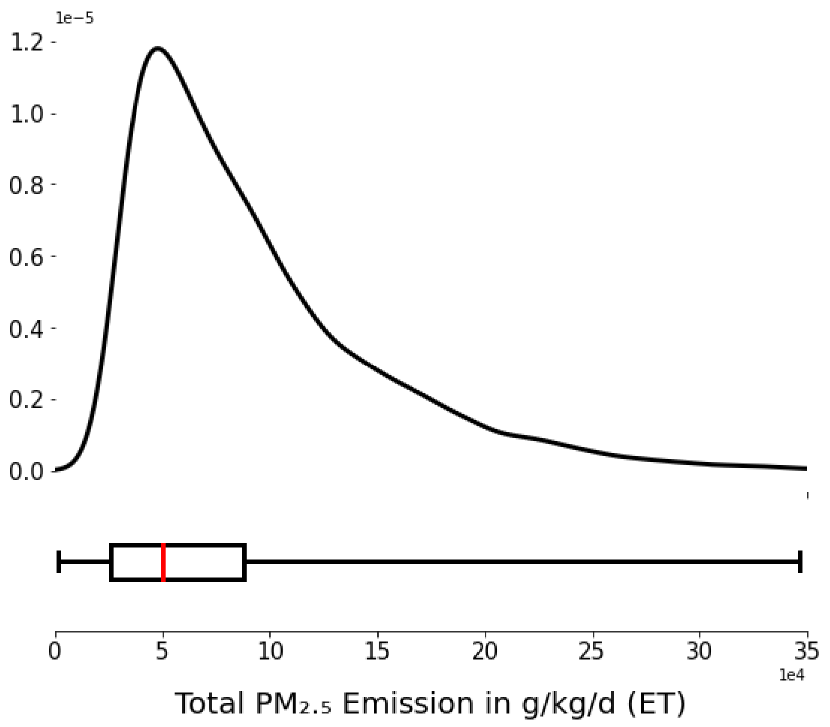


Figure 3.3 Total emission per waste burned with a randomised emission factor.

3.3.4. Estimated concentration for the collected waste by using the Monte Carlo emissions factor

To estimate $PM_{2.5}$ contributions from waste collected in Sharpeville, we employed a sample-based approach using combustibility percentage (Cfrac) data recommended by the US EPA (2018) and Wang et al. (2023). Table 3.5 presents the combustibility percentages (Cfrac) for the waste categories and the corresponding estimated waste burned. The table presents the different emission factors from the simulated results and recent studies conducted in South Africa. Combining yard trimmings, rubber, and wood allowed us to calculate 'other organic ', while 'other wastes' (e.g., building rubble, cement, ashes), 'Glass', and 'Metal' were considered non-combustibles (Cogut, 2016). The emissions factor from Monte Carlo and the emissions factor from Wang et al. (2023) were used to calculate the $PM_{2.5}$ contribution for the waste sample.

The total waste collected served as the basis for calculating the $PM_{2.5}$ emissions. The total calculated waste burned amounted to 22 kg (US EPA Cfrac) and 74 kg (Wang et al. (2023) Cfrac). This signifies that 22 kg (US EPA Cfrac) and 74 kg (Wang et al. (2023) Cfrac) of the 133.2kg collected could undergo combustion. Notably, the 'other organics' category had the highest estimated waste burned due to its high combustibility, while 'food waste' exhibited the lowest. Wang et al. (2023) indicated that food had a 100% combustible percentage due to the high fuel content. The 'glass' category had the smallest sampled size among all categories had the smallest sampled size among all. Wang et al. (2023) did not provide emission factors for 'Metal', Glass, and 'Other waste'. Upon applying a randomised emission factor to the data in Table 3.5, the average $PM_{2.5}$ emissions were estimated at 215 g for the 22 kg of waste burned. $PM_{2.5}$ emissions were estimated at 215 g for the 22 kg of waste burned.

Table 3.5 Estimate emission, in grams, from waste burned using the US EPA (2018) and Wang et al. (2023) combustible percentage of each waste type collected in Sharpeville.

Waste Categories	**Sampled Waste (kg)**	**CF (%)**		**$PM_{2.5}$ emissions from waste burned (g)**			
				Monte Carlo EF		Wang et al. (2023) **EF**	
		US EPA	Wang et al. (2023)	**US EPA**	Wang et al. (2023)	**US EPA**	Wang et al. (2023)
Paper and cardboard	25.3	12.16	69	29.47	168.31	21.31	121.172
All plastic, polystyrene	12.3	16.27	97	19.2	115	13.88	82.72
Food waste	10.1	21.85	100	21.22	97.36	15.34	70.09
Other organic	39.4	32.22	87	121.82	330.46	88.07	237.90
Metal	5.4	8.54	--	4.41	--	3.192	--
Glass	4.9	4.75	--	2.21	--	1.59	--
Other Waste	35.8	4.32	--	14.88	--	10.76	--
Total Weight	**133.2**			**213.21**	**711.13**	**154.142**	**511.882**

Note: CF – Combustible Fraction; **EF** – Emission Factor

The largest $PM_{2.5}$ concentration is caused by 'other organic' excluding food. The $PM_{2.5}$ concentration for organic waste ranges between 88 g to 330 g for the collected waste sample. 'Other organics' were the largest waste type and had the highest combustible fraction according to the US EPA percentages. The results of Wang et al. (2023) had the highest emission factor for the individual waste type, and plastic was the second lowest waste type and had the third highest concentration.

Non-combustibles ('Other waste,' 'Metal,' 'Glass') were the waste types with the lowest amount estimated to be burned. Although the second-largest fraction of the waste composition is 'other waste', it had the lowest combustible percentage from the US EPA (2018). Food waste had the second-largest combustible percentage of all the waste types. This can be a result of the fuel load in the food (Wang et al., 2023). The 'paper and cardboard' were the second-highest amount of the collected samples. All plastics and polystyrene waste combustible is 16.27%, and only 2.0 kg of the plastic waste burns. The emissions factor used a uniform distribution. The uniform distribution was appropriate due to it being used for a product of the total emissions.

The Monte Carlo simulation relies on the assumptions of the inputs. There are many complexities regarding waste burning emissions, and it is difficult to capture these complexities (IPCC, 2006). The quality of the data output is reliant on the data completeness. To have a statistical representation of the waste burned and contributing emissions data availability is limited. To have a statistical representation of the waste burned and contributing emissions, data availability is limited, particularly for less well-studied waste types or regions such as SA.

3.4. Limitation

The following limitations were identified in the study and should be considered. Although the area is well represented, the whole community of Sharpeville was not covered. Only one site was sampled once during July of 2017. The biggest waste site was used for the waste composition study. Multiple waste characterisation could give the seasonal variation of accumulated waste and waste burning in the study area. Characterising more than one site could give a better spatial representation of Sharpeville's waste types. The waste fraction percentage of the samples was dependent on the ratio of other waste fractions (Aitchison, 1982) in the waste stream, which resulted in the waste fraction percentage being closed since the space is limited from 0 to 100% (Edjabou et al., 2017). A manual hanging scale with an accuracy of 0.1 fractions of a kilogram was used to weigh the waste fractions during the waste characterisation.

3.5. Conclusion

Several factors influence waste management, waste generation, and population growth, and challenges arise with inefficient WMS. SA had a decline in access to WMS, with a lack of research on waste burning emissions. South African households engage in waste burning activities, contributing to increasing $PM_{2.5}$ concentrations. Estimating the waste burning emissions clarifies the importance of understanding sources and the contribution of $PM_{2.5}$ from waste burning. This study aimed to quantify $PM_{2.5}$ emissions from open informal waste burning in a low-income settlement and attempted to address the data gaps and uncertainties from waste burning by using a Monte Carlo approach. The simulation provides a range of waste burned in Sharpeville, ranging between 380 kg and 23582 kg per day. The simulation provides a range of waste burned and $PM_{2.5}$ emissions with significant variability. The results can be used for dispersion modelling to assist in policymaking, and solving waste management challenges, which could ultimately create intervention on waste collection services and reduce informal disposal of waste.

CHAPTER 4: MODELLING AMBIENT $PM_{2.5}$ EMISSIONS FROM INFORMAL WASTE BURNING

ARTICLE MANUSCRIPT II

Research Objective III: Model the ambient $PM_{2.5}$ concentrations in Sharpeville originating from informal waste burning using AERMOD.

Abstract

Informal open waste burning in South Africa's Highveld region contributes significantly to $PM_{2.5}$ pollution. However, due to limited data, the Vaal Triangle Airshed Priority Area (VTAPA) Air Quality Management Plan (AQMP) did not quantify emissions from open waste-burning activities in its First Baseline Report. To address this, the AERMOD model was used to simulate the dispersion of hourly and daily $PM_{2.5}$ emissions associated with open waste-burning activities in the densely populated residential community of Sharpeville, situated in the Gauteng Province of South Africa. The model incorporated all identified waste disposal sites, including remediated sites. Multiple AERMOD runs were executed, each with different calculated emission rates ranging from 1.52 $x10^{-5}$ $g.s^{-1}$ to 400 $x10^{-5}$ $g.s^{-1}$. The model predicted hourly $PM_{2.5}$ concentrations ranging from 9 to 2441 $\mu g.m^{-3}$ and daily between 1 and 401 $\mu g.m^{-3}$. Air quality monitoring data was used to establish the contribution waste burning has to each model run. Run 1 underestimated the contribution, while runs 4 and 5 overestimated the hourly contributions. The results highlight the need to quantify the contribution of waste burning to improve decision-making, especially as some of the scenarios predicted $PM_{2.5}$ concentrations that exceed the National Ambient Air Quality Standards for daily $PM_{2.5}$ mass concentrations.

