HEALTH RISK ASSESSMENT OF AIRBORNE $PM_{2.5}$ EMISSIONS IN THE STEVE TSHWETE LOCAL MUNICIPALITY, MPUMALANGA, SOUTH AFRICA.

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Declaration

I, **Odwa Maquthu (student number: 1921588)**, declare that the research project entitled *"Health risk assessment of airborne pm2.5 emissions in the Steve Tshwete Local Municipality, Mpumalanga, South Africa."* is my research work undertaken under the supervision of Dr Tafadzwa Makonese and Prof Masilu Daniel Masekameni. The work is being submitted in partial fulfilment for the degree of Master of Science in Medicine (Exposure Science) at the School of Public Health, University of the Witwatersrand, Johannesburg. This work has not been presented for examination at any other university. The author designed the study, carried out all fields of the study and wrote the research report. Parts of this research report have been planned to be published in peer-reviewed journals and presented at conferences. All the sources cited in this study have been acknowledged through comprehensive references.

Dedication

I dedicate this research to God, whose guidance and blessings have illuminated my path and granted me strength and wisdom throughout this endeavor. To my beloved family, classmates, and supervisors, your endless encouragement, and sacrifices have been my greatest source of inspiration. This work reflects your unwavering support, and I am forever grateful for your presence.

This research is also dedicated to all those who seek knowledge, strive for excellence, and endeavor to make a meaningful contribution to the world through research and scholarship.

Abstract

Background

Air pollution is a significant global public health concern, causing 8.1 million deaths in 2021, and is the second-leading risk factor for mortality worldwide. The issue is particularly dire in developing countries, where socio-economic and environmental factors heighten the risk of exposure to harmful pollution levels. In 2019, air pollution was responsible for 7 million premature deaths, with 91% of these occurring in low- and middle-income countries. Fine particulate matter ($PM_{2.5}$), a major element of ambient air pollution, is closely associated with cardiovascular, respiratory, and metabolic diseases. Exposure to $PM_{2.5}$ raises the risk of death, especially from cardiopulmonary diseases and lung cancer, with each 10 $\mu g/m^3$ rise in $PM_{2.5}$ levels linked to an increase in mortality rates.

In South Africa, a country heavily reliant on coal for energy, the health risks related to $PM_{2.5}$ exposure are significant. Coal combustion accounts for over 90% of the nation's energy, making South Africa one of the top global contributors to coal-based electricity generation. This reliance has placed the country as the fourth highest in Africa for deaths related to $PM_{2.5}$ exposure. Although efforts such as transitioning to renewable energy and implementing stricter emission standards have been made, progress has been slow. With limited research and monitoring, particularly in marginalized areas, the health impacts of air pollution remain under-explored. Despite the World Health Organization's recommendation of a yearly average $PM_{2.5}$ level of 5 $\mu g/m^3$, many urban areas, including Johannesburg and Cape Town, experience significantly higher concentrations. This thesis examines the health impacts of $PM_{2.5}$ exposure in South Africa, focusing on vulnerable populations and the ongoing efforts to mitigate the public health risks of air pollution.

Aim: The aim of this study is to assess the health risks caused by airborne $PM_{2.5}$ exposure in the Steve Tshwete local municipality, Mpumalanga Province in South Africa.

Methods: The study utilized a cross-sectional research design with secondary data from the South African Air Quality Information System (SAAQIS), collected over a 12-month period in 2022 through a stationary air quality monitoring station. The data was validated, with spike detection algorithms applied to remove outliers, and stored securely using Google Cloud Storage. Hourly averaged $PM_{2.5}$ data was categorized by seasons (Summer, Autumn, Winter, Spring) and analyzed to calculate seasonal and daily averages. A health risk assessment was performed using the United States Environmental Protection Agency's (USEPA) framework, focusing on inhalation exposure for adults (65+) and children (6-12). Hazard Quotients (HQ) for $PM_{2.5}$ were calculated, with a threshold of 1 indicating a negligible risk. A pairwise statistical analysis using a one-way Analysis of Variance (ANOVA) at a 95% confidence interval was conducted to determine significant differences in $PM_{2.5}$ emissions between seasons.

Results: The study analyzed seasonal variations in $PM_{2.5}$ concentrations in Steve Tshwete, showing that environmental factors play a significant role in air quality. Winter had the highest $PM_{2.5}$ levels (30.24 µg/m³), driven by heating emissions, temperature inversions, low rainfall (12.3 mm), and low humidity (59%), which limited secondary aerosol formation. Spring saw a decrease in $PM_{2.5}$ (19.14 µg/m³) due to higher temperatures (18.17°C), increased rainfall (62 mm), and higher humidity (70.67%), promoting pollutant dispersion and washout, though agricultural activities may still influence levels. Summer recorded the lowest concentrations (10.4 µg/m³) because of high rainfall (114.33 mm), higher temperatures (21.1°C), and humidity (79.33%), enhancing pollutant dispersion. Autumn showed a moderate increase in $PM_{2.5}$ (15.78 µg/m³) due to decreased rainfall (53 mm) and cooler temperatures (17.6°C), leading to more stable conditions that hindered pollutant dispersion.

The study found significantly elevated cancer risk (CR) values associated with long-term exposure to $PM_{2.5}$ concentrations averaging 14 µg/m³. The CR for children was 6.9×10^{-3} (equivalent to 6.9 in 1,000), while for the elderly it reached 2.1×10^{-2} (or 2.1 in 100). These values far exceed the typical regulatory thresholds for acceptable cancer risk, which range from 1×10^{-6} to 1×10^{-4}, indicating an unacceptably high potential for lifetime cancer development, particularly among older individuals. Non-carcinogenic health risks were also found to be concerning. The Hazard Quotient (HQ) values were 2.014 for children and 2.46 for the elderly, both exceeding the safety threshold of 1. This indicates that the exposed populations are subject to pollutant levels more than twice the reference concentration considered safe, suggesting a heightened likelihood of adverse health effects beyond cancer. These may include respiratory, cardiovascular, or neurological conditions, particularly in sensitive groups.

Conclusion: This study highlights air quality concerns in Steve Tshwete, where $PM_{2.5}$ levels often exceed World Health Organization (WHO) and National Ambient Air Quality Standards (NAAQS) guidelines, posing health risks. Seasonal trends show higher $PM_{2.5}$ in July, linked to dry conditions and agricultural burning, while lower levels are observed in January due to rainfall and reduced activity. Diurnal patterns reveal peak pollution during the day, emphasizing the need for targeted interventions. Wind pattern analysis and continuous monitoring are essential for identifying pollution sources. Although health risks are within acceptable limits, adults face higher risks due to longer exposure, while children remain more vulnerable. Stricter regulations on agricultural burning, industrial monitoring, and public awareness campaigns are necessary to mitigate these risks, especially during high-risk months like July.

Acknowledgment

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Abbreviations and acronyms

WHO	Word Health Organisation
IARC	International Agency for Research on Cancer
PM2.5	fine Particulate matters
NAAQS	National Ambient Air Quality Standards
STLM	Steve Tshwete Local Municipality
SO2	Sulfur dioxide
NH3	Ammonia
VOC	Volatile Organic Compounds
NOX	Nitrogen Oxides
EASIUR	Estimating Air Pollution Social Impact Using Regression
EPA	Environmental Protection Agency
DEOG	Diesel Emitted Organic Gases
GBD	Global Burden of Disease
LUR	Land-Use Regression
ME	Microenvironmental Exposure
PM	Particulate Matter
PM10	Particulate Matter 10 Micrometres or less in diameter
HRA	Health Risk Assessment
SAAQIS	South African Air Quality Information System
USAID	United States Agency for International Development

USEPA	United States Environmental Protection Agency
AQMS	Air Quality Monitoring Station
ADD	Average Daily Dose
HQ	Hazard Quotient
C	Concentration
IR	Inhalation Rate
BW	Body Weight
FADD	Field Average Daily Doses
SADD	Safe Average Daily Doses
SANAAQS	South African National Ambient Air Quality Standards
HREC	Human Research Ethics Committee

Definitions

SAAQIS: South African Air Quality Information System: SAAQIS is a ‘one-stop-shop’ for all air quality information, from monitoring to legislation, as well as notices, guidelines, and contact information of air quality officials in different jurisdictions across the country

Ambient air quality: Criteria or standards are the concentration of pollutants in the air, which is typically referred to as outdoor air.

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CHAPTER ONE: INTRODUCTION

The chapter begins by providing an introductory exploration into the exposure to $PM_{2.5}$, emphasizing its various exposure pathways and the adverse health impacts on the public. It delves into the diverse demographic groups affected by $PM_{2.5}$ exposure, elucidating on how different groups of the population experience varying degrees of risk. Furthermore, the chapter elaborates on the specific emission factors relevant to areas such as the Steve Tshwete Local Municipality, shedding light on the sources and contributors to $PM_{2.5}$ pollution in that locale.

Building on this context, the chapter presents the problem statement and justifies the need for the study. It emphasizes the urgent necessity of examining $PM_{2.5}$ exposure and its related health impacts within the defined geographical area. Additionally, the chapter outlines the study's aim, research question, and objectives, offering a clear framework for the upcoming research.

1. Background

Air pollution, as defined by the World Health Organization (WHO), refers to the contamination of both indoor and outdoor environments by chemical, physical, or biological agents that alter the natural properties of the atmosphere (Howlett-Downing et al., 2023). It represents a major global health risk, causing around seven million premature deaths annually, according to WHO. Nearly 99% of the global population is exposed to air pollutants at levels that surpass WHO's recommended guidelines (Zhang et al., 2023). In particular, ambient and household air pollution are responsible for approximately 4.2 and 3.8 million deaths each year, respectively. Alarmingly, 91% of the world's population lives in areas where air quality exceeds WHO's standards (Nabizadeh et al., 2019). The severity of the problem is demonstrated by the WHO's conclusion that exposure to outdoor air pollution causes between 3 and 9 million premature deaths every year. Furthermore, according to Amann et al. (2020), 90% of the world's urban population is exposed to PM2.5 levels above the WHO-recommended threshold of 10 $\mu g/m^3$.

South Africa has a moderate-income level and heavily depends on coal for 77% of its primary energy needs, including generating power, producing synthetic fuel, and operating petrochemical facilities. In addition, 93% of the nation's electric power is produced from coal. The most concerning pollutant is particulate matter (PM), identified in many places in South Africa (Altieri & Keen, 2019). In addition, there needs to be more surveillance in many developing countries and preventative health interventions catering to populations exposed to elevated ambient air pollutants. In South Africa, research on $PM_{2.5}$ levels and the human health impacts of air pollution in marginalized areas is scarce due to inadequate monitoring and health data (Edlund et al., 2021).

Air pollution is the fourth leading risk factor for global mortality, surpassing other well-known risks such as alcohol consumption and physical inactivity (Alves et al., 2023). The International Agency for Research on Cancer (IARC) has classified outdoor air pollution, particularly particulate matter, as a Group 1 carcinogen to human health, highlighting its serious implications (Behera et al., 2024). Fine particulate matter ($PM_{2.5}$) has garnered significant attention from international organizations and the public due to its severe health impacts associated with personal exposure (Xu et al., 2019). Globally, exposure to $PM_{2.5}$ has been linked to 4.58 million deaths and 142.52 million cases of disability (Behera et al., 2024). Studies suggest that various types of ambient $PM_{2.5}$, including mineral dust, anthropogenic pollutants, biomass burning, and mixed aerosols, are significantly associated with under-five and maternal mortality rates in Africa (Xu et al., 2019).

Exposure to $PM_{2.5}$ is significantly associated with increased mortality risk. Each 10 $\mu g/m^3$ rise in ambient $PM_{2.5}$ concentration correlates with a 4% increase in all-cause mortality, a 9% rise in deaths from cardiopulmonary diseases and lung cancer, and a 17% higher risk of ischemic heart disease (Hajizadeh et al., 2020). $PM_{2.5}$ is a major contributor to elevated health risks, underscoring its importance (Alves et al., 2023). Additionally, $PM_{2.5}$ exposure has been linked to adverse pregnancy outcomes, including reduced newborn size, lower birth weight, increased risk of low birth weight, preterm delivery, and small size for gestational age (Yuan et al., 2019). Organic pollutants within $PM_{2.5}$ have been associated with mutations, cancers, cardiovascular diseases, neuropathy, and respiratory issues such as cough, asthma, and bronchitis through various exposure pathways, including inhalation, ingestion, and digestion (Bui et al., 2023; Castellani et al., 2022; Wu et al., 2019; Yang et al., 2019; Zhong et al., 2019). Furthermore, maternal exposure to ambient air pollution has been identified as a risk factor for adverse birth outcomes (Zhu et al., 2015).

The possible health impacts of $PM_{2.5}$ exposure are a major worry for the entire world community. Because they can be more harmful to the public's health than bigger particles, these microscopic particles are a cause for concern. This is mostly because of their small size, which enables them to enter the human bloodstream and possibly even the respiratory system

(Yang et al., 2019). The suspended particles in the air contain various chemical elements. People are exposed to these particles through inhalation during respiration. The most vulnerable groups to this exposure are children between the ages of 2 and 6, children between the ages of 6 and 12, and adults who are 70 or older (Díaz and Dominguez, 2009).

National policies for controlling air pollution were implemented to tackle some of the previously mentioned concerns. The World Health Organization (WHO) established maximum air quality guidelines for $PM_{2.5}$ levels in surrounding air at 5 µg/m^3 for the yearly average and 15 µg/m^3 for the 24-hour average. The Air Quality Act of 2004 set the National Ambient Air Quality Standards (NAAQS) for $PM_{2.5}$ in South Africa, with progressively higher standards until 2030 (Edlund et al., 2021).

1.1 Problem statement

Everyone has the right to a healthy and safe environment, according to Section 24(a) of the Constitution of the Republic of South Africa Act, 1996 (Act No. 108 of 1996). However, the Steve Tshwete Local Municipality consistently records high ambient pollutant concentrations, some above the NAAQS (*https://www.iqair.com/south-africa/mpumalanga/middelburg*). The main local municipality in the district, Steve Tshwete, is famous for having several Eskom power plants and is primarily impacted by its mining and industrial industries. These economic activities are the primary sources of local emissions, contributing significantly to the province's total emissions. Despite a relatively small population of 229,831 in 2011, the municipality exhibits notably higher Gross Value Added (GVA) per capita, energy consumption, and emissions per capita compared to similarly sized municipalities. This disparity is closely linked to the high carbon intensity of the mining and industrial sectors, highlighting the importance of considering these factors in a comprehensive analysis of greenhouse gas (GHG) emissions.

The significant electricity generation activities within the local municipality account for this phenomenon. Additionally, in the year 2012, Steve Tshwete saw emissions of just over 7 million tons of carbon equivalent (tCO2e) and 19.8 million GJs. These emissions were primarily attributed to community activities (i.e., Residential, Industrial, Transportation, etc.), accounting for 97.86% of the total, while the local authority's operational activities, including electrical losses, contributed 2.14% (Verma et al., 2021).

Through inhalation, atmospheric $PM_{2.5}$ causes a detrimental impact on human well-being (LiT et al., 2018). Populations living in low- and middle-income countries bear a disproportionate burden of the effects of $PM_{2.5}$, with the most at-risk populations, such as expectant women, infants, and young children, experiencing the most significant repercussions. (Edlund et al., 2021).

Failure to address this issue could lead to a surge in premature mortality and morbidity rates, heightened dependence on therapeutic medications, and an increase in visits to healthcare professionals or emergency rooms, as highlighted by Díaz and Rosa Dominguez (2009). This study seeks to evaluate the health risks linked to exposure to elevated $PM_{2.5}$ concentrations, aiming to inform policies designed to improve air quality and protect human health in identified hotspot areas. By comprehensively understanding the health implications of $PM_{2.5}$ exposure, policymakers can implement targeted interventions and regulatory measures to mitigate the adverse effects on public health and ensure a healthier living environment for affected communities.

1.2 **Justification for the study**

Research that fully evaluates the health concerns associated with airborne $PM_{2.5}$ emissions in areas with considerable industrial and power generation operations is lacking in South Africa. While epidemiological studies offer valuable insights into the health risks of $PM_{2.5}$ exposure, they often place less emphasis on detailed exposure assessments. For instance, a study in the Vhembe District (Edlund et al., 2021) highlighted that local communities near brickmaking industries are exposed to high $PM_{2.5}$ levels, particularly during winter, but did not delve deeply into individual exposure assessments. Lack of exposure assessments in epidemiological studies leads to an increased uncertainty of the research findings. The study utilized ambient $PM_{2.5}$ concentration and carried out a human health risk assessment. Additionally, the study utilized data from available databases to account for variables such as body weight, life expectancy, inhalation rates, and exposure duration to advance the risk assessment outputs. The outcomes of this study are poised to substantially augment the existing body of knowledge, offering scientific insights into the levels of exposure risk faced by individuals residing in such areas. These findings hold considerable significance as they can inform regulatory agencies and key stakeholders involved in ambient air pollution management, facilitating the implementation of targeted mitigation measures. By employing emission reduction controls and implementing remedial actions, stakeholders can effectively safeguard the health and well-being of individuals exposed to elevated levels of airborne $PM_{2.5}$ pollutants in these regions.

1.3 Study aim

The aim of this study was to evaluate the health risks caused by airborne $PM_{2.5}$ exposure in the Steve Tshwete local municipality, Mpumalanga Province, in South Africa.

1.4 Research question

What are the adverse health risks of $PM_{2.5}$ exposure for the different groups of people (children 6 to 12 years and adults (+65 years)) residing in the Steve Tshwete Local Municipality?

1.5 Study objectives

The study seeks to achieve the following objectives:

1. To characterize diurnal and annual ambient $PM_{2.5}$ emissions in Steve the Thswete Local Municipality;
2. To determine seasonal variations of ambient $PM_{2.5}$ in the Steve Tshwete Local Municipality;
3. To assess the health risks of exposure to $PM_{2.5}$ and risk characterization for different subgroups (children and adults) in the Steve Thswete Local Municipality.

CHAPTER TWO: LITERATURE REVIEW

This chapter reviews previous literature concerning $PM_{2.5}$ exposure, aiming to establish connections between this study and prior research. The chapter elaborates on various aspects, including emission factors and the mechanisms governing $PM_{2.5}$ generation and transport, the chemical and physical transformations of $PM_{2.5}$ during transport with a focus on the influence of meteorological parameters, seasonal variations, and meteorological influences on $PM_{2.5}$ composition. Additionally, it explores health effects and susceptible population groups, risk assessment methods, techniques for measuring $PM_{2.5}$ in outdoor environments, and the pathways through which individuals are exposed to $PM_{2.5}$.

2. **Literature review**

2.1 **Seasonal Variations and Meteorological Influences on PM2.5 Composition.**

Particulate matter (PM) consists of a mixture of substances, including dust from the Earth's crust, sea salt, plant and animal debris, and particles primarily produced by the combustion of fuels in vehicles, industries, power plants, and homes. These particles are categorized based on their size. According to Bambelo (2024), PM10 comprises particles with a diameter of 10 micrometers or less, whereas $PM_{2.5}$ comprises particles with a diameter of 2.5 micrometers or less.

$PM_{2.5}$ consists of a complex mixture of primary particles directly emitted from various sources and secondary particles formed through atmospheric chemical reactions of gaseous precursors (Sun et al., 2022). Climate change influences atmospheric $PM_{2.5}$ levels and overall air quality, while air quality and particulate matter also contribute to climate change (Bhattarai et al., 2024). Rising temperatures can increase ground-level ozone in many regions, complicating attempts to fulfill ozone and particle matter air quality criteria. The impact of climate change on particulate matter is evident in its potential to elevate atmospheric concentrations, thereby degrading ambient air quality (Bambelo, S., 2024). Pollutants such as black carbon, ozone, and aerosol particles also affect climate patterns by altering precipitation and temperature (Brook et al., 2024).

The amount of airborne dust in the atmosphere is mainly determined by two factors: emission sources and climatic variables (Berhane et al., 2024). The impact of weather on $PM_{2.5}$ is more complex due to the mechanisms of particle generation and removal, as well as the diverse components that make up these particles. For example, high temperatures encourage the formation of water vapor, which then condenses onto primary particles. Additionally, particles are effectively removed from the atmosphere through wet deposition, where clouds and rain help to scavenge particles (Bambelo, 2024).

The seasonal divisions, defined by statistical classification, are as follows: Summer (December, January, February), Autumn (March, April, May), Winter (June, July, August), and Spring (September, October, November) (van der Walt & Fitchett, 2020). Previous research has seldom explored the seasonal variations in the chemical composition and origins of fine particulate matter ($PM_{2.5}$), particularly regarding how emission sources change across different pollution levels and seasons (Xie et al., 2019). Among the four seasons, winter typically shows the highest $PM_{2.5}$ concentrations, followed by spring, autumn, and summer (Ai et al., 2023; Kong et al., 2020; Xing et al., 2022). Wind speed plays a crucial role in dispersing $PM_{2.5}$ particles (Liu et al., 2018). In winter, many northern Chinese cities experience elevated $PM_{2.5}$ levels due to unfavorable meteorological conditions and increased coal burning for heating (Lee et al., 2023). In contrast, summer's favorable weather and reduced coal heating lead to the lowest $PM_{2.5}$ concentrations (Duan et al., 2021). In Mpumalanga, higher secondary aerosol levels during summer and autumn are mainly attributed to regional transport from industrial activities (Bambelo, 2024). In spring, secondary aerosols are likely generated by intensive agricultural activities in the Free State Province (Muyemeki et al., 2021).

A study by Tao et al. (2013), identified significant seasonal variations in $PM_{2.5}$ composition, with particulate organic matter (POM) and soil dust concentrations reaching 31.1% and 15.0%, respectively, in spring. These levels are notably higher compared to other seasons. Additionally, the correlation between Elements of carbon (EC) and organic carbon (OC) was lower in spring compared to other seasons, suggesting more complex sources for carbonaceous aerosols during this period, with dust storms and burning playing pivotal roles. Further investigations detailed the impacts of these factors on $PM_{2.5}$ characteristics, shedding light on major contributors to springtime $PM_{2.5}$ pollution.

It is essential to recognize that specific meteorological conditions, including static wind and temperature inversions, frequently occur during the winter and autumn months. These conditions can contribute to extended periods of severe pollution, as emphasized by Liao et al. (2017). For instance, in Chengdu, China, the average $PM_{2.5}$ concentration was considerably higher in winter compared to other seasons. Wang et al. (2004) reported an average $PM_{2.5}$ concentration of 156 µg/m^3 in July 2001–2002, significantly higher than the 56 µg/m^3 observed in January. Similarly, Tao et al. (2013) found that the average $PM_{2.5}$ concentration in Chengdu in June 2010 reached 225.5 ± 73.2 µg/m^3, based on data from 2009 to 2010. During the winter of 2013–2014, Chengdu experienced several severe pollution events, with $PM_{2.5}$ levels reaching extreme levels. For example, on Lunar New Year's Day (31 January 2014), $PM_{2.5}$ concentrations peaked at 557.3 µg/m^3 (Liao et al., 2017). These results highlight the significant influence of meteorological conditions on $PM_{2.5}$ levels and underscore the necessity for effective pollution control measures to safeguard public health in urban centers like Chengdu. Moreover, the region's typical basin climate, characterized by a precipitation period concentrated between July and September, high humidity, frequent static winds, and atmospheric stability under neutral weather conditions during winter, plays a crucial role in $PM_{2.5}$ accumulation (Liao et al., 2017).

Additionally, distinct seasonal patterns in Particular matter concentrations were observed throughout the year. These variations typically exhibit greater quantities in the winter and fall and lower amounts in the summer, as reported by Tao et al. (2013). The lower concentrations observed during summer are likely attributed to frequent rainfall events. Precipitation serves as an effective mechanism for removing particles from the atmosphere through a process known as precipitation scavenging. Notably, approximately 70% of the annual precipitation occurs during the three-month period from July to September (Speirs et al., 2023). Conversely, the higher PM concentrations observed during winter and fall can be attributed, at least in part, to specific meteorological conditions. Factors such as lower mixing heights and reduced wind speeds during these seasons contribute to less effective dispersion of pollutants. These conditions hinder the vertical and horizontal dispersion of pollutants, resulting in their accumulation in the atmosphere.

Meteorological conditions significantly influence $PM_{2.5}$ dynamics. Liao et al. (2017) observed that unfavorable diffusion conditions during winter in Chengdu led to the accumulation of pollutants near the ground, while high relative humidity promoted aerosol hygroscopic growth.

Similarly, studies by Wang et al. (2016) and Amil et al. (2016) highlighted the seasonal variability of $PM_{2.5}$ pollution and its composition, emphasizing the role of meteorological factors such as temperature, synoptic circulation patterns, and regional transport in affecting $PM_{2.5}$ concentrations and chemical variability. They also noted a distinct monthly pattern of $PM_{2.5}$ concentrations, with peak levels in winter and troughs in late summer, influenced by seasonal meteorological factors and gaseous parameters.

Synoptic circulation patterns, as discussed by Sun et al. (2022), regulate atmospheric processes and influence the regional transport of air pollutants. Climate changes, particularly the East Asian monsoons, impact the seasonal and interannual variations of aerosol concentrations over China. Chen et al. (2020) added that $PM_{2.5}$ concentrations exhibit national-scale trends, with the lowest concentrations in summer and the highest in winter. These variations are driven by factors such as fuel combustion for central heating in winter and reduced anthropogenic emissions in summer. However, regional variations exist; for instance, enhanced open biomass burning occurs in certain regions during spring.

These studies (Chen et al. 2020; Liao et al., 2017; Amil et al. 2016; Wang et al. 2016; Tao et al. 2013) collectively highlight the complex interactions between meteorological conditions and $PM_{2.5}$ composition, emphasizing the necessity for further research to understand and mitigate the effects of seasonal variations and meteorological influences on air quality. For instance, research in China (Wang et al. (2004) has demonstrated significant spatial and seasonal variations in the relationships between $PM_{2.5}$ concentrations and meteorological factors, underscoring the importance of considering these dynamics in air quality management.

2.2 Exposure pathway analysis

$PM_{2.5}$ particles primarily enter the human body through inhalation, penetrating deep into the respiratory tract and reaching the alveoli. From there, they can translocate into the bloodstream, potentially causing systemic effects (Ye et al., 2023). In South Africa, $PM_{2.5}$ originates from various sources, including industrial emissions, residential burning of solid fuels, vehicle exhaust, dust, and biomass combustion. Once released, these fine particles are carried by air currents, traveling substantial distances and impacting both urban and rural regions (Basith et al., 2022; Muyemeki et al., 2021). Beyond direct inhalation, exposure can occur through dermal absorption and ingestion of contaminated food and water. Upon entering the body, $PM_{2.5}$ induces oxidative stress, inflammation, and cellular damage, contributing to respiratory and cardiovascular diseases, as well as adverse neurological effects (Ye et al., 2023), Understanding these exposure pathways is crucial for assessing health risks associated with $PM_{2.5}$ and for developing effective mitigation strategies.

2.2.1 Sources of PM 2.5

Particulate matter (PM) is air pollution that comes from both natural and human sources (Bambelo, 2024; Marcy et al., 2024; Tiwari et al., 2024). In South Africa, three Air Quality Priority Areas have been designated: the Vaal Triangle Airshed, Highveld, and Waterberg-Bojanala. These areas are particularly prone to exceeding the National Ambient Air Quality Standards (NAAQS) (Wright et al., 2025). Mpumalanga is identified as a significant nitrogen dioxide hotspot, comparable to regions in Germany, India, and China, which are characterized by dense clusters of coal-fired power plants. South Africa's Minimum Emission Standards are notably weaker than those of other countries, allowing coal plants to emit up to 36 times more nitrogen dioxide than the levels permitted in China or Japan (Euripidou et al., 2022).

Particulate matter (PM_{10} and $PM_{2.5}$) pollution in South Africa primarily originates from several key sources, including industrial activities, residential burning of solid fuels, vehicular emissions, dust, and biomass combustion (Basith et al., 2022; Muyemeki et al., 2021). $PM_{2.5}$ comprises a variety of harmful substances, including elevated concentrations of toxic heavy metals and a higher proportion of hazardous components such as sulphates and ammonium salts, which can irritate the respiratory tract and cause adverse health effects (Cui et al., 2025). Diesel engine emissions, domestic coal and wood burning, heavy oil use, and biomass burning from vegetation fires, woods, and agricultural waste all contribute to black carbon, a combustion indicator (Alfeus et al., 2024). For air quality planners to properly prioritize and handle major pollution sources, they must have a thorough grasp of the compositions and contributions of various PM sources.

The South African government has designated the Mpumalanga Highveld as a Highveld Air Pollution Priority Area (HPA) due to substandard air quality in key towns such as eMalahleni, Middelburg, Secunda, Standerton, Edenvale, Boksburg, and Benoni. The National Ambient Air Quality Standards have been surpassed or are under danger of being surpassed in these areas, necessitating targeted air quality management interventions. Satellite data highlights air pollution as a significant concern in Mpumalanga, with major contributors including coal-fired power plants, petrochemical facilities, metal smelters, and mining operations. Notably, Mpumalanga hosts 12 of South Africa's 14 coal-fired power stations, underscoring its central role in the nation's energy production and associated emissions (Fokazi, 2023).

Secunda, a major coal combustion site in Mpumalanga, significantly contributes to air pollution and health issues, despite its economic importance. Environmental groups demand stricter emission controls due to its global impact as a top emitter (Tang, 2022). Because air pollution has a negative impact on the environment and human health, it is more important than ever to mitigate exposure to it. Identifying specific sources of local air pollution is essential. Source apportionment studies are crucial as they reveal pollution sources and quantify their contributions.

Domestic fuel burning

Electricity costs and individual preferences have an impact on South African electrified families' ongoing usage of solid fuels (Adeeyo et al., 2022). Homeowners contribute 4% of particulate matter, which is 42% of emissions from domestic sources (Fokazi, 2023). Around 4.2 million people die each year from ambient air pollution worldwide, and an additional 3.8 million die from indoor air pollution caused by fuels and cookstoves (Wright et al., 2025).

Energy-saving techniques are contributing to extremely high levels of residential air pollution (HAP). The most recent WHO estimates indicate that 4.3 million fatalities occurred in 2012 because of an exposure to HAP from cooking, according to global burden of disease data (Fokazi, 2023; Matandirotya et al., 2023). Therefore, indoor PM produced during cooking has been reported to cause over 2.5 million premature deaths annually, with estimates predicting this number will rise to 27 million by 2030 (Buthelezi et al., 2025). While 1.2 billion people use simple kerosene lamps for lighting, 2.8 billion people still cook and heat their homes using solid fuels (wood, dung, crop wastes, charcoal, and coal) and simple stoves in the twenty-first century. These practices continue to be used by over 3 billion of the world's poorest people, which raises the level of air pollution in homes (Fokazi, 2023).

Wood and biomass combustion is characterized by a high potassium (K^+) content, with minor contributions from sulfate (SO_4^{2-}) and nitrate (NO_3^-) ions. Since potassium is released when plant materials burn, it is a crucial indication of biomass burning. In low-income settlements, elevated potassium levels are particularly indicative of wood burning, given wood's essential role in cooking and heating. Additionally, biomass burning encompasses activities such as open-field burning for agricultural purposes, including crop residue disposal and land preparation (Muyemeki et al., 2021).

Biomass burning significantly contributes to particulate matter, especially during winter months in rural and township areas. During these periods, ambient particulate concentrations can reach hazardous levels, primarily due to domestic fuel combustion for heating. The dry season, spanning August to October, also sees increased fire activity, further elevating particulate matter levels. Notably, biomass burning is predominantly concentrated in the tropical belt, accounting for over 80% of global biomass combustion, with approximately half occurring during savannah fires (Bambelo, 2024). Planning for air quality and putting into practice efficient pollution mitigation techniques require an understanding of the chemical makeup and sources of particulate matter.

In South Africa, the combustion of coal, paraffin, and wood for cooking and heating in low-income areas significantly contributes to urban air pollution. Burning these fuels releases pollutants such as particulate matter, volatile organic compounds (VOCs), carbon monoxide, and sulfur dioxide (Atafar et al., 2025). The amount of sulfur dioxide, hydrogen sulfide, and carbon dioxide produced depends on the type of fuel and the combustion process. Most households rely on simple, small-scale cook stoves, which contribute to the problem, as many of these stoves lack proper hoods or flues to remove pollutants from indoor air. Additionally, unfavorable combustion conditions lead to high emission rates, significantly affecting local air quality. Despite these challenges, (Bambelo 2024) notes that South Africa has made limited progress in developing an inventory of residential combustion emissions.

Industrial Emissions

The environment and human health are adversely affected by industrial emissions, which are a significant source of air pollutants and waste exhausts from numerous operations. These emissions raise significant concerns for the safety and occupational health of workers due to associated odor problems (Zhang et al., 2024). Industrial pollution is typically characterized by high levels of metals such as zinc (Zn), iron (Fe), lead (Pb), nickel (Ni), chromium (Cr), manganese (Mn), and vanadium (V), which are primarily linked to smelters and metallurgical industries. Vanadium is particularly associated with the combustion of bunker fuel (Wang et al., 2024).

In South Africa, the main energy sources powering industrial operations are coal, coking coal, and heavy fuel oil. One major source of particulate matter (PM) that affects both low-income families and industrial processes is the burning of coal. This combustion process releases hydrogen chloride (HCl) gas, which can react with atmospheric ammonia (NH_3) to form ammonium chloride (NH_4Cl) particles. Given coal's dominance in South Africa's energy landscape—accounting for approximately 77% of primary energy needs it stands as a major contributor to HCl emissions. (Muyemeki et al., 2021).

In response to the growing electricity demand driven by the nation's socio-economic development, numerous coal-fired power plants (CFPPs) were established in South Africa, predominantly in the central Mpumalanga Province. Mpumalanga accounts for 83% of the country's coal production and hosts 12 of its 15 CFPPs, underscoring its pivotal role in the nation's energy sector. These CFPPs are predominantly (90%) owned and operated by Eskom, with 80% located within Mpumalanga (Ngamlana et al., 2024). Industrial emissions are a major cause of air pollution, with waste gases from various activities posing risks to human health and damaging the ecosystem. Microparticles from industrial enterprises and vehicles enter the atmosphere of cities (Buzek et al., 2023). The largest emitters in Mpumalanga are found to be residential burning, biomass, mining, industry, and automobiles (Fokazi, 2023).

Odors are released by a variety of industrial sectors as a result of the volatile organic compounds (VOCs) and volatile inorganic compounds (VICs) produced by their operations, such as petroleum refineries, latex processing, bulk drug and pharmaceutical production, tanneries, waste treatment plants, poultry farms, and fish processing facilities. These processes release significant quantities of organic molecules, carbon monoxide, hydrocarbons, and chemicals into the atmosphere. The greenhouse effect is exacerbated by the significant emissions of carbon dioxide, which, while beneficial in moderate amounts by absorbing infrared light from the planet's surface, contribute to climate change when released in excess. The excessive release of these gases and particulate matter leads to adverse environmental impacts (Bambelo, 2024).