Keywords

AERMOD, air dispersion modelling, waste burning, particulate matter, South Africa, Highveld Region

4.1. Introduction

It is emphasized that on a global scale, MSW will increase from 1.3 billion tons in 2012 to 2.2 billion tons by 2025 (Hoornweg & Bhada-Tata, 2012), while South Africa generates 122 million tons of waste and 12.7 million contributes to MWS (Ngalo & Thondhlana, 2023).

Population growth is one of the main drives for waste generation in any economy (Haywood et al., 2021; Iyamu et al., 2020). The Gauteng province in South Africa has an economic position where migration and urbanisation are encouraged, increasing population growth. Along with population growth and urbanization, there is a rapid growth in waste generation (Abu Qdais, 2007; Guerrero et al., 2013)

This increase in waste generation caused a lack of waste management services in communities, especially in low-income settlements (Muzenda, 2014; Nahman & Godfrey, 2010). It is an environmental issue and can have negative social and economic impacts (Lohri et al., 2014).

This results in communities in low-income settlements finding alternative ways to dispose of their waste that is not collected by waste management services. One of the methods that the community resorts to is the disposal of waste in public spaces or the back of their yard, where these disposal waste sites undergo informal waste burning (Ghanimeh et al., 2019; Sharma et al., 2019; Wilson & Webster, 2018). It is estimated that 29% of Sharpeville households lack efficient waste collection services, with 6.2% of households contributing to open informal burning (NOVA, 2018a).

There are many other drivers for the communities to burn the waste, including odour from the disposal site, or it is unpleasant to look at (Cogut, 2016; Grobler et al., ; Wiedinmyer et al., 2014). Uncontrolled burning is still a solid waste management issue in developing countries (Das et al., 2018; Rabaji, 2019). Approximately 40% to 50% of the waste generated globally undergoes uncontrolled burning as a disposal method (Wiedinmyer et al., 2014).

The burning of waste gives rise to environmental issues such as poor air quality (Krecl et al., 2021). Particulate Matter (PM) contributes to poor air quality globally along with other pollutants such as SO_2, CO, and NO_2 (Boman et al., 2003; Cohen et al., 2005; Zhang & Smith, 2007). $PM_{2.5}$ is particulate matter with a diameter smaller than 2.5 microns (Xing et al., 2016). Particulate matter is one of South Africa's criteria pollutants (NAAQS). In addition, the 2010 global anthropogenic $PM_{2.5}$ emission estimated was 29% of open waste combustion (Wiedinmyer et al., 2014).

Townships in South Africa frequently exceed the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ (Engelbrecht et al., 2001).

According to the Vaal Triangle Air Quality Management Plan, the primary sources include industrial and domestic fuel- and waste burning (DEA, 2009b). The Second draft of the VTAPA Baseline report attempted to quantify waste burning using waste burning calculation, literature, and modelling (DEA, 2019b).

The quantification of $PM_{2.5}$ emissions from informal waste burning is challenging and coincides with high uncertainty. Due to this uncertainty, a limited amount of data is available in South Africa to estimate the contribution of open waste burning to $PM_{2.5}$ mass concentrations in vulnerable communities, such as Sharpeville. Previous studies that have determined emission factors for municipal solid waste burning (Park et al., 2013; Wiedinmyer et al., 2014) have not accounted for specific waste types (Wang et al., 2023), further complicating the situation. Nonetheless, their findings can be leveraged to address uncertainties in model inputs.

To account for the situation's complexity and provide more reliable emission results for different outcomes, a Monte Carlo simulation employing a mathematical method that selects samples randomly is utilized (Tan et al., 2014). This statistical sampling technique is particularly useful when the specific outcome is uncertain beforehand (Raychaudhuri, 2008). The total estimated emissions outputs from the Monte Carlo simulation are used to improve the Emission Rate for more reliable AERMOD results and to reduce uncertainties surrounding informal waste burning, which has contributions to the ambient $PM_{2.5}$ mass concentrations within the Sharpeville community. The use of AERMOD can aid in reducing uncertainties in waste burning emissions from open waste disposal sites, leading to better air quality policies and decision-making.

4.2. Materials and method

4.2.1. AERMOD study design and model configuration

The United States Environmental Protection Agency (US EPA) provides guidelines on the regulatory applicability of air quality dispersion models (U.S. EPA, 2004). The American Meteorological Society/Environmental Protection Agency Regulatory Model (AERMOD) is a Gaussian dispersion model, which is a level 2 regulatory model and one of the preferred dispersions for modelling intra-urban low air pollution (Kesarkar et al., 2007). Gaussian models assume that the meteorological conditions are a steady state with three-dimensional continuous emissions, where under specific atmospheric conditions, the plume distributes in vertical and horizontal directions (Rzeszutek & Szulecka, 2021).

The present study used the AERMOD approach, with the modelling conducted within the AERMOD View modelling system, version 10.2.1 (Lakes Environmental Software, Ontario, Canada). The modelling system has three main components. The meteorological processor, AERMET, handles meteorological and land use data (EPA, 2019a). The terrain processor, AERMAP, processes elevation data (EPA, 2019b). Finally, the Gaussian plume model, AERMOD (version 21112), performs the dispersion calculations. The model requires the integration of various inputs and order of processing, as delineated in Figure 4.1. The modelled $PM_{2.5}$ data in this study were compared to the measured $PM_{2.5}$ data at an ambient air quality monitoring station (AQMS) in the study area to estimate the contribution of informal waste burning to local ambient $PM_{2.5}$ pollution. The modelled $PM_{2.5}$ concentrations are hourly, daily, and annual averages.

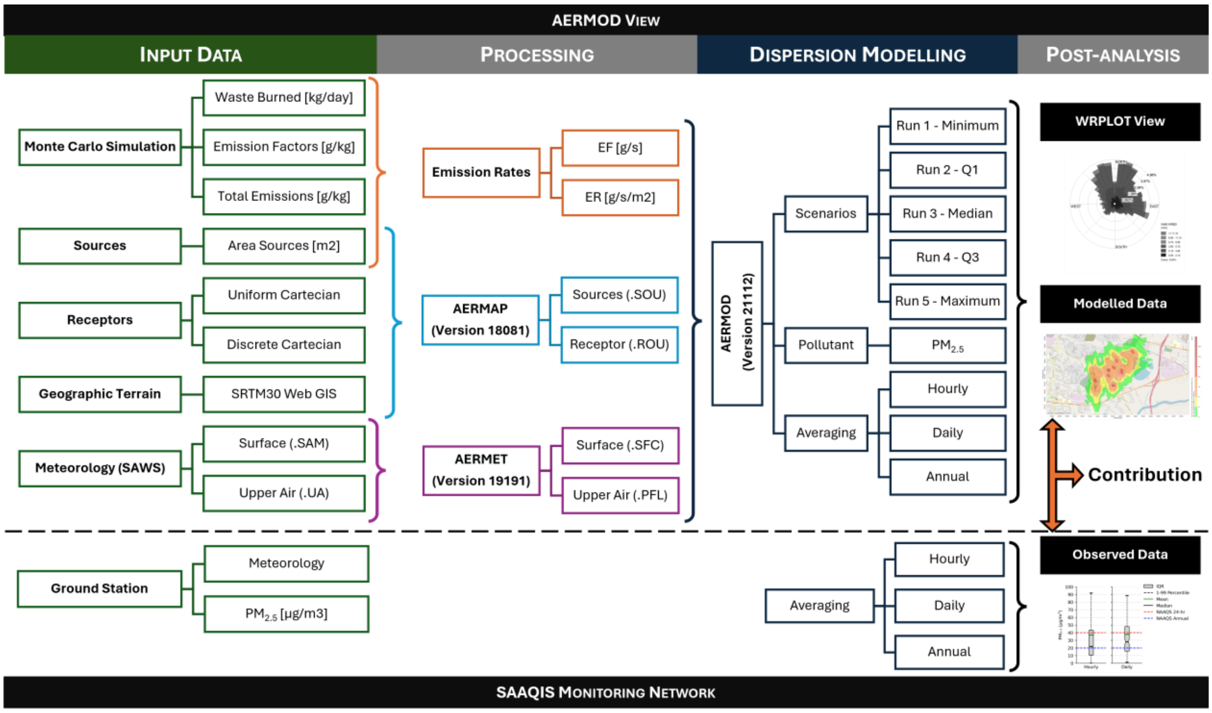


Figure 4.1 Flow diagram indicating the data, data processing, and analysis for modelled and observed data.

4.2.1.1. Study Domain, Receptors and Sources

The study focuses on Sharpeville (Figure 2.2), a low-income residential community in Gauteng Province, located approximately 56 km southwest of Johannesburg, between Vereeniging and

Vanderbijlpark. The settlement is under the Emfuleni Local Municipality's jurisdiction, and its total area is around five km². It has a population of approximately 40,000 people, with a population density of approximately 7536 people per km².

The community is part of the Vaal Triangle Airshed Priority Area (VTAPA), the first of three ambient air quality priority areas in South Africa (DEAT, 2006). The region is impacted by emissions from various sources, including industry, mining, motor vehicles, residential solid fuel combustion, fugitive dust, biomass burning, and open waste burning (Feig et al., 2015; Muyemeki et al., 2021; Scorgie et al., 2003). Due to the various sources and climatic conditions, particulate pollutants frequently exceed the national ambient air quality standards (NAAQS) (Govender & Sivakumar, 2019), especially in low-income residential communities (Hersey et al., 2015).