Mining

Rare earth element (REE) sources in $PM_{2.5}$ include heavy oil combustion, metal smelting, mining, and oil refining. Additionally, different levels of REEs are released into the atmosphere by road dust, coal combustion, soil, and traffic emissions (Shen, 2024). Open cast mining, in particular, causes significant air pollution issues due to dust and fine particles. Particulate emissions from mines are primarily responsible for air pollution, and the considerable quantity of airborne respirable dust produced by mining operations has been linked to the development of respiratory disorders in mine workers (Gbondo et al., 2024). However, the impact of poor air quality extends beyond mine workers to nearby communities. Air pollution can leave a long-term environmental legacy by destroying local ecosystems and biodiversity. Contaminated air can harm crops, destroy healthy forests, and damage building materials (Bambelo, 2024).

Agricultural sources

Ammonia (NH_3) emitted from agricultural activities plays a significant role in the formation of secondary inorganic aerosols, which contribute to $PM_{2.5}$ air pollution. According to Lan et al. (2024), ambient $PM_{2.5}$ concentrations might be reduced by 13 and 42 $\mu g\ m^{-3}$, respectively, by reducing agricultural NH_3 emissions by 50% and 100%Agricultural emissions account for 30% of all $PM_{2.5}$, as agriculture is both a source of NH_3 emissions and a contributor to $PM_{2.5}$ formation (Wyer et al., 2022). Ammonia released from livestock manure and heavily fertilized fields enters the atmosphere as a gas, further contributing to air pollution. Additionally, agricultural activities often release harmful chemicals, including pesticides and fertilizers (Singh et al., 2024).

Flooded crop fields can also produce methane due to anaerobic decomposition, which occurs when organic matter reduces oxygen levels in the soil. Although methane emissions are much lower than CO_2, they have a significant impact on global warming, contributing about 20% to its effects despite being 200 times less prevalent in the atmosphere than carbon dioxide (Miller et al., 2019). Methane is naturally released from sources such as lakes, coal seams, grasslands, and marshes, as well as from human-made sources like manure management facilities, coal mines, paddy fields, oil and gas drilling, pastures, wastewater treatment plants, and agricultural activities (Bambelo, 2024). Additionally, domesticated animals like cattle, which emit methane, and natural sources such as pine trees, which release volatile organic compounds, also contribute to air pollution (Fokazi, 2023).

Wildfire

Wildfire releases substantial amounts of primary particles and trace gases into the atmosphere. Over the past two decades, the average annual $PM_{2.5}$ emissions from wildfires have been around 36, 18, and 14 million tons per year in the world (Choi et al., 2024). The rising levels of $PM_{2.5}$ from wildfire smoke significantly impact respiratory health, with studies indicating that wildfire-related $PM_{2.5}$ may be more harmful than non-smoke $PM_{2.5}$ pollution (Aguilera et al., 2023). Wildfire-specific $PM_{2.5}$ particles are smaller and contain a higher proportion of oxidative and proinflammatory components, making them more toxic, especially for vulnerable populations such as fetuses (Zhang et al., 2024). Wildland fire smoke is a complex mixture of pollutants, with $PM_{2.5}$ being a key indicator of exposure due to its significant presence in smoke (Ma et al., 2024). Large wildfires release substantial amounts of fine particulate matter, deteriorating regional air quality and causing adverse health effects (Kiely et al., 2024).

Known as "the fire continent," African nations regularly endure a high frequency of fire incidents. Fires have been common in places like KwaZulu-Natal, Mpumalanga Province, and the Western Cape (Adom et al., 2025). When biomass is burned during wildfires, pollutants like carbon monoxide, carbon dioxide, and ozone are produced. Although commonly associated with human activities, pollutants such as particulate matter, carbon monoxide, and volatile organic compounds are also major emissions produced during wildfires, contributing to air quality deterioration (Ma et al., 2022). In the Western Cape, wildfires are common in the summertime, often triggered by dry weather. Rising temperatures during the dry season dry out fynbos vegetation, which increases the risk of fire. Over the last 20 years, 34,851 hectares of vegetated land in the Cape Peninsula have been burned (Bambelo, 2024).

Vehicle emission

Air quality is declining due in large part to vehicle emissions, especially in cities (Wallington et al., 2022). There are an increasing number of cars on the road in South Africa since private vehicle ownership is preferred over public transit. Fuel consumption has increased as a result of the increase of automobiles (Romero et al., 2024). One of the main causes of air pollution is motor vehicle emissions (Shen et al., 2024), and the problem has been exacerbated by the decline of the train system. With frequent train delays and deteriorating rail infrastructure, many residents have been compelled to depend on private vehicles for transportation, leading to a further rise in vehicle emissions in urban areas (Avesh et al., 2024).

Car emissions account for up to 95% of carbon monoxide and 70% of nitrogen oxides in the atmosphere (Azhar et al., 2024). These emissions are a significant contributor to the formation of photochemical smog, especially in areas with heavy traffic congestion (Hoekman & Welstand, 2021). In urban settings, vehicular emissions are the leading cause of ambient air pollution. As the number of car owners grows, developing nations face an increased risk of pollution from vehicle emissions. Moreover, the likelihood of traffic congestion rises as vehicle numbers continue to climb (Bambelo, 2024). With a number of benefits over internal combustion engine vehicles (ICEVs), including fewer greenhouse gas emissions, less noise pollution, and no harmful exhaust pollutants, electric vehicles (EVs) are becoming more and more accessible worldwide. EVs nevertheless emit non-exhaust particulate matter (PM), even though they are frequently regarded as environmentally beneficial or zero-emission vehicles because they don't emit exhaust. EVs' tires and brakes emit PM pollutants and resuscitate road dust, much like ICEVs do, which can have an adverse effect on the atmosphere.

Additionally, there are currently no active regulations addressing these non-exhaust PM emissions (Woo et al., 2022). Vehicle emissions are a significant threat to both human health and the environment, contributing to long-term greenhouse gas increases and climate change. In urban areas, transport emissions are a primary source of particulate matter, which is linked to higher respiratory risks. Diesel vehicles release higher levels of particulate matter and nitrogen oxides, whereas gasoline vehicles emit greater quantities of hydrocarbons (HC), carbon monoxide (CO), and polycyclic aromatic hydrocarbons (PAHs). Exposure to diesel exhaust is especially detrimental to health. Road traffic is the largest source of air pollution, contributing 41.4% of total emissions (Kumar et al., 2023).

Other Natural and Anthropogenic Sources

$PM_{2.5}$ is naturally produced by burning biomass, dust storms, and ocean spray. However, a number of human activities, including power generation, vehicle traffic, agricultural burning, industrial operations, and the use of domestic fuels, also create $PM_{2.5}$ and its precursors (Zhang et al., 2021).

In South Africa's low-income communities, irregular waste collection results in the accumulation of solid waste, which residents often handle by burning. This practice releases significant amounts of ammonium ions (NH_4^+) and smaller quantities of chloride (Cl^-) and potassium (K^+). The presence of Cl^- is likely due to salt-containing food items and chlorine-based materials in household waste, while mixing domestic waste with garden waste may explain the K^+ levels (Muyemeki et al., 2021).

Pollutants such as particulate matter ($PM_{2.5}$), volatile organic compounds (VOCs), carbon monoxide (CO), sulfur dioxide (SO_2), and ammonia (NH_3) are produced when municipal solid waste (MSW) is burned openly. Chlorine has the highest emission factors among the elements measured, with rubber materials contributing significantly due to their chlorine content. Furthermore, burning dry vegetation releases about ten times more polycyclic aromatic hydrocarbons (PAHs) than burning moist vegetation, with a marked preference for odd-numbered n-alkanes (Wang et al., 2023).Coarse particulate matter (PM_{10}) in South Africa's low-income settlements primarily originates from dust-related sources characterized by crustal elements such as calcium (Ca), magnesium (Mg), silicon (Si), aluminum (Al), iron (Fe), titanium (Ti), and manganese (Mn). These elements are generated both locally, through soil resuspension and construction activities, and via regional transportation of dust aerosols. This source is also influenced by resuspended dust from motor vehicle traffic on unpaved roads. Metals like chromium (Cr) and vanadium (V) found in dust may result from soil contamination by industrial emissions.

Important markers of vehicle emissions include nitrate (NO_3^-), lead (Pb), zinc (Zn), manganese (Mn), and iron (Fe). Both gasoline and diesel-powered cars, as well as wear from engines and brakes, are associated with zinc, manganese, and iron. Iron is found in catalysts used for the combustion of gasoline, whereas zinc is frequently added to lubricating oils and can be released during the combustion of diesel engines. For low-income areas to implement successful air quality management plans, it is essential to comprehend the contributions of various sources (Muyemeki et al., 2021).

Pollutants such as SO2, NOx, and NH3 from different direct sources undergo chemical modification to generate secondary aerosols, which are mostly composed of SO4^2$^-$, NO3$^-$, and NH4+. Long-distance transit can also produce these aerosols. Because Cl is displaced in sea salt particles by acidic impurities (H2SO4 and HNO3), resulting in the creation of sulfate and nitrate salts, aged sea salt sources are generally characterized by high amounts of Na and low levels of Cl. Cl loss may also happen as air masses travel great distances to deliver sea salt to the research location (Muyemeki et al., 2021).

Natural sources of air pollution include volcanoes, which emit particles, chlorine, and sulfur, and wildfires, which produce smoke, carbon dioxide, and carbon monoxide (Fokazi, 2023). Sea salt aerosols, bushfires, crustal dust, vegetation (including pollen and fungal spores), volatile organic compounds (VOCs), and animal carcasses are some of the main natural sources of particulate matter. Engine combustion, power plants, mining, different industrial processes, agriculture, and home heating systems are examples of man-made sources (Fokazi, 2023).

Indoor pollution

Combustion products, in addition to tobacco smoke, can originate from a variety of sources, including wood stoves, gas stoves, fireplaces, unvented kerosene, and gas space heaters. Particulate matter, radon, nitrogen dioxide, and carbon monoxide are among the contaminants released by these sources. Research indicates that children who reside in households with wood stoves experience a notably higher number of respiratory problems compared to those who do not (Bambelo, 2024).

2.2.2 Emission factors and mechanisms governing the generation and transport of PM2.5.

An emission factor quantifies the number of specific pollutants discharged per unit mass of combustion or energy produced. By identifying these emission factors as the pollutants are generated, constructing more precise emissions inventories becomes viable (Zhang et al., 2021). This allows for an evaluation of the true impact of a specific pollution source on air quality, human health, and climate crises (Guerrero et al., 2019). Additionally, with the rapid industrialization of human society, the majority of $PM_{2.5}$ sources, aside from natural ones, are increasingly linked to human activities (Xiao et al., 2023).

Atmospheric particulate matter (PM) can be divided into two fundamental categories: naturally occurring $PM_{2.5}$ and human-induced $PM_{2.5}$. Naturally occurring $PM_{2.5}$ is mainly linked to dust storms, while anthropogenic $PM_{2.5}$ emissions can be classified into indoor and outdoor sources. Outside activities such as warming, preparing food, and tobacco use release $PM_{2.5}$ particles in indoor spaces. $PM_{2.5}$ emissions are caused by anthropogenic outdoor activities such as smoking, burning fossil fuels, incinerating garbage, and cooking outside (Moniruzzaman et al., 2022; Singh et al., 2021; Guerrero et al., 2019; Brook et al., 2007). Beyond these primary categories, particulate matter (PM) in the atmosphere is caused by air pollutants such as sulfur dioxide (SO2), ammonia (NH3), and volatile organic compounds (VOCs) from various industrial and other sources. As stated by Xu and colleagues (2019), burning wood at home, burning fossil fuels, uncontrolled traffic and industry, burning garbage, and road dust are the main man-made causes of $PM_{2.5}$.

These industrial emissions contribute to the increased concentration of $PM_{2.5}$ particles in the atmosphere (Xue et al., 2023). The scale and intensity of global field combustion have notably increased in recent years, largely driven by environmental factors and human activities (Mateos et al., 2019; Zhang et al., 2020). Combustion-related emissions predominantly release $PM_{2.5}$, contributing to over 90% of the released PM (Huang et al., 2023). Traffic emissions, including car exhaust and road dust, significantly contribute to atmospheric particulate matter. Among these sources, fuel combustion and the release of fine particles from vehicle engine exhausts play a substantial role (Zhu et al., 2023). When $PM_{2.5}$ particles remain suspended in the atmosphere for prolonged durations, they can form aerosols. These aerosols negatively affect regional climate change, air quality, and radiation in the Earth's surface-atmosphere system. Consequently, they contribute to the exacerbation of climate change (Romanov et al., 2022).

Understanding the impact of $PM_{2.5}$ exposure requires a thorough understanding of its chemical composition, sources, sinks, and formation mechanisms at various scales, as emphasized by Tao et al. (2013). In exposure science research, $PM_{2.5}$—which is composed of primary particles from various emission sources and secondary aerosols created by chemical interactions of gaseous precursors in the atmosphere—is a major problem. Simon et al. (2023) note that $PM_{2.5}$ can either be directly emitted into the atmosphere or formed through chemical and physical processes involving precursors such as VOCs, nitrogen oxides (NOx), and SO2. Furthermore, Hu et al. (2023) emphasizes stationary climatic conditions, such as calm winds, significant thermal inversions, and a limited boundary layer height, and substantial emissions of anthropogenic pollutants exacerbate air quality. This interaction of emissions, atmospheric chemistry, and meteorological factors underscores the complexity of $PM_{2.5}$ dynamics and stresses the need for comprehensive investigations in exposure science.

The primary constituents of $PM_{2.5}$, along with their precursors, participate in the formation of secondary $PM_{2.5}$ through reactive processes (Tao et al., 2024). Notably, secondary $PM_{2.5}$ comprises sulfate, nitrate, ammonium, organic carbon, black carbon (primary), and soil (primary), with black carbon, essentially soot, and soil serving as primary sources (Hao et al., 2020). On the other hand, unlike primary $PM_{2.5}$, the other substances that are categorized as secondary $PM_{2.5}$ do not originate from mobile sources directly. Rather, through coagulation, chemical reactions, and other processes, they contribute to $PM_{2.5}$. As previously mentioned, the primary source of secondary $PM_{2.5}$ particles is the chemical reaction between ammonia and SO2 (in the presence of water) or ammonia and NOx (also in the presence of water), which results in the creation of ammonium sulfate or ammonium nitrate (Hodan & Barnard, 2004).

Moreover, secondary formation typically occurs through chemical reactions in the atmosphere and often appears downwind of the original emission source. Primary emissions can take the form of solids, liquids, or gases (Seinfeld et al., 2016). Particles emitted directly in solid or liquid states, as well as those formed solely through cooling after being released into the atmosphere (known as condensibles), are classified as primary particles. In contrast, secondary particles are exclusively generated from gases undergoing reactions within the atmospheric environment (Hodan & Barnard, 2004).

Generally speaking, precursor molecules that have not yet developed into particulate matter are referred to as diesel-emitted organic gases (DEOG). According to Hodan and Barnard (2004), these DEOG components have the potential to condense and produce particle debris, which is typically less than 0.1µm. Additionally, during biomass burning events, significant concentrations of levoglucosan (LG), organic carbon (OC), water-soluble organic carbon (WSOC), and K+ and Cl− ions have been detected in ambient PM2.5.These same compounds have also been quantified in significant quantities within smoke particles originating from the combustion of wheat straw and rape straw in controlled experiments simulating near-source conditions (Tao et al., 2013).

Assessing the transmission pathways and potential sources of $PM_{2.5}$ is essential for creating speculative plans to enhance air quality. This is especially critical for identifying key regions where emission reduction measures can be most effectively implemented during periods of heavy pollution (Liao et al., 2017). According to various reports, mobile sources contribute differently to the present airborne $PM_{2.5}$ concentrations. Three primary pathways lead to $PM_{2.5}$ emissions from mobile sources: direct emissions from vehicle tailpipes, re-entrainment of materials on roadways (commonly referred to as fugitive dust), as well as secondary production from precursor emissions such ammonia (NH3), nitrogen oxides (NOx), sulfur dioxide (SO2), and volatile organic compounds (VOCs). The first two processes are typically categorized as primary $PM_{2.5}$ emissions (Hodan & Barnard, 2004). The pollution of $PM_{2.5}$ in a basin can easily escalate from a local to a regional scale due to the intricate terrain, which enhances the intra-transport and trapping of pollutants (Liu et al., 2024).

To sum up, understanding how $PM_{2.5}$ is produced and transported is essential for assessing its consequences and creating practical plans to lessen them for both the environment and human health. Research by (Tao et al., 2013; Hodan & Barnard, 2004: Simon et al., 2023; Hu et al., 2023) offers valuable insights into the complex nature of $PM_{2.5}$, highlighting the importance of considering its chemical composition, sources, sinks, and formation mechanisms at various scales.

2.2.3 Chemical and Physical Transformations of $PM_{2.5}$ During Transport: Influence of Meteorological Parameters.

$PM_{2.5}$ is a complicated mixture of secondary particles created by chemical reactions of gaseous precursors in the environment and primary particles directly released from a variety of sources (Sun et al., 2022). This dynamic nature of $PM_{2.5}$ is heavily influenced by meteorological conditions, which play a crucial role in its chemical and physical transformations during transport. Understanding the complex interplay between meteorological conditions and the chemical and physical transformations of $PM_{2.5}$ is crucial for effective air quality management.

Sun et al. (2022) provide valuable insights into the pivotal role of meteorological conditions in shaping various aspects of $PM_{2.5}$ dynamics. Weather factors like temperature, wind speed, humidity, and atmospheric stability have a big impact on how $PM_{2.5}$ behaves in the atmosphere. For instance, temperature inversions can trap pollutants near the surface, leading to local accumulation of $PM_{2.5}$, while prevailing wind patterns determine the regional transport of pollutants over large distances. Additionally, meteorological conditions impact the chemical conversion of air pollutants, including $PM_{2.5}$ constituents, through processes such as photochemical reactions and atmospheric mixing (Alves et al., 2023). Moreover, wet, and dry depositions of $PM_{2.5}$ are influenced by precipitation patterns, atmospheric turbulence, and boundary layer dynamics, which affect the removal of particles from the atmosphere (Sun et al., 2023). The interplay of these meteorological factors ultimately shapes the concentrations and spatial distribution of $PM_{2.5}$, highlighting the need for a comprehensive understanding of their role in determining air quality.

(Chen et al., 2020) provide additional insight into the intricate connection between $PM_{2.5}$ levels and weather. They emphasize that human emissions and dispersion conditions, which are influenced by topographical features and climatic factors, are the primary cause of notable spatiotemporal patterns of $PM_{2.5}$ concentrations. Complex patterns of $PM_{2.5}$ pollution are created by the interaction of meteorological factors and variations in emissions sources, such as industrial operations and vehicle traffic (Han et al., 2023). For instance, mountainous terrain can affect the dispersion of pollutants, leading to higher concentrations in valleys compared to surrounding areas. Additionally, seasonal variations in meteorological conditions, such as temperature inversions and precipitation patterns, further modulate $PM_{2.5}$ concentrations throughout the year. This underscores the complexity of $PM_{2.5}$ dynamics, which are shaped not only by emissions sources but also by meteorological conditions.

(Wang et al., 2022) highlight the difficulties in analyzing $PM_{2.5}$ trends over several years, pointing out that variations in meteorology, in addition to variations in emissions or atmospheric chemistry, might influence recorded $PM_{2.5}$ concentrations. This highlights the need for careful consideration of meteorological factors in interpreting long-term trends in $PM_{2.5}$ concentrations. (Xu et al., 2016) indicates the role of both synoptic circulations and local meteorology in influencing air quality, particularly during severe $PM_{2.5}$ pollution episodes. They note that abnormal synoptic situations, such as sustained weak pressure and inversions in the low troposphere, can lead to severe pollution events. Furthermore, the development of the planetary boundary layer (PBL) and microscale meteorological phenomena like mountain-valley wind and sea-land breeze can significantly impact local air quality, particularly when it comes to diurnal changes.

(Amil et al., 2016) emphasize the diverse sources of $PM_{2.5}$ constituents, including volatile, non-volatile, and semivolatile components, which contribute to the complexity of $PM_{2.5}$ composition and its variability in the atmosphere. (Simon et al., 2023) discuss the regional and seasonal variations in the chemical constituents of $PM_{2.5}$, highlighting the role of emissions sources; atmospheric chemistry; and meteorological conditions in shaping $PM_{2.5}$ composition.

According to a study by Zhang et al. (2022), emissions, weather conditions, and geographic location all affect $PM_{2.5}$ concentrations. The diffusion, accumulation, and transmission of $PM_{2.5}$ are significantly influenced by meteorological conditions in particular. The study emphasizes how climatic variables including temperature, humidity, wind speed, atmospheric pressure, and boundary layer height affect $PM_{2.5}$ levels both directly and indirectly.

The complex relationship between weather and $PM_{2.5}$ is demonstrated by these studies (Hanet al., 2023; Simon et al., 2023; Wang et al., 2022; Zhang et al. 2022; Xu et al., 2016), highlighting the need for in-depth investigation to fully understand and mitigate the negative impacts of $PM_{2.5}$ pollution on the environment and public health.

2.2.4 **Exposure route and uptake**

$PM_{2.5}$ particles are generated through a series of chemical reactions involving gaseous substances, which can be absorbed or dissolved. Most of these fine particles result from the condensation of vapors formed through chemical reactions of various gas-phase precursors. Consequently, $PM_{2.5}$ particles can either be newly formed or result from the aggregation of particulate elements produced by existing particles. These particles have varying atmospheric lifetimes, ranging from days to weeks, and can travel significant distances, from hundreds to thousands of kilometers (Radulescu et al., 2015).

Heavy metals are among the most significant components of $PM_{2.5}$ because they can enter the human body through ingestion, inhalation, and skin contact, and they can persist in the atmosphere for extended periods (Xiao et al., 2023). Globally, nine out of ten people (90%) breathed polluted air that exceeded the WHO 2005 air quality guideline of 10 $\mu g/m^3$ in 2019, contributing to approximately 7 million premature deaths annually due to the combined effects of ambient and household air pollution (Bhattarai et al., 2024).

Additionally, $PM_{2.5}$ elements can transport various harmful substances that bypass the nasal filtering process, reach the top of the nasal passages due to airflow, and then spread throughout the body via the respiratory system, causing long-lasting damage (Amnuaylojaroen & Parasin, 2023). Exposure can happen through skin, ingestion, or inhalation. It has been argued that inhalation is the most prevalent and detrimental exposure route (Wang et al., 2022).

The inhalation rate of $PM_{2.5}$ for cyclists is estimated to be 5.92 to 8.99 times higher than for car users. Dons et al. (2012) discovered that individuals using active transportation modes inhale twice as much $PM_{2.5}$ compared to those using passive modes. The degree of physical exertion while travel raises the inhaling dose. Underestimating exposure levels might result from applying a consistent breathing rate in various settings. The health effects associated with exposure may be underestimated if factors including lung deposition, tidal volume, and breathing frequency are ignored (Singh & Agarwal, 2024).

2.3 Health effects and susceptible population groups.

As a major source of death and morbidity worldwide, air pollution presents a serious environmental risk to human health (Chen & Hoek, 2020). One significant air pollutant that has a significant negative impact on human health is fine particulate matter ($PM_{2.5}$) (Amnuaylojaroen et al., 2022). Numerous indoor and outdoor air pollutants have been associated in epidemiological studies with respiratory symptoms, hospitalizations, and the emergence of a wide range of illnesses (Williams et al., 2025). Research indicates a potential association between $PM_{2.5}$ exposure and increased rates of illness and death (Liu et al., 2023; Nunez et al., 2021; Wu et al., 2020). In addition to influencing $PM_{2.5}$'s physicochemical characteristics, key chemical elements such as organic carbon (OC), elemental carbon (EC), and different ions also provide serious health dangers. Furthermore, a variety of health problems are exacerbated by trace hazardous substances such polycyclic aromatic hydrocarbons (PAHs) and heavy metals that are present in $PM_{2.5}$. For example, lead (Pb) is recognized as a neurodevelopmental toxin impacting children's health and cognitive development (Xu et al., 2019). Due to their small size, $PM_{2.5}$ particles can penetrate deep into the human respiratory system, gaining considerable attention because of their potential health impacts (Zhang et al., 2023).

Chronic exposure to air pollution, particularly $PM_{2.5}$, greatly increases the risk of developing various health issues, including asthma (Bhosale et al., 2025; Caffè et al., 2025; Huang et al., 2025), cardiovascular diseases (Kumar et al., 2025; Zhou et al., 2025; Krittanawong et al., 2023; Hayes et al., 2020), and skin disorders (Rauf et al., 2024; Wang et al., 2024). Additionally, adverse birth outcomes (Fussell et al., 2024; Parasin et al., 2024) and diminished sperm quality (Abilash & Sridharan, 2024) have been associated with $PM_{2.5}$ exposure. Exposure to $PM_{2.5}$ has been linked to increased hospitalization and mortality from chronic obstructive pulmonary disease (COPD), a condition causing breathing difficulties and ranking as the fourth leading cause of death globally. Fine particles like $PM_{2.5}$ have been associated with an elevated risk of developing COPD (Air pollution, 2024). Furthermore, $PM_{2.5}$ exposure can disrupt blood clotting pathways and induce cellular changes, triggering inflammatory responses that heighten the risk of cardiovascular diseases (Hu et al., 2024).

Additionally, there is an increased risk of type 1 and type 2 diabetes (Chin et al., 2024; Li et al., 2024; Chen et al., 2024), lung cancer (Chen et al., 2025; Amnuaylojaroen & Parasin, 2024; Attiq et al., 2024), and heightened morbidity and mortality from COVID-19 (Maniat et al., 2024; Jacobs et al., 2024; Zhao & Wang, 2024). Furthermore, $PM_{2.5}$ exposure contributes to overall disease mortality (Tariq et al., 2023).

Additionally, the following list highlights some of the major diseases and health issues associated with $PM_{2.5}$ exposure, emphasizing the importance of addressing air pollution to protect public health:

- **Heart Disease**: 32% of deaths are from heart disease. Exposure to $PM_{2.5}$ home air pollution is responsible for around 12% of all fatalities related to ischemic heart disease, amounting to over a million premature deaths per year (WHO, 2022).

- **Stroke**: 23% of deaths are from stroke. Approximately 12% of all stroke deaths can be attributed to daily exposure to $PM_{2.5}$ residential air contamination from the combustion of solid fuels (WHO, 2022).

- **Lower Respiratory Infections (LRIs)**: 21% of mortality is due to LRIs. Exposure to $PM_{2.5}$ home air pollution causes 44% of all pneumonia deaths in children under the age of five. Adults exposed to $PM_{2.5}$ household air pollution are at increased risk for developing acute lower respiratory infections, accounting for roughly 22% of all adult pneumonia deaths (WHO, 2022).

- **Chronic Obstructive Pulmonary Disease (COPD)**: 19% of deaths are from COPD. Exposure to $PM_{2.5}$ household air pollution causes around 23% of all adult fatalities from COPD in low- and middle-income nations (WHO, 2022).

- **Lung Cancer**: 6% of lung cancer-related fatalities in adults are attributable to exposure to carcinogens in $PM_{2.5}$. The use of solid fuels like charcoal and coal for domestic energy needs results in home air pollution (WHO, 2022).

The Global Burden of Disease (GBD) study reveals that air pollution, both indoor and outdoor, was responsible for a staggering 9 million deaths worldwide in 2019, with the majority—61.9%—linked to increased cardiovascular mortality (Krittanawong et al., 2023). The health impacts of $PM_{2.5}$ exposure are closely connected to cellular and molecular inflammation, as well as oxidative stress responses, which are recognized as key mechanisms behind cardiopulmonary effects (Aztatzi-Aguilar et al., 2016). Additionally, heavy metals tend to accumulate in the human body, causing toxic effects such as respiratory and lung diseases, and potentially increasing the risk of lung cancer (Xiao et al., 2023).

Association has been established between higher levels of $PM_{2.5}$ and the occurrence of cardiovascular and respiratory disorders, primarily affecting older individuals and those with pre-existing pulmonary impairment (Al-sareji et al., 2022; Alves et al., 2023; Vinson et al., 2020). For example, children are inherently more vulnerable to the adverse health impacts of air pollution than adults due to their increased respiratory rate and frequency of breathing through their mouths, resulting in a greater uptake of harmful substances (Frazenburg et al.,2025; Amnuaylojaroen & Parasin, 2023; Mainka & Fantke, 2022; Sánchez-Soberón et al., 2019). As a result, they are considered a highly vulnerable population when it comes to exposure to $PM_{2.5}$ and its accompanying metallic components. Moreover, exposure to $PM_{2.5}$ in pregnant women worsens recession in children during their teenage years (Ju et al., 2023). The young population may have a genetic predisposition to lung damage and is more susceptible to toxic metal exposure from airborne particulate matter (Radulescu et al., 2015). Furthermore, extended exposure to surroundings with high levels of heavy metals can affect people in unforeseen ways, especially youngsters (Zhu et al., 2015). In Cape Town, $PM_{2.5}$ concentrations exceeded WHO guidelines, posing increased health risks to adults, children, and infants (Alfeus et al., 2024).

Moreover, lung cancer mortality is influenced by PM2.5 (Xu et al., 2023). The International Agency for Research on Cancer (IARC) has classified poor air quality due to PM_{10} and $PM_{2.5}$ particles as having carcinogenic qualities, according to recent research findings (Alves et al., 2023; Cui et al., 2023; Thangavel et al., 2022).

2.4 Methods of measuring $PM_{2.5}$ in outdoor spaces

Given the intricate interplay between humans and their surroundings, it becomes imperative to incorporate contextual elements, including environmental, socioeconomic, and behavioral factors, into exposure assessment. This holistic approach encompasses all facets of estimating or measuring exposure to a particular agent. To explore variations in individual exposure to concerning pollutants, factors such as age, gender, socioeconomic status, neighborhood attributes, activity levels, or ethnicity necessitate the development of novel methods and tools (Steinle et al., 2015).

Advanced spatial models have been built utilizing machine learning technology to improve the accuracy of short-term $PM_{2.5}$ exposure estimates while taking spatiotemporal variability into consideration. In epidemiological studies, one of the most popular models for predicting $PM_{2.5}$ exposure levels is land-use regression (LUR). The LUR model uses regression models, gathers data using geographic information systems, and aggregates ambient $PM_{2.5}$ observations from a limited number of sites to predict geographical variations in $PM_{2.5}$ levels (Zhang et al., 2020).

Zhan et al. (2017) and Chen et al. (2018) used a geographically weighted gradient boosting machine and a random forest, respectively, to estimate daily $PM_{2.5}$ concentrations across China. Wong et al. (2021) estimated daily outdoor $PM_{2.5}$ levels in Taiwan using land-use regression (LUR) and the XGBoost algorithm. Bi et al. (2020) used a similar approach to predict daily $PM_{2.5}$ exposure in California by combining satellite, land-use, and low-cost sensor data in a spatially weighted regression model with random forests. Hu et al. (2017) used a random forest model, aerosol optical depth data, weather, and land-use characteristics to forecast daily $PM_{2.5}$ levels across the United States. Meanwhile, Brokamp et al. (2018) estimated daily $PM_{2.5}$ concentrations (1 × 1 km) in Cincinnati using a random forest model that used satellite, meteorological, atmospheric, and land-use data.

The microenvironmental exposure (ME) model forecasts $PM_{2.5}$ exposures for individuals and communities using indirect measurements such as microenvironmental concentrations and individual time-activity data. Previous research (Bi et al., 2020; Chen et al., 2018; Hu et al., 2017; Zhan et al., 2017) has demonstrated the effectiveness of this model, positioning it as a promising alternative method. Additionally, by incorporating both spatial and temporal concentrations, accounting for the infiltration of outdoor contaminants into indoor areas, and taking into account the mobility patterns of individuals or communities, the ME model can effectively calculate exposures across many contexts. Therefore, in epidemiological research, the ME model is regarded as a useful method for calculating daily exposure to $PM_{2.5}$ and other gaseous air pollutants (Hsu et al., 2024).

The rigorous quality control and assurance procedures in regulatory monitoring ensure that $PM_{2.5}$ measurements are of reference-grade quality, often considered the "gold standard" (Bi et al., 2024). However, the high operational costs of regulatory monitoring limit spatial coverage, making it difficult to capture fine-scale variations in pollution levels. To address this issue, optical low-cost monitors (LCMs) have emerged as a promising complement to traditional regulatory $PM_{2.5}$ monitoring efforts (Bi et al., 2024).

(Wang et al., 2016) have monitored the mass concentration of PM_{10} and $PM_{2.5}$ at hourly intervals using an online particulate monitor (FH 62 C14 series, Thermo Fisher Scientific Inc.) equipped with beta attenuation and validated PM_{10} or $PM_{2.5}$ cyclones. The gold standard for external individual-level exposure assessment is generally accepted to be personal monitoring, which entails sampling air in a person's breathing zone (Xu et al., 2024).

To address the health risks associated with PM exposure, various control measures have been implemented (Xu et al., 2016). Understanding the sources of $PM_{2.5}$ is essential for effective pollution mitigation strategies, often achieved through multi-pollutant source identification using receptor models. Additionally, reducing personal exposure to $PM_{2.5}$ during cooking activities is crucial for maintaining health. Studies have explored methods for mitigating cooking emissions, such as upgrading ventilation systems to optimize airflow patterns.

2.5 Risk Assessment Methods

Assessing human health risks is a valuable approach used to evaluate possible risks to human health caused by exposure to a chemical substance within a given timeframe (Ghaderpoori et al., 2019). Evaluating the health impact associated with $PM_{2.5}$ offers critical insights into the main sources and components of $PM_{2.5}$ that contribute to adverse health effects. This assessment aids in identifying environmental health concerns and establishing targeted air pollution control measures to effectively address these issues (Zhang et al., 2020). There are four primary steps in the HRA process: (i) determining the risks of the chemicals, (ii) determining the dose-response relationship between the chemical and its toxic effects, (iii) determining the duration and extent of human exposure to the designated contaminant, and (iv) calculating the total risk to human health (risk assessment) (Amoatey et al., 2018).

Unlike the United States, which has a Federal Reference Method (FRM), Canada does not yet have a standardized protocol for this specific methodology. Much of Canada's newer $PM_{2.5}$ monitoring systems use "continuous" measurement devices such as the Beta Attenuation Monitor (BAM) or the Tapered Element Oscillating Microbalance (TEOM). These cutting-edge tools have been carefully used to meet real-world requirements, allowing for the timely and ongoing reporting of data. This real-time data availability is instrumental not only for air quality index reporting but also for forecasting, thus enhancing the overall efficacy of air quality management efforts (Brook et al., 2007).

The Comprehensive Air Quality Model with Extensions (CAMx) and the Community Multiscale Air Quality (CMAQ) model are two popular photochemical models used to support scientific and regulatory assessments of $PM_{2.5}$. When compared to field measurements, these models—which are available at https://www.epa.gov/cmaq and https://www.camx.com, respectively—have proven to be accurate in simulating the amounts and relative proportions of chemically speciated $PM_{2.5}$. Additionally, these modeling tools have been effectively utilized to analyze the impacts of $PM_{2.5}$ emissions from individual sources, as demonstrated in a study by (Simon et al., 2023).

Microenvironmental exposure (ME) and land use regression using machine learning (LUR_ML) models are two modeling methodologies that have been effectively used in population health studies to assess short-term $PM_{2.5}$ exposure. In particular, by employing region-specific microenvironmental measures as opposed to generic data, ME model 1 has proven to be capable of precisely estimating individual-level $PM_{2.5}$ exposure (Hsu et al., 2024).