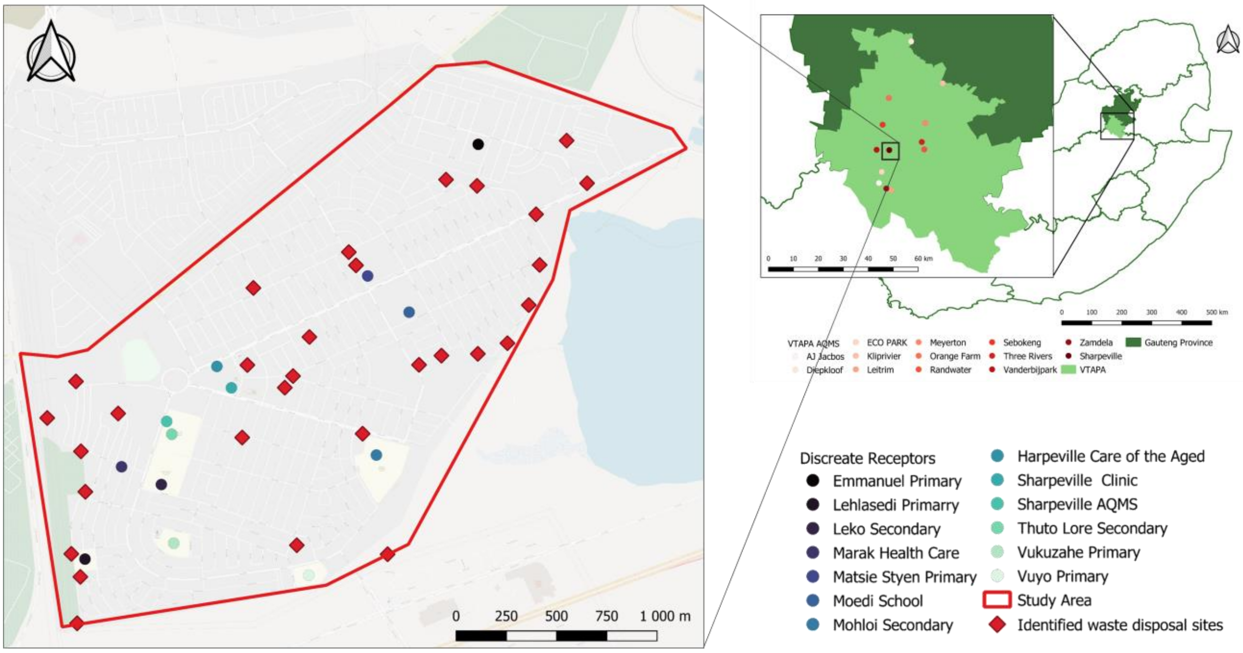


Figure 4.2 The geographic location of Sharpeville indicates the boundary of the community (solid red line), the ambient monitoring station (black circle), and the 30 area sources (red diamonds). The discrete receptors are also indicated.

The AERMOD model uses the Universal Transverse Mercator (UTM) projection with the World Geodetic System 1984 (WGS84) datum, employing meters as the unit of measurement. Specifically, it operates within UTM zone 35N, which accurately represents geographical locations and distances in air quality dispersion modelling. The model domain consists of a square area centred in the community of Sharpeville (at X = 588899.71m and Y = 7049224.91m), with the domain boundaries summarized in Table 4.1.

Table 4.1 The AERMOD domain boundaries for the Sharpeville study area.

Domain	Length [m]	Spacing [m]	Boundary Point UTM 35N [m]	Coordinates [Decimal Deg]
X-Axis	8575	175	583249.71 (X_{MIN})	27.836305
			594549.71 (X_{MAX})	27.950656
Y-Axis	8575	175	7043574.91 (Y_{MIN})	-26.623846
			7054874.91 (Y_{MAX})	-26.726576

The domain was discretised using a Uniform Cartesian Grid, with 2500 (50 x 50) receptors spaced uniformly across the domain, with 175 meters spacing between each receptor. Thirteen (13) discrete Cartesian receptors (Table 4.2), located near waste disposal sites, including several schools, a clinic, a nursing home, and the ambient air quality monitoring station (AQMS), were also used. The total number of receptors used was 2513, and their heights were at ground level.

Table 4.2 Summary of the discrete receptors within the AERMOD study area domain.

#	Category	Description	Coordinates [Decimal Deg]		Point UTM 35N [m]	
			Latitude	Longitude	X Coord	Y Coord
1	Schools	Moedi School	-26.684360	27.880100	587508.40	7048216.19
2		Thuto Lore Secondary	-26.690431	27.867415	586393.26	7047600.51
3		Lekoa Shandu Secondary	-26.693002	27.867003	586336.72	7047393.19
4		Vuyo Primary	-26.697085	27.874762	587029.36	7046794.78
5		Vukuzahe Primary	-26.697208	27.874645	586354.00	7046991.11
6		Mohloli MSI Secondary	-26.691353	27.878016	587393.74	7047375.91
7		Lehlasedi Primary	- 26.696654	27.864060	585937.78	7046893.73
8		Emmanuel Primary	-26.676344	27.883564	587888.48	7049183.69
9		Matsie Steyn Primary	-26.682665	27.877686	587371.75	7048421.94
10		Titima Primary School	-26.689107	27.869438	586602.15	7047946.04
11*	Monitoring	Sharpeville AQMS	-26.689808	27.867764	586602.15	7047946.04
12*	Health Care	Sharpeville Care for the Aged	-26.686995	27.870182	586316.30	7047576.95
13		Sharpeville Clinic	-26.683689	27.27.878322	586754.50	7047782.70
14		Marak Health Care	-26.692068	27.865507	586123.12	7047375.91

*Receptors 10 and 11 were combined as a discrete receptor in AERMOD due to their proximity.

In 2017, the NOVA Institute and North-West University conducted a study to identify all informal waste dumping sites in Sharpeville (Rabaji, 2019). The identified sites serve as a spatial indicator of open waste disposal practices. The study identified 33 sites included in the AERMOD model for analysis. In two separate instances, sites were combined due to their geographic proximity: sites 27, 28, and 29, and separately sites 30 and 31. This also improves computational efficiency within the AERMOD model. The individual source sites were outlined and used in AERMOD as area sources (28) and area polygon sources (2). The source areas ranged from 10 to 2500m^2, with an average size of 540.83 m^2 (SD) ±529.78 m^2. Figure 2.2 shows the geographic location and distribution of the study domain, discrete receptors, and source areas.

4.2.1.2. Emissions estimation for $PM_{2.5}$ from informal waste burning

A Monte Carlo simulation (Frey, 1998), a technique introducing randomness to the analysis, was used to estimate the waste burned (WB) by the community (IPCC, 2006; Wiedinmyer et al., 2014) Equation and various parameters inputs derived from literature:

$$WB = P \times PF \times MWS_g \times B_{frac}$$

Equation 3.2 Waste Burned

The population (P) used in this equation was sourced from the South African 2011 census (Statistics South Africa, 2020). The percentage of the population engaged in waste-burning activities (PF) was obtained through a household energy survey (NOVA, 2018a). The daily waste generation rate (MSWg), in kg/day, was determined by considering a range of 0.45 to 1.5kg.day^{-1}, which is applicable for low- to middle-income settlements in South Africa (DEA, 2011; Rodseth et al., 2020). The fraction of waste subjected to burning (BF) was established at ~60% (IPCC, 2006; Wiedinmyer et al., 2014). The burned fraction consists of combustible percentages, recognizing that waste types inherently possess combustible elements, and a combustible percentage cannot be 0% due to low temperature and oxygen levels (Krecl et al., 2021; Lemieux et al., 2004). The assumption was made that the burning fraction could be anywhere from 20-97% (Reyna-Bensusan et al., 2018; Wang et al., 2023). Waste burning undergoes incomplete combustion due to low temperatures (Tai et al., 2010), which releases PM emissions (Lemieux, 1998; Mihai et al., 2019).

A total of 10,000 runs were completed using the Monte Carlo simulation. Table 4.3 presents the descriptive statistics of waste burned (kg/day), emission factors (g/kg), and total emissions (g/day), reflecting the variability inherent in the simulation runs. The outputs from a Monte Carlo simulation were employed to calculate the emissions rate inputs for the dispersion model (McMurray et al., 2017).

Table 4.3 Descriptive statistics of the 10000 reiterations of the Monte Carlo simulation output ranges.

Parameter	**Unit**	**Minimum**	**25%**	**Median**	**75%**	**Maximum**	**Mean**	**±SD**
Waste Burned	kg/day	380	3451	5787	8949	23582	6581	4147
Emission Factor	g/kg	2.30	6.00	9.57	13.33	16.99	9.64	4.20
Total Emission	g/day	1318.01	25882	50251	88110	346224	64831	52181

The US EPA's AP42 (1995) and Wiedinmyer et al2014) equation were applied to calculate the emission rate (ER). The emissions rate (ER), in $g.s^{-1}$, resulting from open waste burning (Equation 4.), is determined by the active rate (AR) of waste burned ($kg.day^{-1}$) and the range of $PM_{2.5}$ emission factor (EF) in g, obtained as outputs from the Monte Carlo simulation.

$$ER = AR \times EF$$

Equation 4.1 Emission Rate

Five distinctive run scenarios were defined for AERMOD based on the specific percentiles and central tendencies for the Monte Carlo of the outputs (Table 4.4), namely: minimum (Run 1), 25th percentile (Run 2), median (Run 3), 75th percentile (Run 4), and maximum (Run 5). The calculated ERs for the individual runs ranged from $1.52x10^{-5}$ (Run 1) to $400x10^{-5}$ (Run 5) $g.s^{-1}$.

Table 4.4 Calculated emission rate inputs for individual AERMOD runs.