Studies (Hsu et al., 2024; Simon et al., 2023) have applied various models to assess the economic value of reducing $PM_{2.5}$ pollution. The estimation of the monetized health benefits from PM2 has relied heavily on these models, including the Intervention Model for Air Pollution (InMAP), Air Pollution Emission Experiments and Policy Analysis (APEEP) version 2 (AP2), and Estimating Air Pollution Social Impact Using Regression (EASIUR). Five cuts. Additionally, the source apportionment- based benefit-per-ton (SA BPT) methodology was created by the Environmental Protection Agency (EPA) to calculate the marginal health benefits in dollars per ton of lower $PM_{2.5}$ and O3 emissions from different emission sources. The technique for developing Source Apportionment-Based Air Quality Surfaces (SABAQS), which has been used in recent EPA rulemaking proceedings pertaining to the power industry, is also presented in this study (Simon et al., 2023).

CHAPTER THREE: METHODOLOGY

3. Study design

The methodology used in this study paper is focused on using secondary data from the South African Air Quality Information System (SAAQIS) to determine $PM_{2.5}$ concentration values. Furthermore, the United States Environmental Protection Agency's (US EPA) recommendations have been essential in assessing the related health concerns. In order to ensure a solid and trustworthy methodology, this section describes the methodical approach taken to data collection, analysis, and interpretation. This study attempts to give a thorough grasp of $PM_{2.5}$ concentrations and their effects on public health in South Africa by utilizing well-established frameworks and reliable data sources.

3.1 Study site

3.1.1 *Description of the study settings*

Steve Tshwete Local Municipality, located in Middelburg, Mpumalanga Province, is strategically situated less than 150 km from Pretoria and 170 km from Johannesburg, with coordinates at 25º47,760' S latitude and 29º27,840' E longitude. The municipality, with a population of 278,749 people, benefits from its proximity to the N4 highway, facilitating connections to Mozambique and Richards Bay port. Renowned for hosting Columbus Stainless, the only steel plant in Africa, the municipality is characterized by its dominance in the mining and manufacturing sectors. Being the largest municipality in the district, it houses several power stations that significantly contribute to emissions in the province.

3.2 Study population

Not applicable, because the use of direct human subjects is not applicable in this study, as the study relies on hypothetical reference values for children (6 years to 12 year) and adults (+65 years) based on guidelines provided by US EPA.

3.3 Study sample

It is not applicable, because the study does not have a sample size.

3.4 Sample size

Not applicable, because the study does not involve direct sampling of individuals or their biological samples. Instead, existing air quality monitoring data and epidemiological studies will be used, to evaluate the potential health effects linked with $PM_{2.5}$ exposure. The study relies on population-level data rather than individual samples.

3.5 Data collection

Data collection and characterization of ambient PM2.5 emissions (Objective 1)

Secondary data for the study came from the publicly accessible South African Air Quality Information System (SAAQIS) website. The Steve Tshwete Local Municipality operated two Air Quality Monitoring Stations (AQMS) that tracked a range of air pollutants, including PM_{10}, $PM_{2.5}$, SO_2, NO_2, O_3, CO, BTEX, and Hg, in addition to meteorological data including temperature, relative humidity, wind direction, and wind speed. These stations employed the GRIMM #180 ambient dust monitor to continuously collect air samples, including $PM_{2.5}$ particles and other pollutants, with hourly readings. The monitor used a controlled airflow pump and measured particles through orthogonal light scattering, where a laser illuminated the particles, and a mirror captured the scattered signal. This signal was sent to a diode for amplification, size classification was performed, and the data was transmitted to the corresponding size channels. The data was then converted into a mass distribution every minute, providing PM_{10}, $PM_{2.5}$, and PM_1 values, which were displayed as mass distribution in micrograms per cubic meter ($\mu g/m^3$). One-hour average data were used to calculate diurnal and annual average $PM_{2.5}$ data sets.

Determine seasonal variations of PM2.5 (Objective 2)

Hourly averaged $PM_{2.5}$ data for the seasons of summer (December, January, February), autumn (March, April, May), winter (June, July, August), and spring (September, October, November) of 2022 were extracted from the South African Air Quality Information System (SAAQIS). Diurnal and seasonal $PM_{2.5}$ datasets were generated by aggregating one-hour average data into various time intervals to accurately capture seasonal variations. Average daily $PM_{2.5}$ concentrations were computed by summing the 24-hour averages for each day and dividing by 24 to yield the daily average.

The daily average $PM_{2.5}$ data were categorized into seasonal subsets by selecting and grouping data points corresponding to each season. Seasonal averages were then determined by averaging the daily $PM_{2.5}$ concentrations. For example, the daily values for the spring season were averaged to ascertain the average $PM_{2.5}$ concentration for the spring months (September, October, and November).

Health risk assessment (Objective 3)

Hazard identification

This study identified potential health concerns associated with $PM_{2.5}$ exposure by conducting a thorough evaluation of the body of existing scientific literature. Research by Al-sareji et al. (2022), Alves et al. (2023), and Vinson et al. (2020) validated the review's finding that exposure to $PM_{2.5}$ is strongly linked to an elevated risk of respiratory and cardiovascular disorders. Furthermore, recent research has indicated a link between $PM_{2.5}$ exposure and the death rate from lung cancer (Xu et al., 2023). Alves et al., 2023; Cui et al., 2023; Thangavel et al., 2022) The International Agency for Research on Cancer (IARC) also declared poor air quality due to PM_{10} and $PM_{2.5}$ particles to be carcinogenic based on recent studies. It is crucial to stress, nonetheless, that the primary focus of this study was on the non-carcinogenic health impacts of $PM_{2.5}$ exposure.

The extensive literature review highlighted the increasing body of evidence connecting $PM_{2.5}$ exposure to harmful health effects, particularly cardiovascular and respiratory diseases, emphasizing the need to address air quality issues. While the carcinogenic effects of PM_{10} and $PM_{2.5}$ pollutants have received considerable attention from researchers, this study aimed to explore a wider range of health risks associated with $PM_{2.5}$ exposure, specifically concentrating on non-carcinogenic health problems.

Exposure assessment

In this study, the standardized health risk assessment framework established by the United States Environmental Protection Agency (USEPA, 2022) was utilized. This framework offered a structured approach to evaluating potential health risks associated with environmental exposures, with a specific focus on inhalation as the primary pathway of exposure to PM2.5.

The researcher chose to concentrate on inhalation exposure due to its significance as the most prominent route of exposure to airborne pollutants like $PM_{2.5}$. Given the complex spatial and temporal variations in ambient $PM_{2.5}$ concentrations, accurately accounting for other potential exposure pathways was challenging. By focusing solely on inhalation exposure, the researcher aimed to streamline the risk assessment process while ensuring a comprehensive evaluation of the health effects associated with $PM_{2.5}$ exposure.

Additionally, this study assumed that exposure to $PM_{2.5}$ remained continuous throughout the study period. This assumption simplified the risk assessment process by providing a consistent basis for evaluating health risks over time. However, it is important to acknowledge that real-world exposure scenarios may have varied temporally and spatially, and the study's findings reflect this assumption.

In the human health risk assessment, the Concentration air-adjusted (Cairadj) and Hazard Quotient (HQ) for $PM_{2.5}$ through inhalation exposure were calculated. This assessment considered two age groups: adults aged 65 and above, and children aged 6 to 12 years, as they may have different susceptibility levels to air pollutants. The Cairadj was determined using a mathematical equation tailored to estimate the daily intake of $PM_{2.5}$ through inhalation for each age group. This calculation was essential for quantifying the amount of $PM_{2.5}$ that individuals were exposed to daily, providing a crucial metric for assessing health risks associated with air pollution.

$$Cair_{adj} = Cair \times \left(\frac{ET}{24hrs}\right) \times \left(\frac{EF}{365days}\right) \times (ED/AT)$$

Equation 1

This equation and its application are detailed in the Agency for Toxic Substances and Disease Registry (ATSDR) guidance and USEPA 2002. C in the risk assessment stands for the pollutant concentration, in this case $PM_{2.5}$, which is expressed in micrograms per cubic meter (µg/m^3). ET denotes the exposure time (hours/ day). EF represents the exposure frequency of both children and adults, measured in days per year (days/yr). ED means the exposure duration, measured in years (yr), and AT represents Averaging time (period over which exposure is averaged), measured in days (days). For carcinogens: AT = Lifetime (70 years) 365 days per year

The South African Air Quality Information System (SAAQIS) provided the pollutant concentration statistics for 2022, with a particular emphasis on $PM_{2.5}$. In order to assess exposure levels, this dataset offered vital information on ambient air quality levels. Furthermore, as shown in Table 1, information on exposure frequency and duration for both adults and children was obtained from the US Environmental Protection Agency (US EPA), a trustworthy source. This data source offered the standardized and verified information required to precisely evaluate the health hazards related to exposure to $PM_{2.5}$.

Table 1: Variables and assumptions used for health risk assessment.

VARIABLES	POPULATION	VALUE	SOURCE
EXPOSURE DURATION	Elderly	15 years	US EPA (2002)
	Children	6 years	US EPA (2002)
EXPOSURE FREQUENCY	Elderly	350 days/year	US EPA (2002)
	Children	350 days/year	US EPA (2002)
EXPOSURE TIME	Elderly	22 hours	Assumed
	Children	18 hours	Assumed

Risk characterization

To assess the non-carcinogenic health risks associated with exposure, hazard quotients (HQ) were calculated for each exposure scenario using Equation 2. Where (RfC) represents Reference concentration in mg/m3 and ($Cair_{adj}$) represents Concentration air adjusted.

$$HQ = \frac{Cair\_adj}{Rfc} \qquad \text{Equation 2}$$

This equation and its application are detailed in the Agency for Toxic Substances and Disease Registry (ATSDR) guidance and USEPA 2002. Reference Concentration (RFC), which is measured in ($\mu g/m^3$), is a health-based air concentration threshold below which no adverse health effects are expected. The safety benchmark was established at an HQ (Hazard Quotient) of 1. An HQ below 1 signifies insignificance or "negligible risk," indicating that exposure to $PM_{2.5}$ is unlikely to pose significant health risks, such as cardiovascular and respiratory disorders, even among potentially more susceptible individuals. However, if the HQ exceeded 1, it suggested potential non-cancer risks to sensitive individuals because of exposure. Moreover, an HQ surpassing 1 indicated a significant chronic risk, signaling a heightened level of concern regarding potential adverse health effects associated with exposure to the substance.

To assess cancer risks, equation 3 will be used. Cancer risk assessment is a crucial process in environmental health, aimed at estimating the probability of an individual developing cancer due to exposure to carcinogenic substances. This equation helps quantify the risk based on specific exposure levels and the inherent risk associated with the carcinogen.

$CR = Cair\_adj \times IUR$ Equation 3

This equation and its application are detailed in the Agency for Toxic Substances and Disease Registry (ATSDR) guidance and USEPA 2002. CR (Cancer Risk) represents the estimated risk of developing cancer over a lifetime due to exposure to a particular carcinogen. It is a dimensional value, often expressed as probability (e.g., 1 in 100,000). ($Cair_{adj}$) represents Concentration air adjusted, IUR (Inhalation Unit Risk) is a measure of the risk of cancer associated with inhaling a specific concentration of a carcinogen over a lifetime. It is usually expressed as the risk per unit concentration (e.g., risk per $\mu g/m^3$). in this study, it is assumed that IUR is the inhalation unit, which is equal to 0.008 $\mu g/m^3$ (Pope III, 2002).

3.6 Data management

After the data was exported to Microsoft Excel, a thorough validation process ensued to rectify any negative values and address data spikes that might have been overlooked during the initial data collection phase. Spike detection algorithms were applied to identify these spikes, and a threshold was established to distinguish outliers, which were subsequently removed from the database. To ensure data security and reliability, Google Cloud Storage was leveraged for data storage due to its redundancy, backup capabilities, and disaster recovery features.

Subsequently, pivot tables were employed to facilitate the creation of graphical representations, enabling the visualization of trends within the dataset. This visualization process offered insights into the patterns and fluctuations present in the data, thereby enhancing the understanding of key factors and facilitating informed decision-making based on the observed trends.

3.7 Data analysis

To determine if there was a statistically significant variation in $PM_{2.5}$ emissions between seasons, a one-way Analysis of Variance (ANOVA) was conducted at a 95% confidence interval. The average $PM_{2.5}$ emissions for each season were examined in this test to see if there were any notable variations. The range that the true population means were predicted to fall inside with 95% certainty was provided by the 95% confidence interval. The F-statistic, which compares the variation within each season to the variance between seasons, is calculated via ANOVA. This F-statistic was then used to compute the p-value.

A statistically significant difference in $PM_{2.5}$ emissions between at least two of the seasons was indicated if the p-value was less than the predefined significance level, which is usually 0.05 for a 95% confidence interval. On the other hand, there would not be a statistically significant variation in $PM_{2.5}$ emissions between the seasons if the p-value exceeded the significance level. By conducting this one-way ANOVA, researchers could determine if there were meaningful disparities in $PM_{2.5}$ emissions across different seasons and assess the significance of any observed differences. The Bonferroni correction was used to adjust the significance level when multiple comparisons were made, reducing the chances of type I errors.

3.8 **Ethical consideration**

There were no surveys or human or animal participants in this study. In order to evaluate the health hazards related to ambient $PM_{2.5}$ emissions in hot spot areas, the study instead used publicly available air quality data from SAAQIS and reference values from USAID and USEPA. Following submission of the study protocol to the University of the Witwatersrand Human Research Ethics Committee (HREC) for approval and assessment, a request for an ethical clearance waiver was made.

3.9 **Quality control**

Regular, twice-a-week calibration is carried out at the AQMS, and an annual full calibration occurs at an accredited independent laboratory. Monthly assessments remove spikes, correct drifts, and validate the data. The collected data is connected to a Central Internet Server called Ecostat. Verification follows the SANAS TR07-02 guideline with a minimum of 80% verification per parameter.

CHAPTER FOUR: RESULTS & DISCUSSION.

4. Results

The results of the Steve Tshwete Local Municipality's ambient air pollution and $PM_{2.5}$ *airborne pollutants health risk assessment are shown in this section. The results focus on* $PM_{2.5}$ *concentrations and how factors such as temperature, wind speed and direction, and rainfall impact these levels. The results support the goal of the study, which was to assess the health hazards associated with exposure to airborne* $PM_{2.5}$ *in the Steve Tshwete Local Municipality in the South African province of Mpumalanga. The key objectives were to: characterize diurnal and annual ambient* $PM_{2.5}$ *emissions in the Steve Tshwete Local Municipality; determine seasonal variations in* $PM_{2.5}$ *levels; and assess the health risks of* $PM_{2.5}$ *exposure for different subgroups (children and adults) in the region. These goals were outlined in the previous chapter, which detailed the study's methodology.*

Secondary data from the South African Air Quality Information System (SAAQIS) was used to determine $PM_{2.5}$ *concentrations. Furthermore, the United States Environmental Protection Agency's (US EPA) rules played a crucial role in assessing the related health concerns. With an emphasis* on $PM_{2.5}$, *this chapter will delve deeper into the ways that wind patterns, weather, and seasonal variations impact ambient air pollution.*

4.1 To determine seasonal variations of ambient $PM_{2.5}$ in the Steve Tshwete Local Municipality:

Wind Speed and Direction: The present study observed the highest frequency of winds originating from the North-West (NW) and West (W) directions, with other significant wind directions being North-East (NE) and East (E) as illustrated in Figure 1. These findings are consistent with the typical wind patterns observed in the Steve Tshwete region, characterized by moderate wind speeds in the green (1.80 - 3.60 m/s) and blue (3.60 - 5.70 m/s) categories as illustrated in Figure 1. Moderate wind speeds have the potential to disperse particulate matter ($PM_{2.5}$) in the atmosphere, thereby reducing its concentration (Ilenič et al., 2024). (Liu et al., 2018) Also highlighted the important role of wind speed in the dispersion of $PM_{2.5}$, and our results support this by showing that the higher occurrence of moderate wind speeds is associated with lower $PM_{2.5}$ concentrations in the region.

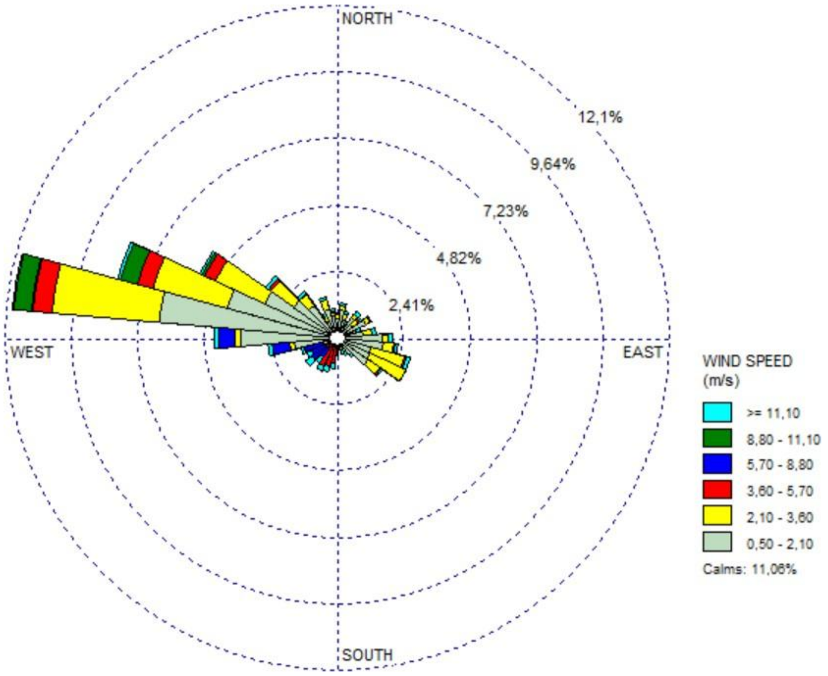


Figure 1: Wind Rose Diagram for Summer 2022.
This figure shows a wind rose diagram generated using WRPlot View Freeware 8.0.2.
The diagram represents wind speed and direction data collected from 1st November 2022 to the end of December 2022.

The directional dominance of winds from the North-West and West suggests that local pollution sources located in these directions, such as industrial emissions, traffic, or residential heating, could be critical in influencing air quality. These conclusions resonate with findings from (Basith et al., 2022; Muyemeki et al., 2021), who similarly found that prevailing wind directions, alongside sources of particulate pollution, strongly influence the distribution of $PM_{2.5}$ concentrations. In the current study, however, the relatively low $PM_{2.5}$ concentration of 10.4 $\mu g/m^3$ in the summer months suggests that local pollution sources in these predominant wind directions may be minimal or less intense during this period. This could be attributed to reduced human activity or decreased emissions from industrial or transportation sources during the summer months, as noted by (Wang et al.,2024), who discussed a seasonal decline in emissions due to lower operational capacities of certain sources like power plants and factories.

Moreover, while wind direction and speed are critical in dispersing pollutants, it is also important to consider seasonal variations in emissions. Our results showing a decrease in $PM_{2.5}$ concentrations during the summer suggest a combination of lower local emissions and favorable meteorological conditions, which align with the findings of (Wang et al., 2024), who found that emissions from certain sources, including power plants and transportation networks, tend to reduce during summer, contributing to lower pollution levels. This seasonal variation is likely a contributing factor to the observed air quality in the Steve Tshwete region, where moderate wind speeds help reduce the concentration of airborne particulate matter.

Wind Speed and Direction: The wind direction data in this study reveals that the most frequent wind direction is from the East-Northeast (ENE), accounting for approximately 9% of the total wind frequency as illustrated in Figure 2. This direction is identified as a primary pathway for pollutants, especially particulate matter ($PM_{2.5}$), to travel into the region. Other significant wind directions include East (E) at around 7% and North-Northeast (NNE) at about 6%. The results indicate that significant sources of $PM_{2.5}$, such as industrial areas or traffic corridors, located in these directions, could affect the region's air quality. However, the influence of these directions may be less frequent than that of the ENE direction, which experiences more frequent wind flow. This observation aligns with the findings of Zabrocki et al. (2022) and Akinyemi et al. (2016), who also identified the ENE direction as an important pathway for pollutant transport, particularly in areas where prevailing winds direct pollutants into densely populated areas.

These results also highlighted the distribution of wind speeds, noting that higher wind speeds (>5.7 knots) are less frequent compared to lower wind speeds (0.5 - 3.6 knots), with the latter being more common as illustrated in Figure 2. This distribution has significant implications for air quality. Low wind speeds, as identified in this research, make it less likely for pollutants, including $PM_{2.5}$, to be carried away or diluted by the atmosphere. This observation is consistent with Zabrocki et al. (2022), who found that low wind speeds lead to the accumulation of pollutants due to weakened dispersal mechanisms. Conversely, higher wind speeds are more effective at dispersing particulate matter over large areas, thereby reducing $PM_{2.5}$ concentrations in the atmosphere.

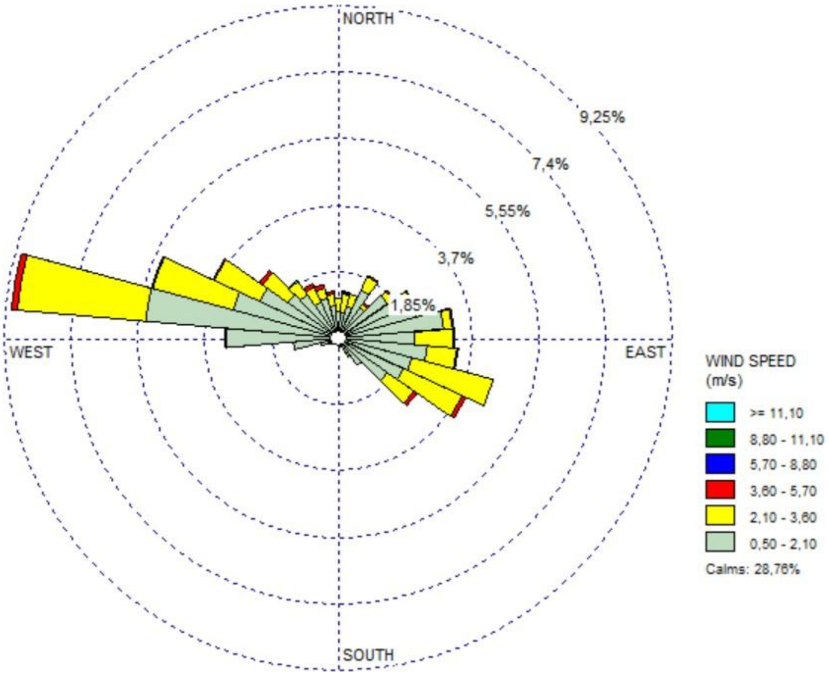


Figure 2: Wind Rose Diagram for Autumn 2022.
This figure shows a wind rose diagram generated using WRPLOT View Freeware 8.0.2. The diagram represents wind speed and direction data collected from 1st March to the end of May 2022.

Periods of poor air quality may arise from the frequent occurrence of lower wind speeds combined with the preponderance of winds coming from the ENE direction. More specifically, pollutants may not be effectively distributed, resulting in increased concentrations of particulate matter, if there is a substantial source of $PM_{2.5}$ upwind in the East-Northeast direction and the wind speed is low. This aligns with Huang et al. (2019), who found that areas downwind of pollution sources often experience elevated concentrations of particulate matter due to the directional flow of air. Moreover, studies by (Liu et al., 2023; Nunez et al., 2021; Wu et al., 2020) support the notion that periods of high $PM_{2.5}$ concentration, exacerbated by weak winds, can lead to adverse health effects, particularly for vulnerable populations.

Furthermore, low wind speeds can also cause $PM_{2.5}$ particles to remain closer to the ground for longer periods, increasing the likelihood of inhalation and deposition of these particles in the lungs. This is particularly concerning respiratory health, especially in regions with poor air circulation. These findings are consistent with the research of Lippmann et al. (2003), who emphasized that low wind speeds contribute to the prolonged presence of fine particulate matter near the surface. In addition, the research by Amnuaylojaroen & Parasin

(2023) further supports the idea that low wind speeds exacerbate the risk of respiratory issues, particularly in areas with limited ventilation.

Wind Speed and Direction: The study's findings demonstrate how wind patterns, particularly in the Steve Tshwete region, have a major impact on the dispersion and buildup of particulate matter in the atmosphere. The two most common wind directions throughout the winter are North-Northwest (NNW) and North-Northeast (NNE), as illustrated in Figure 3. This pattern is consistent with the findings of Liu et al. (2018), who also emphasized the significant role of wind direction in the dispersion of particulate matter ($PM_{2.5}$). However, the study further highlights that although these wind directions are frequent, the wind speeds during this period tend to be lower, with the majority of winds falling within the 0.50 - 3.60 m/s range, as illustrated in Figure 3. This is consistent with research by Zabrocki et al. (2022) and Akinyemi et al. (2016), which found that low wind speeds reduce the wind's ability to disperse pollutants efficiently, which causes particulate matter to build up in the atmosphere

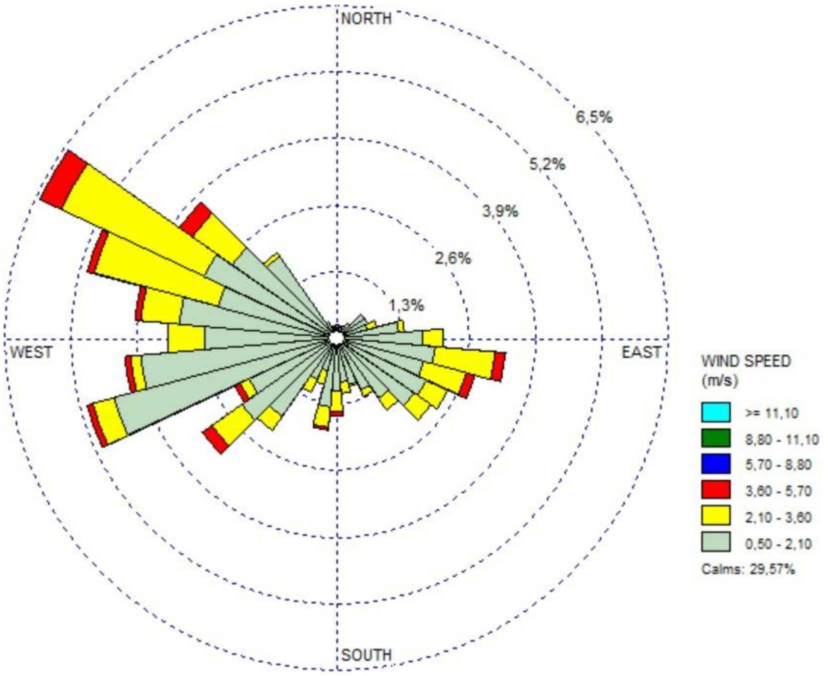


Figure 3: Wind Rose Diagram for Winter 2022.

This figure shows a wind rose diagram generated using WRPLOT View Freeware 8.0.2. The diagram represents wind speed and direction data collected from 1st June to the end of August 2022.

The study also highlights that the combination of low wind speeds, and the predominant NNW and NNE wind directions can lead to easier accumulation of $PM_{2.5}$, especially if there are significant pollution sources upwind in these directions. This observation is consistent with Cichowicz et al. (2020), who found that weak winter winds and a stable atmospheric environment reduce air mixing, trapping pollutants near the ground. The reduced mixing in winter, coupled with low wind speeds, limits the dispersion of pollutants, leading to higher concentrations of particulate matter near the surface. In the context of the Steve Tshwete region, this phenomenon suggests that $PM_{2.5}$ levels may be particularly elevated in the winter months when wind speeds are weaker, and the atmosphere is more stable.

Additionally, cold temperatures often lead to increased residential heating, which in turn can elevate $PM_{2.5}$ emissions from domestic sources. The strength of winds from the NNW and NNE directions may make matters worse. This finding is in line with research by Ai et al. (2023), Kong et al. (2020), Xing et al. (2022), and Tao et al. (2013), which all discovered that domestic heating is a significant source of $PM_{2.5}$ emissions in colder climates. These studies suggest that the combination of emissions from home heating systems and the dispersion of pollutants by wind may lead to higher $PM_{2.5}$ concentrations throughout the winter months.

Wind Patterns: The results of this study show that the East (E) and West (W) wind directions are the most common throughout the spring in the Steve Tshwete region, as illustrated in Figure 4. These directions exhibit the highest wind frequencies during this season, with the majority of winds falling within the moderate speed range of 1.00 - 3.60 m/s, as illustrated in Figure 4. This wind speed range is classified within the light yellow to light orange categories, which indicates moderate winds. Moderate wind speeds are important for the dispersion of pollutants such as $PM_{2.5}$ over a larger area. In this study, it was observed that moderate winds from the East and West are effective in reducing the concentration of $PM_{2.5}$ in localized areas, which helps improve overall air quality. These findings are consistent with the research by (Pan & Ji., 2024; Hong et al., 2018), both of whom emphasized the role of moderate wind speeds in effectively dispersing particulate matter and preventing harmful accumulations at ground level.

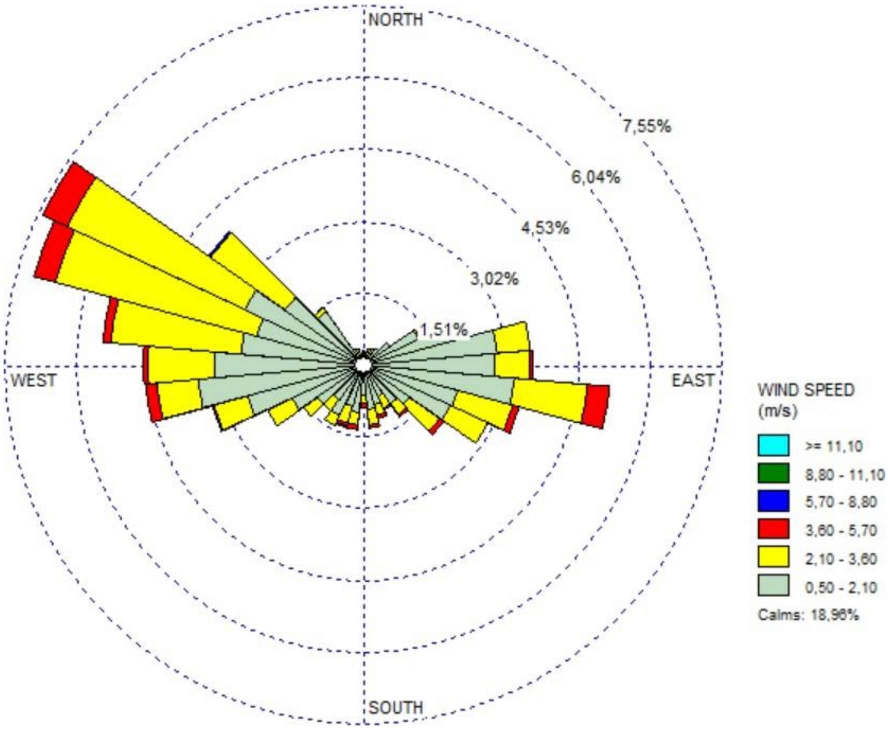


Figure 4: Wind Rose Diagram for Spring 2022.
This figure shows a wind rose diagram generated using WRPLOT View Freeware 8.0.2. The diagram represents wind speed and direction data collected from 1st September to the end of November 2022.

As noted in previous studies, including those by Sadheesh & Jeyanthi (2023), moderate wind speeds are capable of diluting $PM_{2.5}$ particles in the atmosphere, thus reducing the buildup of pollutants at the surface. This dispersion effect contributes to better air quality by ensuring that $PM_{2.5}$ particles are carried away from highly concentrated areas. The ability of moderate winds from the East and West to prevent the accumulation of $PM_{2.5}$ aligns with findings from Song et al. (2025), who suggested that seasonal wind patterns and moderate wind speeds have a crucial role in mitigating the potential health impacts of particulate pollution. These findings emphasize the critical role of wind direction and speed in regulating $PM_{2.5}$ concentrations and improving air quality in areas such as Steve Tshwete.

Additionally, the study suggests that important $PM_{2.5}$ sources in the east and west directions may have an impact on the region's $PM_{2.5}$ concentrations, especially in the spring when these winds are most common. This result is consistent with earlier studies that have demonstrated that local pollution sources upwind of a region can raise $PM_{2.5}$ concentrations in the area downstream (Pan & Ji, 2024). Therefore, any industrial or traffic-related sources of $PM_{2.5}$ located to the East or West of the Steve Tshwete region could potentially impact air quality by increasing $PM_{2.5}$ levels in areas that are predominantly affected by winds from these directions

The $PM_{2.5}$ concentrations in Steve Tshwete Local Municipality, Mpumalanga, South Africa, exhibited significant seasonal variations throughout 2022. Figure 6 indicates that $PM_{2.5}$ levels were highest during the winter months (30.24 µg/m^3) and lowest during the summer months (10,4 µg/m^3). This section discusses seasonal variations, meteorological influences, and activities contributing to high $PM_{2.5}$ levels during different seasons.

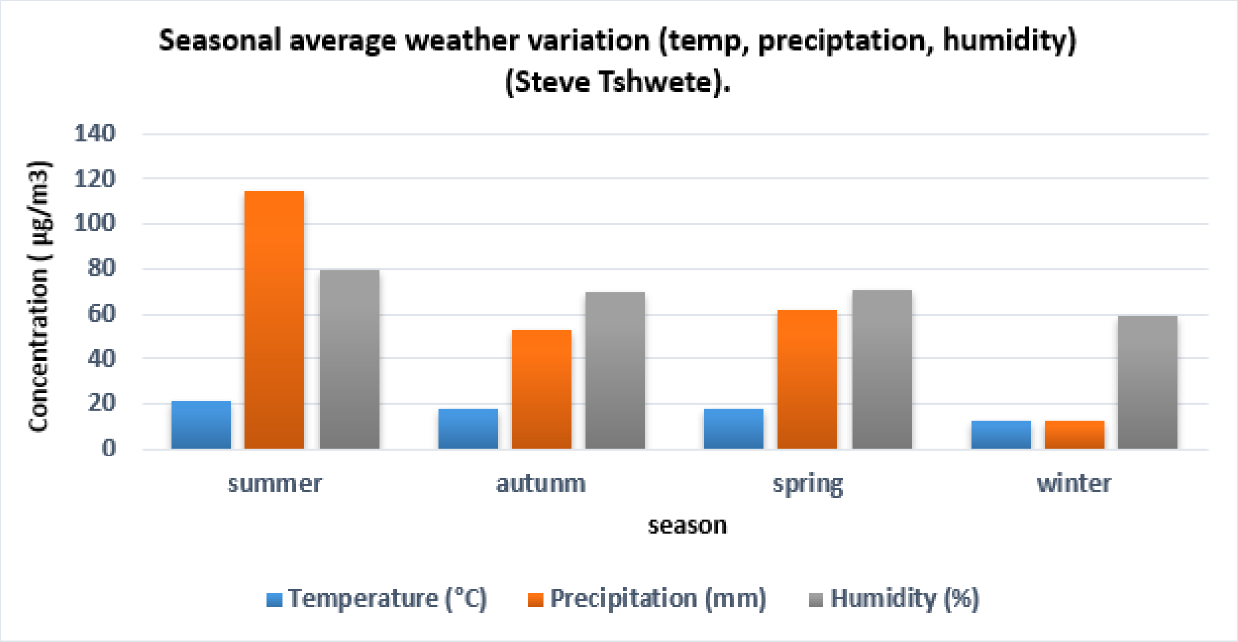


Figure 5: Seasonal average weather parameters (Temperature, Humidity & precipitation) variation in 2022.