Parameter	**Unit**	**AERMOD Run Scenarios**				
		1	**2**	**3**	**4**	**5**
Emission Rate	g/s	1.52×10^{-5}	29×10^{-5}	58×10^{-5}	101×10^{-5}	400×10^{-5}

The emission rate for each run was applied to the individual source areas, whereby the emission rate was converted to $g/s/m^2$ in AERMOD. Table 4.5 provides the emission rates in $g/s/m^2$ for each source area and associated model runs. Most sites were $500m^2$, with the average area size being 540 m^2 ± 529 m^2. The average emission rate across all the sites for Run 1 was $1.56x10^{-7}$ (SD) $\pm3.86x10^{-7}$ $g/s/m^2$, with the second run having an average emission rate of $2.98\times^{-6}$ (SD) $\pm7.36\times^{-6}$ $g/s/m^2$.The smallest source for all the runs had an average emissions rate of 1.06×10^{-4} (SD) ± 1.69×10^{-4} $g/s/m^{2,}$ and the largest source had an average emission rate of 1.20×10^{-6} (SD) $\pm1.33\times10^{-6}$ $g/s/m^{2.}$ The larger the source area, the smaller the emission rate, meaning that larger sites had a smaller $g/s/m^2$ as the $g.s^{-1}$ is allocated to the whole source area of the waste site.

4.2.1.3. AERMAP Pre-processing of Terrain Data

A digital elevation dataset, with a resolution of 30 meters, obtained during the Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007), represents the area's topography. The areas surrounding the community are prevailingly industrial, mining, agricultural, and residential. The average elevation of the rural area of the community is ~1470 meters above sea level. The terrain data underwent pre-processing using AERMAP (EPA, 2019b), version 18081. AERMAP allocated a base elevation for each site as the sources were at ground level. All the identified waste sites were on top of the soil, and no site was in a ditch, excavation site, or basin.

4.2.1.4. AERMET Pre-processing of Meteorology Data

Meteorological conditions are crucial in determining the level of air pollution within the atmosphere, as they influence how pollutants are dispersed and mixed vertically (Seinfeld & Pandis, 2006). The weather conditions in Sharpeville are characterized by atmospheric stability, which translates to low wind velocity and frequent temperature inversions, especially during the winter season (Kumar et al., 2006).

Hourly meteorological data in the year 2017 were used over Vereeniging, which is located approximately 13 km northeast of Sharpeville. While the meteorological data is appropriate for Sharpeville, it may impose certain limitations, as it assumes no substantial differences in the surface or upper air conditions between the two locales, rendering the data transferable and applicable to the Sharpeville context.

The hourly surface and upper air meteorological data were utilized within the AERMET (version 19191) preprocessor to generate both the surface- and profile data files (EPA, 2019a). Before integration into AERMOD, the data were quality assessed for values that were missing or outside the acceptable threshold values, as predefined by AERMET. AERMET merges the two datasets if any missing values are present, although the output file indicates no missing values.

Table 4.5 The emission rates, in $g/s/m^2$, of $PM_{2.5}$ for each of the 30 source areas AERMOD uses are categorized by individual runs.

Source Area [#]	Type	Waste Site [#]	SW Corner		Area [m^2]	Base Elevation [masl]	Emission Rate [$g/s/m^2$]						
			X Coord [m]	Y Coord [m]			Run 1 [min]	Run 2 [25^{th}%]	Run 3 [median]	Run 4 [75^{th}%]	Run 5 [max]	Runs 1 to 5 Average	Runs 1 to 5 ±SD
1	Area	1	588199.630	7048683.440	500	1442.0	3.04^{*-8}	5.80^{*-7}	2.90^{*-6}	2.02^{*-6}	8.00^{*-6}	2.71^{*-6}	3.17^{*-6}
2	Area	2	588165.450	7048483.280	500	1443.9	3.04^{*-8}	5.80^{*-7}	2.90^{*-6}	2.02^{*-6}	8.00^{*-6}	2.71^{*-6}	3.17^{*-6}
3	Area	3	588136.752	7048200.835	500	1444.8	3.04^{*-8}	5.80^{*-7}	1.16^{*-6}	2.02^{*-6}	8.00^{*-6}	2.36^{*-6}	3.24^{*-6}
4	Area	4	588004.470	7048082.530	500	1446.3	3.04^{*-8}	5.80^{*-7}	3.39^{*-7}	2.02^{*-5}	8.00^{*-6}	5.83^{*-6}	8.70^{*-6}
5	Area	5	587831.838	7048001.665	400	1451.0	3.80^{*-8}	7.25^{*-7}	4.39^{*-7}	2.53^{*-6}	1.00^{*-5}	2.75^{*-6}	4.17^{*-6}
6	Area	6	587715.109	7047994.882	500	1453.0	3.04^{*-8}	5.80^{*-7}	1.16^{*-6}	2.02^{*-6}	8.00^{*-6}	2.36^{*-6}	3.24^{*-6}
7	Area	7	587537.517	7047984.238	600	1457.7	2.53^{*-8}	4.83^{*-7}	1.16^{*-6}	1.68^{*-6}	6.67^{*-6}	2.00^{*-6}	2.68^{*-6}
8	Area	8	587533.530	7047746.580	200	1458.7	7.60^{*-8}	1.45^{*-6}	1.16^{*-6}	5.05^{*-6}	2.00^{*-5}	5.55^{*-6}	8.29^{*-6}
9	Area	9	587295.394	7047545.206	1600	1463.0	9.50^{*-9}	1.81^{*-7}	1.45^{*-6}	6.31^{*-7}	2.50^{*-6}	9.54^{*-7}	1.03^{*-6}
10	Area	10	587032.320	7046873.146	500	1468.9	3.04^{*-8}	5.80^{*-7}	1.16^{*-6}	2.02^{*-6}	8.00^{*-6}	2.36^{*-6}	3.24^{*-6}
11	Area	11	585900.250	7046556.930	600	1478.6	2.53^{*-8}	4.83^{*-7}	9.67^{*-7}	1.68^{*-6}	6.67^{*-6}	1.97^{*-6}	2.70^{*-6}
12	Area	12	585879.040	7046766.930	400	1478.1	3.80^{*-8}	7.25^{*-7}	5.80^{*-6}	2.53^{*-6}	1.00^{*-5}	3.82^{*-6}	4.11^{*-6}
13	Area	13	585868.430	7046941.940	500	1478.0	3.04^{*-8}	5.80^{*-7}	1.01^{*-6}	2.02^{*-6}	8.00^{*-6}	2.33^{*-6}	3.25^{*-6}
14	Area	14	585881.156	7047202.856	25	1478.6	6.08^{*-7}	1.16^{*-5}	1.09^{*-6}	4.04^{*-5}	1.60^{*-4}	4.27^{*-5}	6.75^{*-5}
15	Area	15	585828.131	7047486.045	500	1482.7	3.04^{*-8}	5.80^{*-7}	2.32^{*-6}	2.02^{*-6}	8.00^{*-6}	2.59^{*-6}	3.17^{*-6}
16	Area	16	585635.090	7047829.690	1200	1484.4	1.27^{*-8}	2.42^{*-7}	5.80^{*-5}	8.42^{*-7}	3.33^{*-6}	1.25^{*-5}	2.55^{*-5}
17	Area	17	585879.525	7047830.905	10	1481.3	1.52^{*-6}	2.90^{*-5}	3.63^{*-7}	1.01^{*-4}	4.00^{*-4}	1.06^{*-4}	1.69^{*-4}
18	Area	18	586109.200	7047699.230	500	1481.4	3.04^{*-8}	5.80^{*-7}	1.45^{*-6}	2.02^{*-6}	8.00^{*-6}	2.42^{*-6}	3.21^{*-6}

Source Area [#]	**Type**	**Waste Site [#]**	**SW Corner**		**Area [m²]**	**Base Elevation [masl]**	**Emission Rate [g/s/m²]**						
			X Coord [m]	**Y Coord [m]**			**Run 1 [min]**	**Run 2 [25th%]**	**Run 3 [median]**	**Run 4 [75th%]**	**Run 5 [max]**	**Runs 1 to 5**	
												Average	**±SD**
19	Area	19	586689.077	7047524.007	400	1472.6	3.80^{*-8}	7.25^{*-7}	1.16^{*-6}	2.53^{*-6}	1.00^{*-5}	2.89^{*-6}	4.08^{*-6}
20	AreaPoly	20	586909.798	7047844.561	400	1470.4	3.90^{*-8}	7.43^{*-7}	5.80^{*-5}	2.59^{*-6}	1.03^{*-5}	1.43^{*-5}	2.48^{*-5}
21	AreaPoly	21	586951.283	7047900.146	30	1470.5	2.56^{*-8}	4.88^{*-7}	1.16^{*-6}	1.70^{*-6}	6.74^{*-6}	2.02^{*-6}	2.71^{*-6}
22	Area	22	586693.930	7047931.010	10	1473.8	7.60^{*-8}	1.45^{*-6}	1.16^{*-6}	5.05^{*-6}	2.00^{*-5}	5.55^{*-6}	8.29^{*-6}
23	Area	23	587042.051	7048089.530	250	1466.7	1.52^{*-6}	2.90^{*-5}	2.32^{*-5}	1.01^{*-4}	4.00^{*-4}	1.11^{*-4}	1.66^{*-4}
24	Area	24	586774.980	7048373.250	500	1470.6	6.08^{*-8}	1.16^{*-6}	1.16^{*-6}	4.04^{*-6}	1.60^{*-5}	4.48^{*-6}	6.60^{*-6}
25	Area	25	587279.030	7048479.575	100	1463.3	2.86^{*-8}	5.46^{*-7}	1.45^{*-6}	1.90^{*-6}	7.54^{*-6}	2.29^{*-6}	3.02^{*-6}
26	Area	26	587245.798	7048542.304	600	1463.0	1.52^{*-7}	2.90^{*-6}	9.67^{*-7}	1.01^{*-5}	4.00^{*-5}	1.08^{*-5}	1.68^{*-5}
27	Area	27, 28, 29	587702.150	7048960.380	1500	1449.0	2.66^{*-8}	5.07^{*-7}	4.83^{*-7}	1.77^{*-6}	7.00^{*-6}	1.96^{*-6}	2.89^{*-6}
30	Area	30, 31	587828.330	7048926.860	2500	1447.8	8.89^{*-9}	1.70^{*-7}	2.90^{*-6}	5.91^{*-7}	2.34^{*-6}	1.20^{*-6}	1.33^{*-6}
32	Area	32	588402.910	7048935.494	200	1443.6	1.15^{*-8}	2.20^{*-7}	9.77^{*-7}	7.65^{*-7}	3.03^{*-6}	1.00^{*-6}	1.20^{*-6}
33	Area	33	588285.497	7049099.472	200	1447.1	7.60^{*-8}	1.45^{*-6}	1.49^{*-6}	5.05^{*-6}	2.00^{*-5}	5.61^{*-6}	8.25^{*-6}
Note: * [×10]				540.83	1463.69	1.56^{*-7}	2.98^{*-6}	5.96^{*-6}	1.10^{*-5}	4.11^{*-5}	**Av×**	**±SD**	
				529.78	13.94	3.86^{*-7}	7.36^{*-6}	1.47^{*-5}	2.57^{*-5}	1.02^{*-4}	**±SD**		

The prevailing wind direction in the region of Sharpeville is toward the northeast. The average wind speed ranges between 0.5 and 11.1 m/s, and the average percentage of calm conditions is ~9.83% (Figure 4.3).

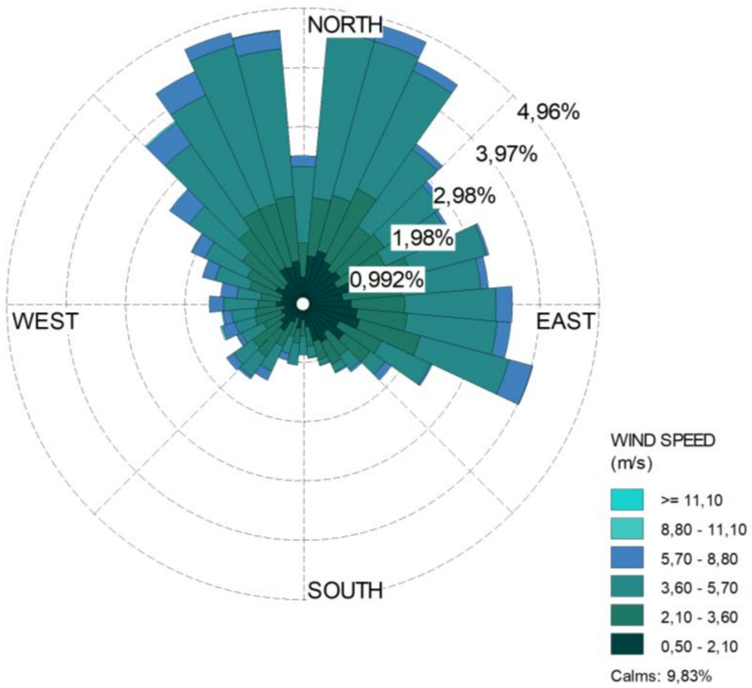


Figure 4.3 Windrose for 1 January 2017 to 31 December 2017 compiled using WRPLOT View (v.10.2.1, Lakes Environmental, Ontario, Canada).

Model Runs for Sharpeville

The AERMOD, version 21112, model simulations were executed for 365 analysis days, from 1 January to 31 December 2017, for the defined study area domain. The model was run using hourly meteorological data and calculated emission rates, as shown in Table 4.5.

The open waste burning sources of emissions were treated as individual polygon area sources in AERMOD, with a plume height at ground level. A combination of both uniform and discrete Cartesian receptors was used. The specified pollutant type was $PM_{2.5}$ with two averaging periods, namely, hourly (1-h), daily (24-h), and annual (8760-h). The area domain was rural, and there were no tall buildings in the settlement and no space between properties. The settlement lacks large shopping centers and has no open spaces to the north and south. To the east, it is bordered by the Leeuikuildam. The terrain elevation of the model extent ranges between 1410 – 1530 m above sea level, with the settlement being between 1440-1480 m above sea level.

4.2.1.5. Ambient Air Quality Monitoring Station

Ambient air quality is monitored at a single AMQS in Sharpeville as a part of the South African Air Quality Information System (SAAQIS) network (DEFF, 2023). The AQMS is operated and maintained by the South African Weather Service (SAWS) and is situated on the premises of Titima Primary School at an altitude of 1478 meters above sea level. The station constantly monitors meteorological parameters and criteria pollutants, including $PM_{2.5}$, and provides hourly time-integrated concentration values. Table 4.6 presents a summary of the station information. Data for the period 1 January 2017 to 31 December 2017 was downloaded from the SAAQIS platform. The data from the monitoring station serves as a reference point for comparison with the model simulation outputs, which indicates the model's predictive accuracy (Kumar et al., 2006).

Table 4.6 The AQMS information for the station within the study area (DEFF, 2023).

Parameter	Details
Station Name	Sharpeville
Province	Gauteng
District	Sedibeng
Station Owner	South African Weather Service
Latitude	-26.689794
Longitude	27.86778
Elevation [masl]	1478
Integration Time	1-h
Station Type	Residential Low-Income

4.2.2. Statistical analysis

Data were analysed using Python, while AERMOD dispersion outputs were spatially analysed using the AERMOD Optical tool and the Map created using QGIS (Version 3.20.3).

4.3. Results

4.3.1. Modelled ambient $PM_{2.5}$ concentrations from open waste burning

As described previously (Table 4.5), the emission rates were applied to the AERMOD model to estimate the $PM_{2.5}$ concentrations resulting from informal waste burning in the study area. Based on the AERMOD model, we estimated the spatial distribution of the hourly (1-h), daily (24-h), and annual (8760-h) $PM_{2.5}$ concentration values in Sharpeville produced by all 30 identified source areas, which we included in the simulation for all five emission rate scenarios.

Table 4.7 indicates the maximum average concentration, in µg/m³, for the hourly, daily, and annual averaging periods across the domain for all five model runs during 2017.

It's worth noting that the first run (Run 1) serves as a baseline scenario with minimal emissions, whereas the fifth run (Run 5) represents an extreme scenario with significantly higher emission rates. An analysis of the data indicates distinct trends across the averaging periods and individual runs. While annual averages (<1 to 37µg/m³) generally show lower levels of $PM_{2.5}$ emissions across all runs, hourly (9 to 2441µg/m³) and daily (2 to 402µg/m³) averages reveal intermittent spikes, which are particularly pronounced in Run 4 and Run 5. The hourly average $PM_{2.5}$ concentrations are a factor of 6 and 68 times higher than the daily and annual averages, respectively. Meanwhile, the daily average concentrations were 11 times higher than the annual concentrations.

Table 4.7 The highest average $PM_{2.5}$ concentration, in µg/m³, was simulated over the Sharpeville study area from 1 January to 31 December 2017.

Period	**Runs**					**NAAQS**
	1	**2**	**3**	**4**	**5**	**Limit**
Hourly	9.276	176.975	353.951	616.363	2441.040	--
Daily	1.527	29.128	*58.256	*101.446	*401.766	40
Annual	0.136	2.592	5.184	9.036	*35.751	20

*Exceeds the given NAAQS limit value

When we consider the difference in emissions between each scenario, it is clear that Run 5, with the higher emission rate, produces $PM_{2.5}$, which is significantly higher than the other scenarios. It is 4-, 7-, 14-, and 263 times higher than Run 4, Run 3, Run 2, and Run 1, respectively. This highlights the temporal variability and intensity of $PM_{2.5}$ pollution.

The compliance of five different scenarios, denoted as Run 1 to Run 5, was evaluated against the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$. Specifically, the extent to which each scenario exceeds the daily and annual NAAQS limits for $PM_{2.5}$. The results show that only scenarios Run 1 and Run 2 are within the daily and annual NAAQS limits. In contrast, scenarios Run 3 to Run 5 exceed the daily NAAQS limit of 40µg/m³, with Run 5 surpassing the annual NAAQS limit of 20µg/m³. This suggests that taking measures to reduce $PM_{2.5}$ emissions from informal waste burning could potentially help to achieve compliance with the NAAQS limits within the residential community of Sharpeville.

Out of the 8760 processed meteorological data, 861 hours were recorded as calm, indicating that ~10% of the weather conditions were stable. The majority of wind speeds were relatively low, with most of them ranging between 0 and 5 m/s for the year 2017. The dispersion analysis showed that the wind was mainly moving towards the northeastern part of the settlement.

4.3.1.1. Emissions and Dispersion of $PM_{2.5}$ over Sharpeville

Figure 4.4 illustrates the dispersion of $PM_{2.5}$ from all identified source areas in Sharpeville, with the hourly (left) and annual (right) for each model's emission rate scenario.

The best-case scenario was represented by model run 1, which had the lowest emission rate, with a gas/s of 1.52×10^{-5}, and the lowest dispersion of $PM_{2.5}$ concentrations, with most of the dispersions being between 1 and 5 µg/m^3. On the other hand, the worst-case scenario was represented by model run 5, which had the highest emission rate and hourly concentration exceeding 2000 µg/m^3, with the entire community exposed to extremely high $PM_{2.5}$ emissions. There are certain sites, often surrounding the area sources, with high-intensity concentrations, with these hotspots surrounding the central parts of Sharpeville. There is a substantial contrast between the $PM_{2.5}$ concentrations at Lehlasedi Primary (10 µg/m^3) and Sharpeville's AQMS (101.62 µg/m^3). The higher the emission rate for the source area, the further the dispersion from the source.