Temperature

This study's findings indicate that the peak average temperature occurs during the summer months, with a recorded value of 21.1°C, aligning with the region's typical climatic patterns. Following summer, the temperature gradually decreases, reaching 17.6°C in autumn, 18.2°C in spring, and the lowest average of 13.0°C in winter, as illustrated in Figure 5. This observed temperature variation demonstrates a clear seasonal pattern with warmer summers and cooler winters. These temperature changes are consistent with the seasonal cycle typically seen in temperate regions, where summer is warmer and winter is colder, leading to significant seasonal temperature fluctuations.

The findings of (Ai et al., 2023; Kong et al., 2020; Xing et al., 2022; Tao et al., 2013) that winter typically has the highest $PM_{2.5}$ concentrations among the four seasons, with spring, autumn, and summer showing progressively lower concentrations, are consistent with this seasonal temperature variation. The conclusion that cooler temperatures during this season are linked to increased quantities of particulate matter, especially $PM_{2.5}$, is supported by the current study's finding that wintertime has the lowest temperatures. This association is in line with the larger body of studies showing that temperature and air quality are inversely correlated, with colder months more likely to trap pollutants near the surface because of less atmospheric mixing.

Precipitation/ rainfall

The results of this study show that summer is the wettest season in the region, with an average precipitation of 114.3 mm, as illustrated in Figure 5. This observation aligns with the general understanding of seasonal rainfall patterns, where summer typically brings higher rainfall due to increased atmospheric moisture and climatic conditions conducive to storms. Following summer, precipitation significantly decreases in autumn (53.0 mm) and spring (62.0 mm), while winter records the lowest average precipitation of 12.3 mm, making it the driest season, as illustrated in Figure 5. These findings demonstrate a clear seasonal trend of higher rainfall in summer, followed by a gradual decrease toward the colder months, which is consistent with typical seasonal rainfall distribution patterns observed in many temperate climates.

These results are supported by previous studies, such as those by (Pascale et al., 2015; Feng et al., 2013), which also highlighted that summer is the wettest season and that precipitation tends to decrease during autumn and spring, with winter often being the driest season. The consistency of the findings in this study with those reported by (Pascale et al., 2015; Feng et al., 2013) further underscores the typical nature of seasonal precipitation patterns in temperate regions, where the intensity of rainfall is highest during summer months and gradually decreases in the autumn, spring, and winter months.

Humidity

The findings of this study reveal that humidity is highest during the summer season in the Steve Tshwete region, with an average value of 79.3%, as illustrated in Figure 5. This increase in humidity aligns with the higher precipitation levels observed during the summer months, as more moisture in the atmosphere typically corresponds to higher relative humidity. Humidity gradually decreases in autumn (70.0%) and spring (70.7%), while winter records the lowest average humidity of 59.0%, as illustrated in Figure 5. This trend is consistent with the seasonal variation in precipitation, where the lowest humidity values coincide with the driest months, particularly in winter. The higher humidity levels in summer are associated with more uncomfortable heat, while the lower humidity in winter is linked to drier conditions, both of which are consistent with the patterns described in (Pascale et al., 2015; Feng et al., 2013).

In conclusion, the seasonal temperature variation shows a clear distinction between warmer and cooler months, with summer being the warmest and winter the coolest. The data indicates a wet summer and a dry winter, with moderate rainfall in autumn and spring. Humidity levels follow the precipitation pattern, being highest in summer and lowest in winter.

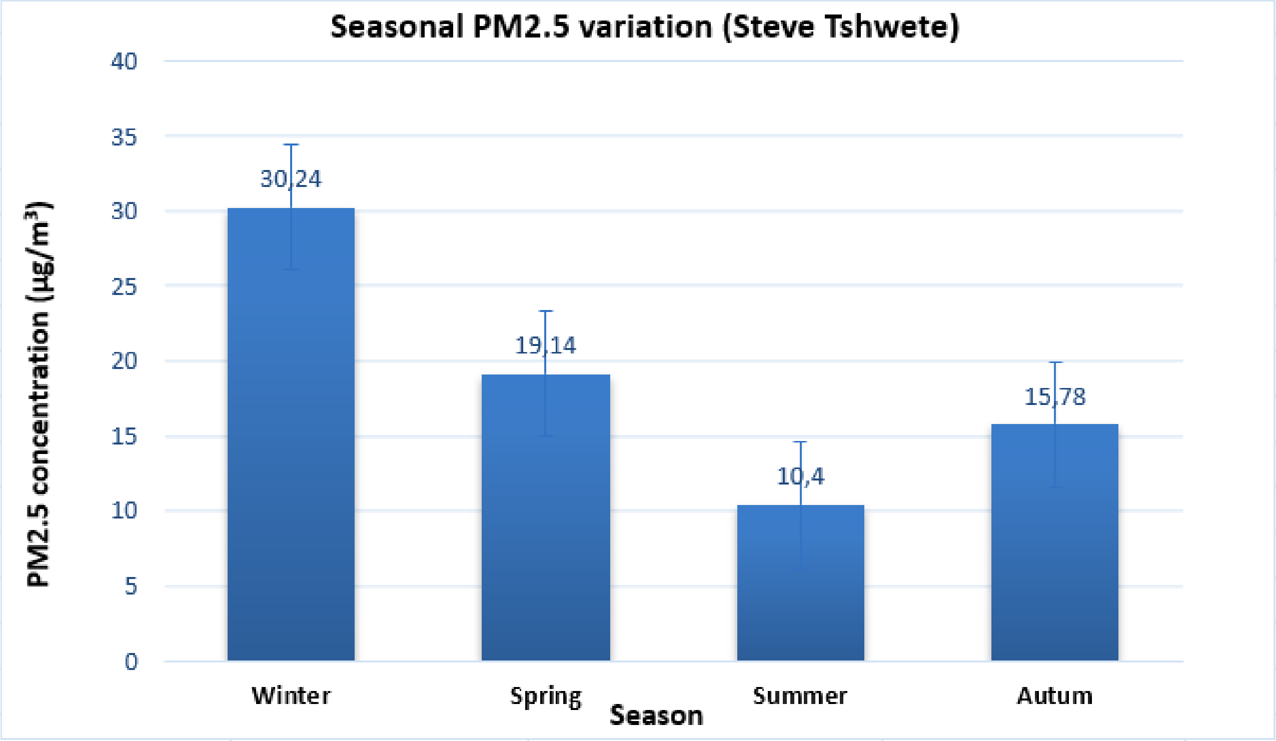


Figure 6Seasonal $PM_{2.5}$ concentration variation in 2022.

Winter (June to August):

The winter months had the highest $PM_{2.5}$ levels (30,24 µg/m^3), as shown in Figure 6. In July 2001–2002, an urban region in Chengdu, China, recorded an average $PM_{2.5}$ concentration of 156 µg m^3 (Wang et al., 2004). This was significantly higher than the value of 56 µg m^3 in January. Similarly to this, Tao et al. (2013) discovered that, based on measurements from 2009 to 2010, Chengdu's average $PM_{2.5}$ concentration in June 2010 was 225.5 ± 73.2 µg m^3. This proves the fact that was stated by Ai et al. (2023; Kong et al. (2020; Xing et al. (2022; Tao et al., 2013), that among the four seasons, winter exhibits the highest $PM_{2.5}$ concentration, with spring, autumn, and summer subsequently having lower levels.

High $PM_{2.5}$ concentrations observed in the winter months are a result of a combination of factors: increased emissions due to heating, temperature inversion that traps pollutants close to the surface, low rainfall that limits the natural removal of particulates, and low humidity that prevents the formation of secondary aerosols as discussed by (Lee et al., 2023). These conditions together create a scenario where particulate matter remains concentrated in the air, especially during the colder months, contributing to poor air quality. Temperature is a key factor in regulating $PM_{2.5}$ concentrations (Li et al., 2024).

Hence, according to this paper's results, it is relevant to highlight that cooler temperatures were observed (13 °C), as shown in Figure 5; these temperatures tend to suppress vertical mixing in the atmosphere, trapping air pollutants close to the surface. This phenomenon, known as temperature inversion, leads to a higher concentration of particulate matter in the air, especially during the early morning and late evening hours.

Lower rainfall contributes to the persistence of higher $PM_{2.5}$ levels, as there is no significant mechanism to remove particulate matter from the atmosphere (Zhai et al., 2020). The results on the present paper indicate lower rainfall, which was recorded at 12,33333333 mm as shown in Figure 5, this then means that in Steve Tshwete region during this season $PM_{2.5}$ concentration were high as a result of reported low rainfall. Also, Lower humidity levels (59 %), as shown in Figure 5, were reported; this then means that the formation of secondary aerosols was reduced. Additionally, in dry conditions, characteristic of the winter months, particulate matter remains suspended for longer periods, contributing to elevated $PM_{2.5}$ concentrations.

Spring (September to November):

A decreasing trend in $PM_{2.5}$ concentrations (19,14 µg/m3) was observed during spring, as illustrated in Figure 5. Rising temperatures, more precipitation, and higher humidity levels are all responsible for this trend, as they all contribute to a decrease in the amount of particulate matter in the atmosphere. According to Muyemeki et al. (2021), human activities also affect $PM_{2.5}$ concentration levels during the spring since secondary aerosols are likely to come from intensive agricultural activities. The increase in temperature (18,2°C), as shown in Figure 5, promotes vertical mixing in the atmosphere, which enhances the ability of air currents to dilute and disperse particulate matter. As the air warms up, it becomes less stable, allowing pollutants such as $PM_{2.5}$ to be carried away from the surface and spread out into the atmosphere. This increased dispersion contributes significantly to the observed reduction in $PM_{2.5}$ concentrations during the spring months.

The recorded increase in rainfall to 62 mm, as shown in Figure 5, during spring is another critical factor that helps reduce $PM_{2.5}$ levels. Precipitation plays an essential role in removing particulate matter from the atmosphere through processes like wet deposition (Li et al., 2024). Rainwater effectively "washes out" airborne particles, including $PM_{2.5}$, by capturing and carrying them to the ground. The combination of more rainfall in the spring months helps to reduce the particulate load in the air physically, contributing to the observed decrease in $PM_{2.5}$ concentrations.

Higher humidity levels (70,7%), as shown in Figure 5, can influence air quality in several ways. While humidity can facilitate the formation of secondary aerosols (e.g., sulfate and nitrate particles) (Meng et al., 2024), which contribute to the total particulate matter, the overall impact of this process is likely outweighed by the effects of increased rainfall. In other words, although higher humidity can support the formation of additional particulate matter, the rain helps to remove both primary $PM_{2.5}$ and secondary aerosols from the atmosphere. Thus, the net effect of increased humidity is less significant compared to the combined impact of temperature and rainfall, which both act to lower particulate concentrations.

Summer (December to February):

The summer months exhibited relatively lower $PM_{2.5}$ concentrations (10.4 µg/m³), as illustrated in Figure 6. This reduction can be attributed to increased rainfall and higher temperatures (21.1°C), as illustrated in Figure 5, which enhance the dispersion and washout of pollutants, as mentioned by Bambelo (2024). In summer, the pleasant weather conditions and decreased use of coal for heating, particularly in residential areas, result in the lowest concentrations of $PM_{2.5}$. Higher temperatures enhance the vertical mixing of air, dispersing pollutants and leading to relatively lower concentrations of $PM_{2.5}$. The increased atmospheric instability allows for better dilution of pollutants, this is also discussed by Duan et al. (2021).

The lower concentrations observed during summer are likely attributed to frequent rainfall events. Precipitation acts as an efficient mechanism for removing particles from the atmosphere, a process known as precipitation scavenging. In fact, a significant portion of the annual precipitation, approximately 70%, occurs during summer (Speirs et al., 2023). The results of the present paper show that rainfall is 114.3 mm, as shown in Figure 5. This means that it acts as a natural cleanser for the atmosphere, removing particulate matter through wet deposition. The higher frequency and intensity of rainfall during this season help wash out particulate matter from the air, lowering the $PM_{2.5}$ concentration levels.

High humidity can increase the hygroscopic growth of particulate matter, resulting in an increase in particle size and mass (Cao et al., 2024). The present study shows that humidity levels are at 79,3%, as shown in Figure 5. This means that particulate matter is more likely to settle, particularly in areas with high humidity during the summer months, thus affecting the levels of $PM_{2.5}$, as shown in Figure 6.

Additionally, Muyemeki et al. (2021) explained that in Mpumalanga, the higher levels of secondary aerosols during summer and autumn are primarily due to regional transportation from industrial activities.

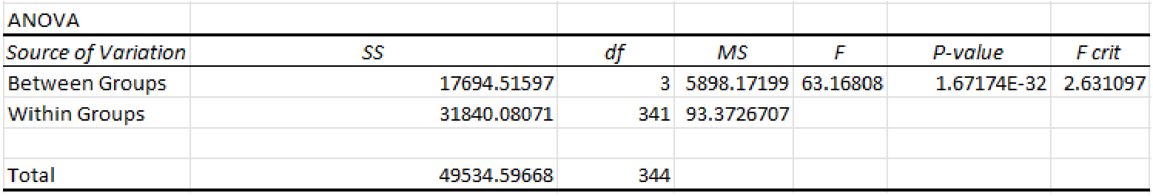
Autumn (March to May):

Moderate $PM_{2.5}$ concentrations (15.78 µg/m3) were observed during autumn, as illustrated in Figure 6, which reflects a gradual increase in pollutant levels as the region transitions from summer to winter. This increase in pollutant concentration can be attributed to several key environmental factors during the autumn season. Firstly, rainfall significantly decreases from 114.3 mm in summer to 53 mm in autumn, as shown in Figure 5. Rainfall plays a crucial role in the washout or scavenging of pollutants from the air (Speirs et al., 2023). In the summer, higher rainfall levels help clear the air by removing particulate matter, resulting in generally lower $PM_{2.5}$ concentrations. However, as rainfall diminishes in autumn, there is less frequent washout of pollutants, allowing $PM_{2.5}$ particles to remain in the atmosphere for longer periods, contributing to the observed moderate concentrations of particulate matter.

Reduced temperature levels were observed from 21,1°C to 17,6°C, as shown in Figure 5. The observed temperature reduction from 21.1°C in summer to 17.6°C in autumn further influences $PM_{2.5}$ levels. Cooling temperatures slow down photochemical processes, which produce secondary pollutants like ozone and secondary organic aerosols (Hagino et al., 2024). As a result, there may be a reduction in the formation of secondary pollutants, but this does not necessarily lead to a significant decrease in $PM_{2.5}$ concentrations, as primary sources of $PM_{2.5}$ (e.g., vehicular emissions, industrial processes) may still be active (Basith et al., 2022; Muyemeki et al., 2021). Additionally, cooler temperatures in autumn may contribute to more stable atmospheric conditions, limiting the dispersion of pollutants and leading to the accumulation of $PM_{2.5}$ near the surface (Masiol et al., 2024).

Moderate humidity levels were observed (70%), as shown in Figure 5, which may have contributed to the formation of secondary aerosols. Thus, affecting the level of $PM_{2.5}$ concentration reported in this season.

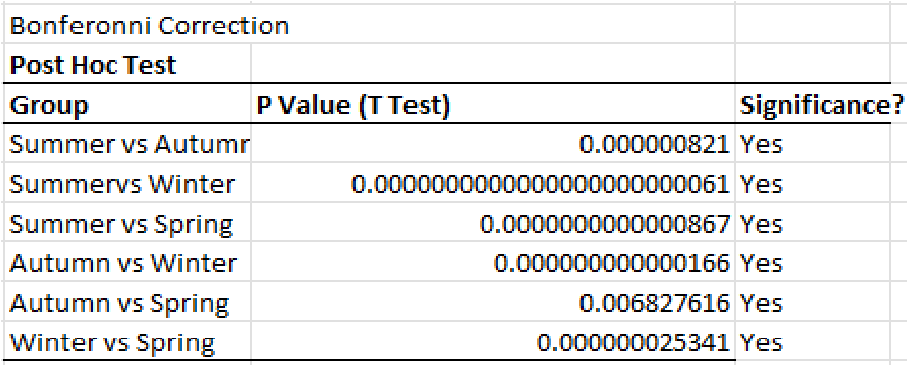
Table 2: ANOVA table for source of variation. To ascertain whether there are statistically significant differences between the means of three or more independent groups, the table displays the findings of an Analysis of Variance (ANOVA) test.



ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	17694.51597	3	5898.17199	63.16808	1.67174E-32	2.631097
Within Groups	31840.08071	341	93.3726707			
Total	49534.59668	344				

A one-way ANOVA revealed a significant effect of seasonal variation on $PM_{2.5}$ concentration, F (3, 341) = [63.16808], p = [1.67174E−32]. The p-value associated with this F-statistic is extremely small (1.67174E−32), indicating that there is a statistically significant difference between seasons. The critical value of F for the given degrees of freedom and significance level is 2.631097. The ANOVA results suggest that there are statistically significant differences between seasons.

Table 3: Bonferroni correction; Test Hoc Test results for Seasonal comparisons.



Bonferonni Correction		
Post Hoc Test		
Group	**P Value (T Test)**	**Significance?**
Summer vs Autumr	0.000000821	Yes
Summervs Winter	0.0000000000000000000000061	Yes
Summer vs Spring	0.0000000000000867	Yes
Autumn vs Winter	0.000000000000166	Yes
Autumn vs Spring	0.006827616	Yes
Winter vs Spring	0.000000025341	Yes

Seasonal changes are statistically significant, as seen by the exceptionally low P values in the table (far less than 0.05). All pairs of seasons show statistically significant differences, according to the results. This implies that there are significant seasonal variations in $PM_{2.5}$ concentrations. These variations may result from a number of things, including modifications to weather patterns, human activity, and natural occurrences.