The daily averaged air dispersion modelling results in Sharpeville depict varying concentrations of $PM_{2.5}$ emitted from waste-burning sources. The different emission rates applied to model runs reveal daily concentrations ranging from 1 µg/m^3 in Run 1 to 401 µg/m^3 in Run 5. Both Runs 1 and 2 notably present low emission rates, portraying the best-case scenarios for $PM_{2.5}$ emissions. However, runs 3 and 4 show higher daily concentrations, with some receptor sites exceeding national ambient air quality standards (NAAQS); however, none of the discrete receptors showed exceedances. Run 5 exceeds the NAAQS at multiple receptors, notably Sharpeville AQMS (including Titima Primary School), Lehlasedi Primary, Matsie Steyn Primary School, and Vuyo Primary School, with concentrations of 63.28, 51.95, 37.15, and 49.25 µg/m^3, respectively. Most waste disposal sites surpass NAAQS for $PM_{2.5}$.

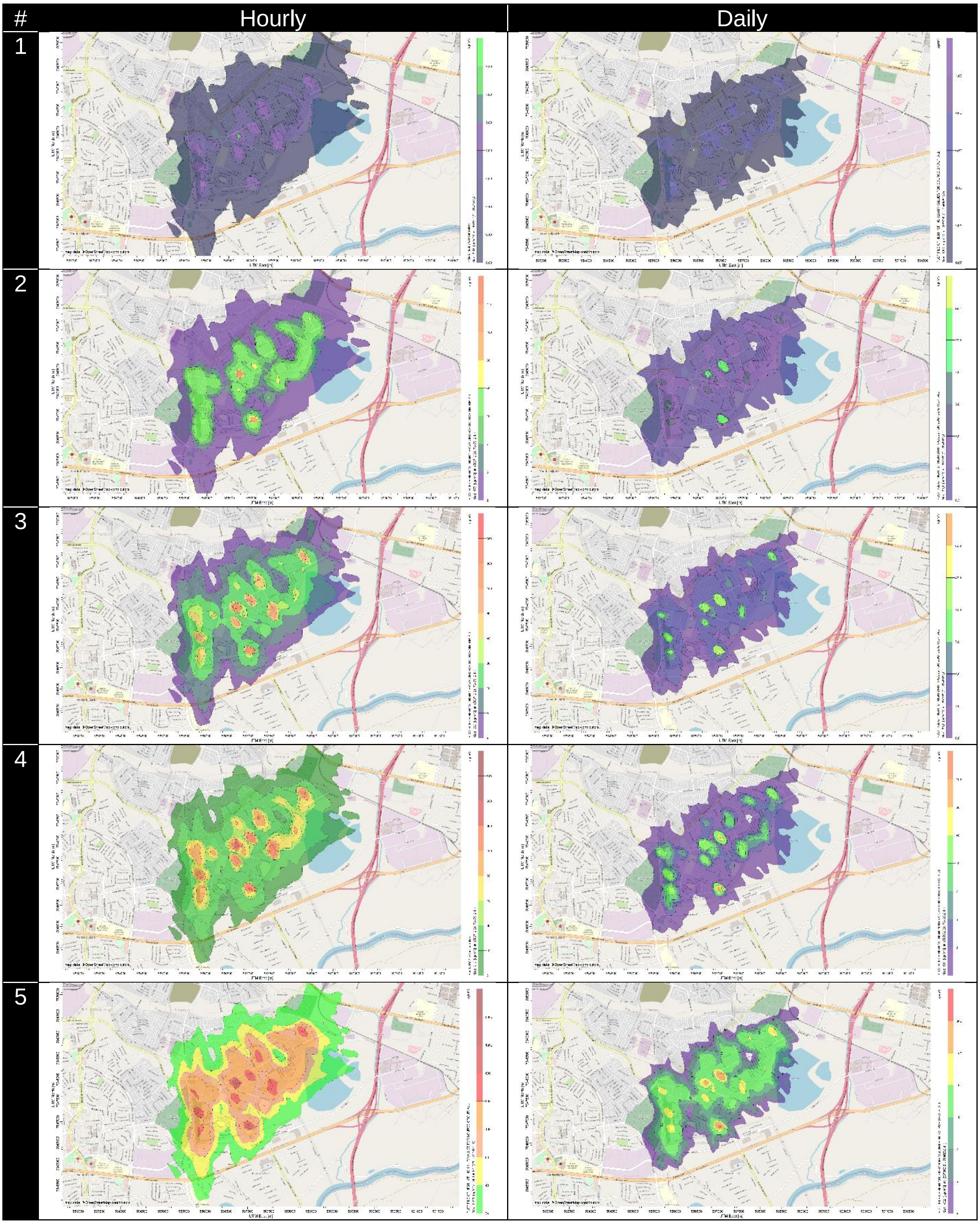


Figure 4.4 The dispersion of hourly (left) and daily (right) modelled $PM_{2.5}$ concentrations, in µg/m³, for 2017 in Sharpeville. Data includes simulations from runs 1 to 5.

The annual emissions concentrations remain below 10 µg/m^3 across Runs 1 to 4, indicating relatively low long-term exposure. While for Run 5, the highest average emission exceeds the annual NAAQS with more than 15 µg/m^3, no exceedances were identified for the discrete receptor sites.

4.3.2. Observed ambient $PM_{2.5}$ concentrations

The $PM_{2.5}$ concentration data from the AMQS in Sharpeville between 1 January 2017 and 31 December 2017 was analysed. During this period, only 57% of the hourly data was available, with most missing data in June, July, and August. This period represents winter, which is the worst-case scenario for ambient air pollution. Therefore, the data does not show the actual ranges as we expect more extreme levels during winter. There were 4969 individual data points for the hourly measurements, while 233 data points were available for the 24-hour measurements.

The descriptive statistics for the hourly and daily averaged $PM_{2.5}$ pollutant concentrations, in µg/m3, are presented in Table 4.8. The mean $PM_{2.5}$ concentrations for the hourly measurements during the monitoring period were 37.01 (SD) ± 58.75 µg/m^3, while that of the daily measurements were 37.75 (SD) ± 35.23 µg/m^3. The maximum values show that short-term increases in $PM_{2.5}$ pollution can reach much higher levels compared to longer-term averages. The hourly maximum is 977.8 µg/m^3, while the daily maximum is 322.4 µg/m^3. This highlights the significance of sudden, more intense pollution events and the potential risk these events could pose over an extended period.

In 2017, the 24-hour $PM_{2.5}$ NAAQS limit, which is set at 40 ug/m^3 (DEA, 2012), was exceeded 75 times, which is 71 times more than the permitted four exceedances per year. Additionally, the annual NAAQS limit of 20 ug/m^3 was also surpassed in 2017, with the annual average being 37.3 ug/m^3.

Table 4.8 Descriptive statistics of the ambient $PM_{2.5}$ (µg/m^3) concentration in Sharpeville from 1 January to 31 December 2017.

$PM_{2.5}$ Concentration [µg/m3]										
Averaging Period	**Count**	**Minimum**	**Q1**	**Median**	**Q3**	**99th %**	**Maximum**	**Mean**	**±SD**	**Exceedances [#]**
Hourly	4969	0.00	10.74	21.88	43.23	278.19	1000.00	37.01	58.75	
Daily	233	1.08	15.84	28.03	47.88	162.11	305.65	37.75	35.23	75 (*4)

*Allowed number of exceedances per year of the 24-hour NAAQS.

4.3.3. Contribution of informal waste burning to ambient $PM_{2.5}$ concentrations

The model simulated $PM_{2.5}$ concentrations at the AMQS, a specific receptor point, were estimated for the hourly (1.53 to 402.46 µg/m^3), daily (0.24 to 63.28 µg/m^3), and annual (0.01 to 2.49 µg/m^3) averaging periods. To estimate the contribution of informal waste burning towards the ambient $PM_{2.5}$, the modelled $PM_{2.5}$ was compared to the monitored values from the AQMS for each model scenario and summarised in Table 4.9. The estimated contributions to $PM_{2.5}$ concentrations varied significantly.

In Run 1, hourly (4%) and daily (<1%) contributions were relatively low, with an annual contribution of <0.5%. Run 2 had higher contributions, particularly in the hourly (79%) and daily (12.15%) estimations, although the annual contribution remained low (<0.05%). On the other hand, Run 3 showed a significant overestimation in the hourly contribution (158%), while the daily (24%) and annual (1%) contributions were relatively lower. Run 4 had even higher contributions across all time scales than Run 3, with the annual contribution surpassing 1%. Lastly, Run 5 had exceptionally high contributions across all time scales, with the annual contribution reaching 7%.

The analysis results have important implications for the model's performance and the emissions it is based on. Runs with lower contributions may suggest that the model underestimates the emissions due to conservative estimates or lower emission factors. On the other hand, runs with higher contributions (as seen in Run 5) may indicate overestimation caused by exaggerated emission rates or higher emission factors. The consistency or variability of contributions across different time scales provides insights into the model's reliability and potential biases. These statistical findings emphasise the need to accurately characterise emissions and their impact on $PM_{2.5}$ concentrations to improve air quality modelling and management efforts.

Table 4.9 Estimated $PM_{2.5}$ concentrations, in µg/m^3, at the AMQS discrete receptor point, and the contribution (%) to ambient $PM_{2.5}$.

Run	Hourly		Daily		Annual	
	ug/m3	(%)	ug/m3	(%)	ug/m3	(%)
1	1.53	4.13	0.24	0.64	0.01	0.03
2	29.18	78.84	4.59	12.15	0.18	0.48
3	58.36	157.68	9.18	24.31	0.36	0.97
4	101.62	274.58	15.98	42.34	0.64	1.70
5	402.46	1087.44	63.28	167.63	2.49	6.68

4.4. Discussion

Some studies used AERMOD modelling to predict concentration and assess air quality in different countries (Amoatey et al., 2018). Although these studies focus more on point sources, there was a good agreement between the model prediction and the measured concentrations (Kakosimos et al., 2011). As shown in Table 4.3, the contribution to waste burning is estimated to be between 380 and 23000 kg.day-1, which indicates a range of emissions that could contribute to $PM_{2.5}$ emissions in Sharpeville. The emission rate ranged between 1.52x10^{-5} and 400x10^{-5} g.s^{-1}, as estimated from the different Monte Carlo outputs. A study on waste burning dispersion estimated that the gas/second for other townships ranges from 0.0432-0.278 g.s^{-1} for $PM_{2.5}$ (Chidhindi, 2022). This is extremely high compared to the Monte Carlo output model prediction.

The results demonstrate a clear correlation between the emission rates of $PM_{2.5}$ and the concentrations observed in Sharpeville. The study compared five different emission scenarios, with Run 1 serving as a baseline and Run 5 representing an extreme scenario with significantly higher emission rates. The findings suggest that while annual $PM_{2.5}$ emissions remain relatively stable, there are significant fluctuations at shorter time scales, particularly on an hourly basis.

The compliance with the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ showed that only scenarios Run 1 and Run 2 were within the daily and annual NAAQS limits. Scenarios Run 3 to Run 5 exceeded the daily NAAQS limit of 40µg/m^3, with Run 5 surpassing the annual NAAQS limit of 20µg/m^3. These results emphasise the need for complex assessments considering emission rates and temporal scale to fully understand the dynamics. In addition, it suggests that taking measures to reduce $PM_{2.5}$ emissions from informal waste burning could help to achieve compliance with the NAAQS limits within the residential community of Sharpeville.

The dispersion analysis showed that the wind was mainly moving towards the northeastern part of the settlement, with certain sites surrounding the area sources having high $PM_{2.5}$ concentrations. Source contribution from informal waste burning for PM2.5 in other informal settlements was estimated to be 4% of all sources in Zamdela (Chidhindi, 2022) and 0,00007% in Kwadela (Bosman, 2018). Cheng et al. (2020) emphasise that informal open waste burning contributes 8.7% of the total emission of anthropogenic sources. Based on the range of contributions percentages obtained from the modelling scenarios, informal waste burning from waste disposal sites is a potentially significant contributor to ambient $PM_{2.5}$, especially concerning the hourly and daily averages.

The impact these levels of $PM_{2.5}$ have on the environment and human health is crucial for the government to implement intervention (Popoola et al., 2022).

4.4.1. Assumptions and limitations

Several assumptions are associated with calculating waste burning emissions due to a lack of data available in South Africa. To address this uncertainty, Monte Carlo simulation estimates realistic concentrations based on the inputs used in the calculation. The model concentration is directly proportional to the emission rate and waste burned or emission factor. Without the Monte Carlo simulation, it would have been difficult to determine values such as the population that burns waste. However, the NOVA Eskom energy survey provided some data to address these uncertainties. It is important to note that the model itself is not unreliable; rather, the precision of data used to calculate the emission rate can affect its accuracy (Bosman, 2018).

It was assumed that all identified waste disposal sites would either burn or have the potential to burn. There were data gaps in the information downloaded from the SAAQIS website, with only 57% of $PM_{2.5}$ concentration data available overall. It takes a considerable amount of time to process the model runs. While the emission inventory provides outdated emission factors, it is the only information available regarding the source type. Waste burning estimated emissions may vary depending on the model's inputs, source type, and emissions calculation (Bosman, 2018). It does not determine a best- or worst-case scenario since the different variables are simultaneously not at their worst or best-case (Raychaudhuri, 2008).

4.4.2. Recommendation

Measuring the ambient concentration directly at the source is more effective than relying on stationary monitoring sites. Using other models, like Positive Matrix Factorisation (PMF) or

Chemical Mass Balance (CMB) and combining them with source apportionment data obtained from the study area, we can divide different sources into sectors to determine their contribution to the $PM_{2.5}$.

4.5. Conclusions

This study used a Monte Carlo simulation to estimate the concentration and dispersion of informal waste burning $PM_{2.5}$ emissions in Sharpeville. The study results indicate that waste burning emissions could significantly impact ambient $PM_{2.5}$ concentrations in informal settlements like Sharpeville. Therefore, there is a need for waste-burning intervention strategies to address informal waste disposal. The model used serves as a valuable tool for estimating waste burning emissions and modelling the dispersion of these emissions across low-income residential communities like Sharpeville. There was a strong agreement between some of the model predictions and ambient $PM_{2.5}$ concentration, indicating that informal waste burning has the potential to contribute to ambient pollution levels. However, the contribution depends on the total waste burned and the associated emission rates. These results can lead to new methods and approaches to estimate waste burning emissions and model these complex sources. The spatial variability in $PM_{2.5}$ emissions from informal open waste-burning sites highlights the importance of considering the variability in the ambient air quality of informal settlements. Overall, this study contributes to understanding the impact of waste-burning emissions on ambient air quality and provides insights into developing effective strategies for reducing this emission type to improve air quality in Sharpeville and other communities facing similar challenges.

CHAPTER 5: SUMMARY AND CONCLUSION

This chapter presents the study's main findings concisely, along with their implications and recommendations for future research and policy. The chapter aims to provide a clear and compelling narrative that ties together the various threads of the study and draws meaningful conclusions from the data gathered.

5.1. Summary of main findings

5.1.1. Estimated emissions from the characterised waste sample

Objective I: Calculate the emissions of $PM_{2.5}$ resulting from informal waste burning in Sharpeville using available waste composition data and emissions factors.

The objective was addressed by using waste composition data from Rabaji, (2019), applying a combustible percentage for each waste type provided by the (U.S. EPA, 2018) and Wang et al. (2023). The waste burning calculations used emission factors from literature and results from a Monte Carlo simulation. The main findings are as follows:

i. Waste types with a higher combustible percentage and more prone to incomplete combustion, such as plastic and organic waste, had a higher estimated $PM_{2.5}$ concentration. There are some waste types that do not have flaming phases such as glass and metal. So, the combustible percentage from the US EPA was used for Glass and Metal.

ii. The median of the Monte Carlo emission factor was estimated to be higher than that of Wang et al. (2023) which measured the combined MSW. This ultimately resulted in the $PM_{2.5}$ emissions using the Monte Carlo emission factor. The US EPA combustible fraction was lower than Wang et al. (2023). This created a range of $PM_{2.5}$ emissions from 154 g to 711 g of the total charaterised waste in Sharpeville.

iii. The organic waste type (Garden and wood waste excluding food) was the largest category of waste. This category had the highest US EPA combustible percentage and could contribute to the highest $PM_{2.5}$ emissions. The estimated Monte Carlo emissions factor with the CF indicated that the concentration from the organic waste type was calculated to be 121.82 and 330.46 g for the US EPA and Wang et al. (2023) CF, respectively. This ultimately indicates that the contribution of burned ‘organic waste’ in Sharpeville was significant in 2017.

iv. Food waste was a category that did not include organic waste as suggested by the adapted waste composition methodology. The CF for the US EPA was 21.85%, while Wang et al. (2023) had a smouldering period of 100% and no flaming phase. The CF not having a flaming phase increased the $PM_{2.5}$ concentration when all the ‘food waste’ samples were estimated to burn. This indicates that approximately 10 kg of food waste would smoulder when referring to Wang et al. (2023) CF.

v. Although ‘paper and cardboard’ are considered as organic materials it has a waste category of it own as it contribute to different air pollutants. Paper and cardboard were the third-largest waste type after organic waste and other waste, with a concentration of 21.31 g to 168.31 g. The CF for paper had a lower percentage for both US EPA and Wang et al. (2023).

vi. Waste types such as metal, glass, and other waste did not have CF from Wang et al. (2023) as these categories are non-combustible material that takes a long time to burn or needs to burn under extreme temperatures (Lemieux, 1998; Park et al., 2013). Wang et al. (2023) emphasise that the temperature of informal waste burning is too low for these waste types to combust.

vii. Non-combustibles such as metal, glass, and rock do not significantly contribute to PM emissions, using the US EPA CF. The lower the combustion percentage is, the lower the $PM_{2.5}$ contribution. Metal and glass were the waste types with the lowest fraction of the waste percentage, which could indicate informal recycling in the area.

viii. There are limited solutions to reduce uncontrolled burning and its environmental effects. However, there is a better understanding of the contribution of the different waste types being burned to the ambient air's PM emission. There is a 52 kg difference in the estimated waste burned from the different CF percentages. The CF used by the US EPA estimated that 22kg of the collected waste would burn and that 74kg of the 134kg of waste would burn when applying Wang et al (2023) combustible percentages. Thus, knowing the waste composition of dumping sites that burn is essential. The waste composition can ultimately contribute to the $PM_{2.5}$ emissions, which should be considered for air quality in South Africa.

5.1.2. Estimating the $PM_{2.5}$ emission while addressing the uncertainties

Objective II: Utilise a Monte Carlo simulation distribution model to estimate the uncertainties associated with the $PM_{2.5}$ emissions from informal waste burning in Sharpeville.

The objective was addressed using a Monte Carlo simulation to estimate the waste burned in Sharpeville, an emission factor, and the total emissions suited for emission rates in the AERMOD modelling. Each value of the Monte Carlo model had a different distribution and range. The main findings are:

i. Variables for waste burning calculations included the population, the population that burns waste, the fraction of waste that burns, and the waste generation in Sharpeville. Most variables were obtained from secondary data sources and literature to create the simulation. The variable mostly followed a uniform or log-normal probability distribution.

ii. The population stayed constant in the simulation as the fraction of the population that burns waste influences the percentage of the population that is estimated to burn waste. The population fraction ranged from 6.2 to 60%. This extreme variability indicates that there are still uncertainties in several people that burn waste, as it can range from 2000 to 21,000 people in the community.

iii. The waste burned was calculated using different variables to be able to quantify the source. The waste burned had a minimum of 380 kg/day and a maximum of 23582 kg/day. The median of the waste burn was estimated to be 5787.37 kg/day. This indicates that, on average, 5787.37 kg of waste is burned daily in Sharpeville. This can contribute to over 2000 tonnes per year. This number for waste burned is an overestimation of the expectation of waste burning in Sharpeville. This emphasise the need for useable emissions inventory data on informal waste burning sources.

iv. The waste burned was used as the active rate for dispersion modelling. The probability distribution of the waste burned had a positive skew with a peak at 5000 kg/day.

v. The total daily emissions were a product of the waste and the emission factor. Sharpeville exhibited a wide range of estimated $PM_{2.5}$ emissions from waste burning. This range spanned between 1318 g/day to 346224 g/day with an average of 64831 g/day for each day. This indicates the daily $PM_{2.5}$ emissions for Sharpeville is approximately 6 tonnes of waste daily.

vi. This can ultimately contribute to approximately 20 tonnes of $PM_{2.5}$ emissions annually. The minimum annual $PM_{2.5}$ emission was below 500 kg while the maximum annual $PM_{2.5}$ emission reached 126 tonnes in Sharpeville ambient atmosphere. Regardless, of whether the simulation attempts to address the uncertainty with waste burning emissions, there continues to be variability in the estimated emissions.

vii. The probability distribution of the total $PM_{2.5}$ emissions in Sharpeville indicated a positive skew with the highest range spanning from 2500 g/day to 5000 g/day.

5.1.3. Modelling $PM_{2.5}$ waste burning emissions

Objective III: Model the ambient $PM_{2.5}$ concentrations in Sharpeville originating from informal waste burning using AERMOD.

The objective was addressed using a regulatory tool, AERMOD, to predict the informal waste burning contribution in Sharpeville using different emission rates and comparing the outputs with AQMS concentrations.

i. AQMS data which include $PM_{2.5}$ observed concentrations were used to estimate the $PM_{2.5}$ exceeded in Sharpeville. The AQMS $PM_{2.5}$ exceeded the NAAQS 75 times during the study period in 2017, where four exceedances are allowed annually. With the data gaps during the time period of the winter months this is extreme high number of exceedances. This depicts that $PM_{2.5}$ is a concerning and contributing pollutant to Sharpeville's poor air quality.

ii. AERMOD modelling are used small local sources. The dispersion of the model results indicated that the highest $PM_{2.5}$ concentrations are in the centre of Sharpeville, where the concentration is distributed along the identified waste disposal sites. The dispersion indicates that the whole township is exposed to $PM_{2.5}$ pollution; however, the exposure level depends on source emission rates.

iii. During the first run, the highest estimated concentration on an hourly basis was 9.3 $\mu g/m^3$. The receptors, which measured the concentration levels, recorded the highest concentration below 2 $\mu g/m^3$. This run did not exceed any of the NAAQS limits.

Moreover, considering the hourly averaged model data, this run contributed to 4.13% of ambient $PM_{2.5}$ concentrations.

iv. During Run 2, the highest estimated concentration ranges daily ranged between <1 and 29 µg/m^3; for hourly, it was between <1 and 177 µg/m^3. Although there was an increase in the estimated concentrations (compared to Run1), the values did not exceed the NAAQS limits. The contribution towards the ambient $PM_{2.5}$ concentration was significantly higher than that of Run 1, at 79% and 12% for the hourly and daily averaging periods, respectively.

v. During Run 3, the highest estimated concentrations for the hourly and daily periods were 58 and 354 µg/m^3. The model overestimates the hourly concentration as the contribution to ambient $PM_{2.5}$ exceeds 100%. The daily concentration does not overestimate the values, with the concentrations indicating a 24.31% contribution to ambient $PM_{2.5}$.

vi. In Run 4 and Run 5, the highest estimated hourly concentrations of $PM_{2.5}$ were 616 µg/m^3 and 2441 µg/m^3, respectively, with daily concentrations of 101 µg/m^3 and 402 µg/m^3. However, it should be noted that these model runs overestimate the hourly (Run 4 and Run 5) and daily (Run 5) emissions and contribution in Sharpeville. The contribution for Run 4 to the daily average $PM_{2.5}$ was estimated at 42%.

vii. The model results compared to the measured $PM_{2.5}$ concentration prove that the informal waste-burning emissions contribute to poor air quality in Sharpeville. The contribution varies from 4 to 1087% hourly, 0.64 to 168% daily, and 0.03 to 7% annually.

5.2. Assumption and limitations

The use of outdated 2011 census data for population estimation before the release of the 2022 census dataset is a limitation that needs to be addressed. In the Monte Carlo simulation, the population was assumed to be constant based on the census data. However, it is important to acknowledge that there is variability in the population of a given area. Therefore, a range of estimated population values should be included in the model to account for this variability. Additionally, the emissions in the simulation were assumed to have a uniform distribution to estimate the total waste burning $PM_{2.5}$ emissions. However, applying a bootstrap method could decrease the uncertainty within the uniform distribution and provide more accurate results.

5.3. Conclusion

This study improves the estimation of $PM_{2.5}$ emissions from informal waste burning using a different statistical approach. It also estimates a more reliable contribution of $PM_{2.5}$ emissions from informal waste burning and the impact on the ambient air quality in Sharpeville. Some results underestimate the contribution, while others overestimate it, which presents an opportunity for improvement. Eventhough the study is relevant to Sharpevlle, the methodlogical aprroach could have broader implications. $PM_{2.5}$ concentrations do have spatial and temporal variation, although when waste burning is identified in a spesific region the approach can be adapted according to similar soio-economic charateristic as emphasise in this study. Policymakers can use the findings to create public awareness and engage with stakeholders to raise awareness about the health and environmental implications of informal waste disposal and burning. Some municipalities have interventions such as drop off point in communities , where skips are places for the community to come drop the waste off. The skip evenatlly gets empty by the municipality when full. This study can assit in creating effective interventions for informal waste burning. Policymakers can introduce recycling programs , clean-up projects and address waste management challenges.

5.4. Recommendation

The waste composition sampling categories and methods used in South Africa can be improved to better characterize waste in the context of the country and informal settlements. Refining the Monte Carlo Simulation variables would reduce uncertainty even more by capturing precise data for each variable, such as the waste generation rate and population that burns waste. To address the knowledge gap, measurements of waste burning emission factors for low-income settlements should be developed and used instead of relying on other studies, and a Monte Carlo simulation can be used.

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This chapter summarised the main findings pertaining to each research objective outlined in Section 1.4. In addition, the main assumption and limitations were outlined, along with the conclusion and recommendations.

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ANNEXURE A: JOURNAL OF SCIENCE AND TOTAL ENVIRONMENT (STOTEN) AUTHOR SUBMISSION GUIDELINES

Impact Factor: 9.8

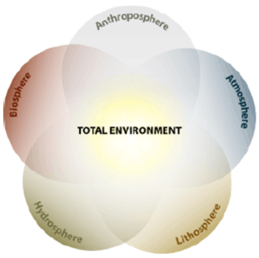
CiteScore: 16.8

Link to full author guidelines: https://www.sciencedirect.com/journal/science-of-the-total-environment/publish/guide-for-authors

Introduction

Aims and Scope

Science of the Total Environment is an international multi-disciplinary natural science journal for publication of novel, hypothesis-driven and high-impact research on the **total environment**, which interfaces the **atmosphere**, **lithosphere**, **hydrosphere**, **biosphere**, and **anthroposphere**.



STOTEN invites contributions of original and high quality interdisciplinary environmental research papers of broad impact. Studies significantly advancing fundamental understanding and that focus on the interconnection of multiple spheres will be given primary consideration. Field studies have preference, while papers describing laboratory experiments must demonstrate significant advances in methodology or mechanistic understanding with a clear connection to the environment. Descriptive, repetitive, incremental or regional-scale studies with limited novelty will not be considered.

1) Subject areas may include, but are not limited to:
- Air quality, atmospheric conditions, and new understanding of their role in adverse health or environmental outcomes
- Atmospheric biogeochemistry
- Ecosystem services and life cycle assessment
- Ecotoxicology and risk assessment
- Eco-hydrology
- Wildlife and contaminants
- Environmental impacts of climate change, agriculture, forestry, and land uses
- Environmental impacts of waste or wastewater treatment
- Drinking water contaminants and health implication
- Environmental remediation of soil and groundwater

FEEDBACK

ANNEXURE B: LETTERS OF CONSENT FROM CO-AUTHORS

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2520
E-mail: Brigitte.Language@nwu.ac.za

20 March 2024

To whom it may concern,

DECLARATION REGARDING USE OF CO-AUTHORED ARTICLES IN MSc THESIS

This letter confirms that my MSc. student, Ms. Aneska Richter (28885260), may submit the following co-authored manuscripts as part of her thesis entitled "Contribution of Waste Burning to Ambient $PM_{2.5}$: A Case Study of Sharpeville, South Africa."

- Chapter 3: Quantifying Open Waste Burning $PM_{2.5}$ Emissions in a South African Low-income Settlement: A Monte Carlo Simulation Study
  - Submitted to the Journal of Science and Total Environment
  - Manuscript number: STOTEN-D-24-10452
- Chapter 4: Modelling ambient $PM_{2.5}$ emissions from uncontrolled open waste burning in Sharpeville, South Africa
  - Target Journal: Journal of Environmental Science and Technology

My co-authorship in these manuscripts primarily focused on supervision, guidance, and assistance in conceptualization, coherence, formulation, and proofreading. The student, Ms. Richter, remains the main contributor to the academic work in the manuscripts.

Sincerely,

Dr. Brigitte Language, Supervisor
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20 March 2024

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Sincerely,

Prof Roelof Burger, Co-supervisor
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20 March 2024

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Sincerely,

Prof. Claudine Roos, MSc Co-supervisor
Unit for Environmental Sciences and Management
Faculty of Natural and Agricultural Sciences
North-West University
South Africa