4.2 To characterize diurnal and annual ambient PM2.5 emissions in Steve, the Thswete Local Municipality:

The $PM_{2.5}$ concentration data for the Steve Tshwete Local Municipality in Mpumalanga for the year 2022 reveals both diurnal and annual patterns in ambient $PM_{2.5}$ emissions. These patterns are influenced by meteorological conditions, human activities, and seasonal variations. The hourly average data highlights the hourly fluctuations in particulate matter levels over the entire monitoring period (12 months). Figure 7 shows the hourly average $PM_{2.5}$ emissions in the Steve Tshwete Municipality over 12 months in 2022.

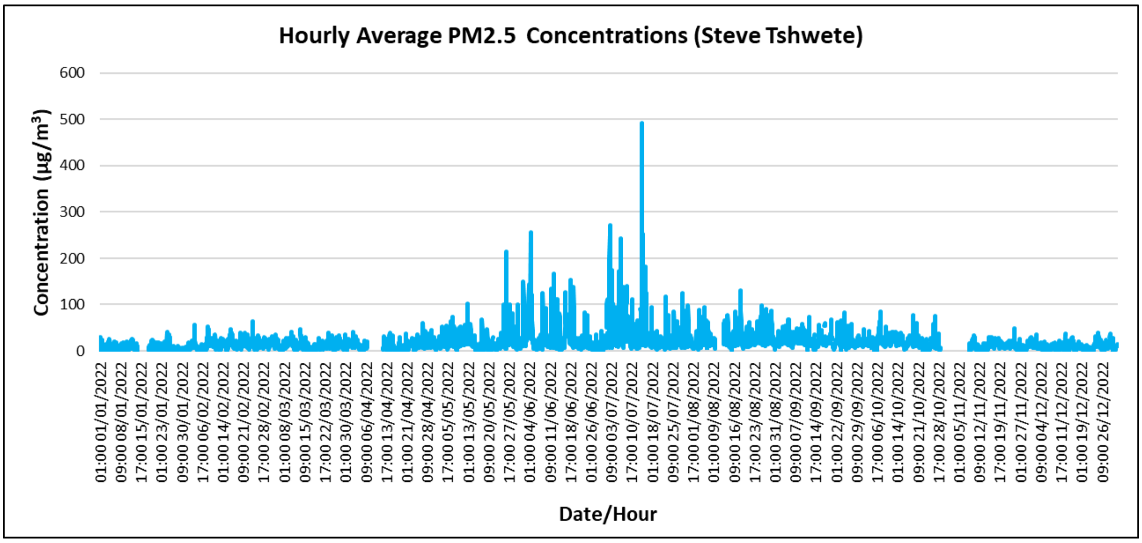


Figure 7: Hourly average $PM_{2.5}$ concentrations in Steve Tshwete for 2022.

The $PM_{2.5}$ levels fluctuate significantly over the year, with several peaks and troughs. This indicates varying air quality, likely influenced by seasonal changes, weather patterns, and human activities. (Bambelo, 2024; Berhane et al., 2024; Bhattarai et al., 2024) emphasize the variability of $PM_{2.5}$ levels throughout the year, supporting the claim that a mix of seasonal changes, weather patterns, and human activities influences fluctuations in air quality. These studies likely corroborate the idea that both natural and anthropogenic factors contribute to the dynamic nature of $PM_{2.5}$ levels.

There are noticeable peaks in $PM_{2.5}$ concentrations at certain times of the year, as illustrated in Figure 7. These peaks could be due to specific events such as industrial activities, increased vehicle emissions, or natural occurrences like wildfires. Basith et al. (2022) and Muyemeki et al. (2021) provide evidence for the correlation between $PM_{2.5}$ peaks and events such as industrial activities, vehicle emissions, and wildfires. These studies align with the paragraph's assertion that the peaks in $PM_{2.5}$ concentrations could result from specific human and natural activities. This suggests that the fluctuations in $PM_{2.5}$ levels are not random but tied to specific sources of pollution.

The lower points in the graph suggest periods of better air quality. These could correspond to times with less industrial activity, favorable weather conditions, or effective pollution control measures. If we look closely, there might be seasonal trends. For example, higher concentrations in winter could be due to the increased use of heating systems, while lower concentrations in summer might be due to better dispersion of pollutants. The idea of seasonal trends is backed by (Ai et al., 2023; Kong et al., 2020; Xing et al., 2022; Tao et al., 2013), these studies indicating that winter may see higher $PM_{2.5}$ levels due to increased heating demands and the use of solid fuels, while summer offers better dispersion due to more favorable weather conditions, such as higher temperatures and wind speeds. This finding is common across several studies, where seasonal weather patterns, such as temperature inversions in winter, prevent the dispersion of pollutants, leading to higher concentrations.

The Steve Tshwete municipality's daily average $PM_{2.5}$ emission levels for 2022 are displayed in Figure 8, and these values are contrasted with the WHO recommendations and the South African National Ambient Air Quality Standards (NAAQS). Results show that $PM_{2.5}$ emissions exceed the SA NAAQS only in winter. On the contrary, when compared to the WHO, the emissions exceed the guidelines throughout the year regardless of the season (Figure 8).

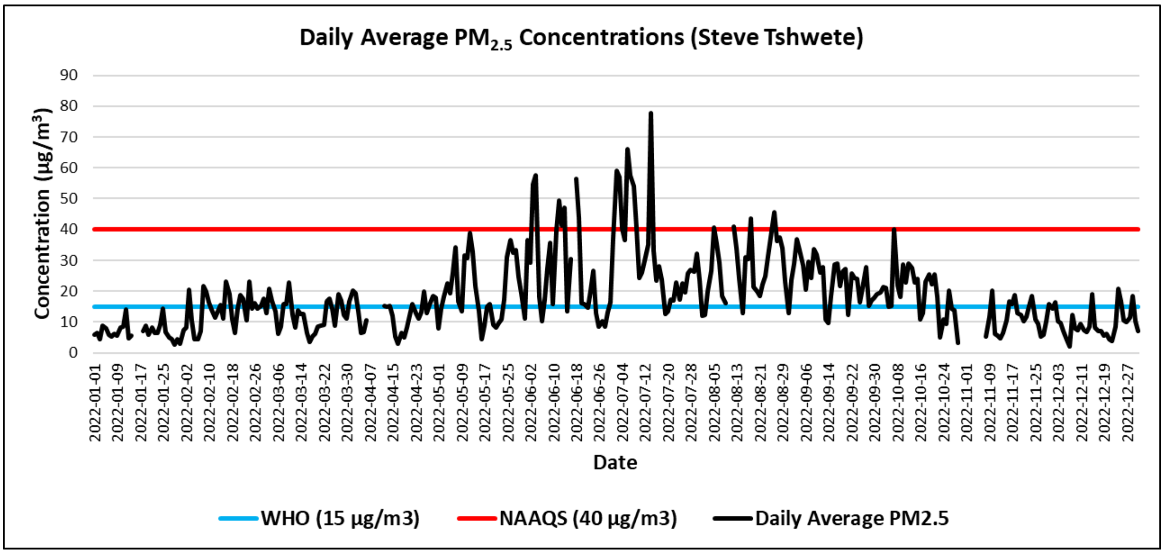


Figure 8: Daily average $PM_{2.5}$ concentrations in Steve Tshwete for 2022 against WHO and South African NAAQS guidelines.

The elevated concentrations of $PM_{2.5}$ observed between 2022/07/04 and 2022/07/12, with a peak of 86.04 µg/m³ as illustrated in Figure 8, align with findings from previous studies that highlight the impact of seasonal variations and specific local activities on air quality (Bambelo, 2024; Berhane et al., 2024; Bhattarai *et al*., 2024). The fluctuations in $PM_{2.5}$ concentrations during this period are likely linked to both meteorological factors, such as temperature inversions and reduced rainfall, and human activities, such as industrial operations, construction, and increased vehicular traffic (Bambelo, 2024; Ai et al., 2023; Kong et al., 2020). The winter months, which are associated with lower temperatures and drier conditions, can contribute to atmospheric stability, trapping pollutants near the ground and preventing their dispersion. This atmospheric stagnation is a well-documented factor that exacerbates air pollution, particularly in urban and industrial regions. Studies by (Ai et al., 2023; Kong et al., 2020) emphasize how the transition between seasons can lead to significant changes in weather patterns that influence $PM_{2.5}$ concentrations.

The frequent exceedances of the World Health Organization (WHO) guideline of 15 $\mu g/m^3$, with 187 exceedances recorded in this study, as illustrated in Figure 8, indicate that air quality in the Steve Tshwete region is consistently poor, with elevated $PM_{2.5}$ concentrations occurring throughout the year. This finding aligns with the results of (Wu et al., 2020; Liu et al., 2023), who observed persistent exceedances of air quality standards in regions with high levels of industrial activity and traffic congestion. These studies highlight the importance of addressing long-term exposure to elevated $PM_{2.5}$ levels, as sustained exposure above the WHO-recommended limits can lead to significant health issues. The findings from (Bhosale et al., 2025; Caffè et al., 2025; Kumar et al., 2025) further support the concern that chronic exposure to $PM_{2.5}$ is associated with respiratory diseases, cardiovascular conditions, and other severe health outcomes, including asthma and heart disease.

The study identified 20 exceedances of the National Ambient Air Quality Standards (NAAQS) threshold of 40 $\mu g/m^3$, as illustrated in Figure 8, which further emphasizes the severity of air pollution in the area. Although the NAAQS guideline only permits four exceedances per year, this study found 16 more than the permitted limit, demonstrating the hazardous nature of the air quality during particular times. This circumstance is consistent with research by Nunez et al. (2021) and Liu et al. (2023), which found that short-term exposure to elevated $PM_{2.5}$ concentrations can worsen pre-existing medical conditions, especially in susceptible groups like children, the elderly, and people with cardiovascular or respiratory disorders. The evidence from these studies and the current research points to the urgent need for targeted interventions to mitigate exposure, such as issuing health advisories during high-pollution periods, reducing industrial emissions, and increasing public awareness of the risks associated with elevated particulate matter levels.

Additionally, research by Bhosale et al. (2025), Huang et al. (2025), and Rauf et al. (2024) have shown the health hazards of chronic exposure to $PM_{2.5}$, underscoring the wider socioeconomic and healthcare implications of persistent air pollution. These risks include not only respiratory and cardiovascular diseases but also adverse birth outcomes, reduced sperm quality, and increased susceptibility to conditions such as diabetes, lung cancer, and even higher morbidity and mortality from infectious diseases like COVID-19 (Chin et al., 2024; Li et al., 2024; Maniat et al., 2024). This aligns with the current findings, which indicate a significant burden on public health due to $PM_{2.5}$ exposure in the region.

To sum up, the results of this investigation underscore the serious and consistent problem of elevated $PM_{2.5}$ concentrations in the Steve Tshwete region, which are linked to both seasonal weather patterns and increased human activities. The frequent exceedances of air quality standards highlight the need for immediate and long-term interventions to address this ongoing public health threat.

Figure 9 shows the monthly average $PM_{2.5}$ concentrations in Steve Tshwete for 2022. The results demonstrate a unimodal trend in $PM_{2.5}$ levels, with the highest recorded above the annual average of 15 µg/m³ in winter (May to August) and parts of spring (September and October). The highest concentration is observed in July, with the lowest recorded in summer and autumn.

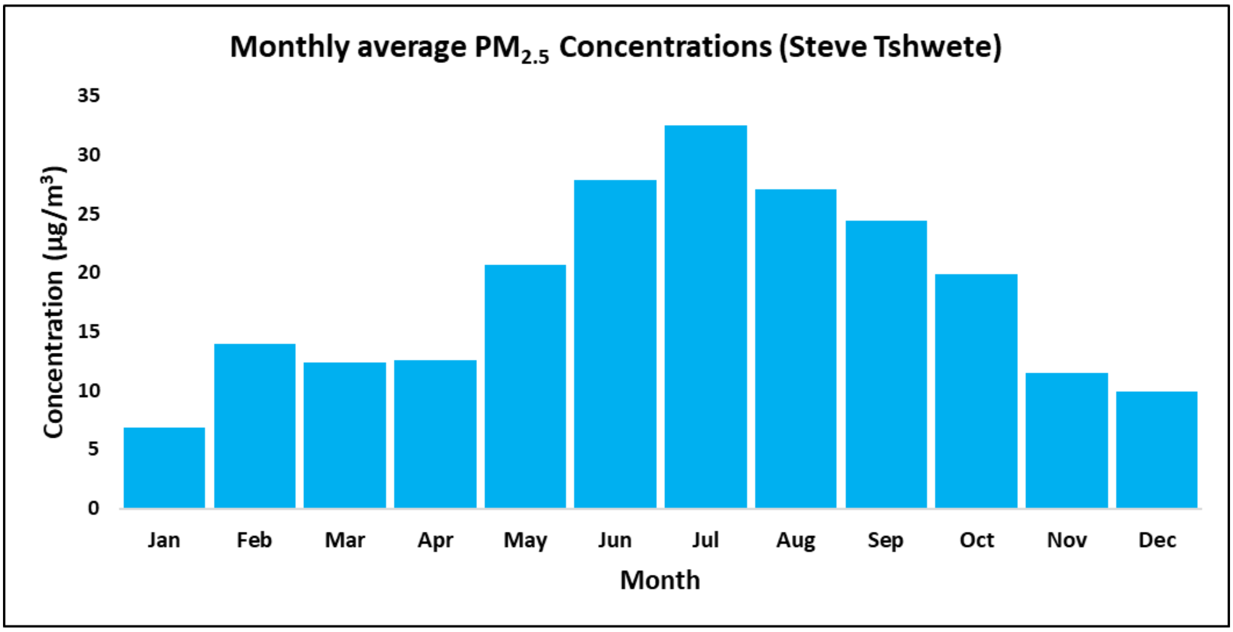


Figure 9: Monthly average $PM_{2.5}$ concentrations in Steve Tshwete for 2022.

The findings of the current study regarding high $PM_{2.5}$ concentrations in July, as illustrated in Figure 9, align with previous research, particularly the work of (Zhao et al., 2018; Wang et al., 2025), which suggest that seasonal weather patterns, increased human activities, and specific meteorological conditions play a key role in elevated $PM_{2.5}$ levels. July, falling within the dry season, is typically associated with higher dust and particulate matter in the atmosphere due to dry conditions and the absence of rain. This seasonal pattern is consistent with the finding that temperature inversions often occur during this time, trapping pollutants near the ground and preventing their dispersion, which further increases $PM_{2.5}$ concentrations. (Wang et al., 2025) also support this notion, highlighting that temperature inversions during the dry season can significantly exacerbate air pollution by restricting vertical mixing and dispersion.

The elevated $PM_{2.5}$ levels that have been observed during this time are probably caused by human activity in addition to weather factors. Increased agricultural activity, especially the burning of crop leftovers, which is a known producer of particulate matter, occurs throughout July. This finding is consistent with (Zhao et al., 2018), who note that agricultural burning is a significant contributor to $PM_{2.5}$ concentrations, especially in the dry season. Furthermore, the study highlights increased construction and industrial activities during this month, both of which are known to elevate particulate matter levels. Wildfires, which are more common in July due to the dry conditions, are also a significant source of particulate pollution, as noted by (Wang et al., 2025). Large amounts of fine particulate matter are released into the atmosphere by the smoke from these fires, which significantly contributes to the high $PM_{2.5}$ levels that have been recorded at this time.

The impact of wind patterns, as discussed by (Zhao et al., 2018), is also evident, as changes in wind direction can bring in polluted air from other regions, exacerbating local $PM_{2.5}$ concentrations. The absence of significant rainfall during July reduces the natural removal of particulate matter from the air, further compounding the pollution problem.

Conversely, the lower $PM_{2.5}$ concentrations observed in January, as illustrated in Figure 9, reflect a stark contrast, and several factors likely contribute to this reduction. As Bambelo (2024) points out, the weather conditions in January, such as increased rainfall, play a crucial role in reducing particulate matter levels. Rain helps to wash away airborne pollutants, significantly reducing $PM_{2.5}$ concentrations. Additionally, higher humidity during this time can cause particulate matter to settle more quickly, while stronger winds can disperse pollutants, leading to lower concentrations. These findings are consistent with the general understanding that wet and windy conditions help improve air quality by facilitating the removal and dispersion of particulate matter.

Moreover, January is often a period of reduced human activities, including industrial operations and construction, as noted by (Bambelo (2024), due to the holiday season. This slowdown in human activities resulted in lower emissions, further contributing to the decrease in $PM_{2.5}$ concentrations. The reduced vehicular traffic during this period also contributes to lower particulate matter emissions. Cooler temperatures in January can inhibit the formation of secondary particulate matter, which, as He et al. (2025) note, is a significant component of $PM_{2.5}$. This reduction in secondary particulate matter formation, combined with other meteorological and human activity-related factors, accounts for the observed lower $PM_{2.5}$ levels in January.

In conclusion, the comparison of the findings from the current study with the studies mentioned (Zhao et al., 2018; Wang et al., 2025; Bambelo, 2024; He et al., 2025) demonstrates the significant impact of both seasonal weather patterns and human activities on $PM_{2.5}$ concentrations. The dry conditions and increased human activities, such as agricultural burning and industrial operations, during July, contribute to higher $PM_{2.5}$ levels, while the wetter and cooler conditions of January, combined with reduced human activity, lead to lower concentrations. These findings highlight the intricate interplay among meteorological conditions, human activities, and atmospheric processes in shaping annual air quality patterns.

Figure 10 shows the diurnal patterns of $PM_{2.5}$ concentrations in Steve Tshwete for 2022. Results indicate that the lowest concentrations of particulate matter occur between 12:00 and 18:00, with values ranging from approximately 13 $\mu g/m^3$ to 14 $\mu g/m^3$. This period typically corresponds to midday and early afternoon hours, when several factors contribute to lower $PM_{2.5}$ levels

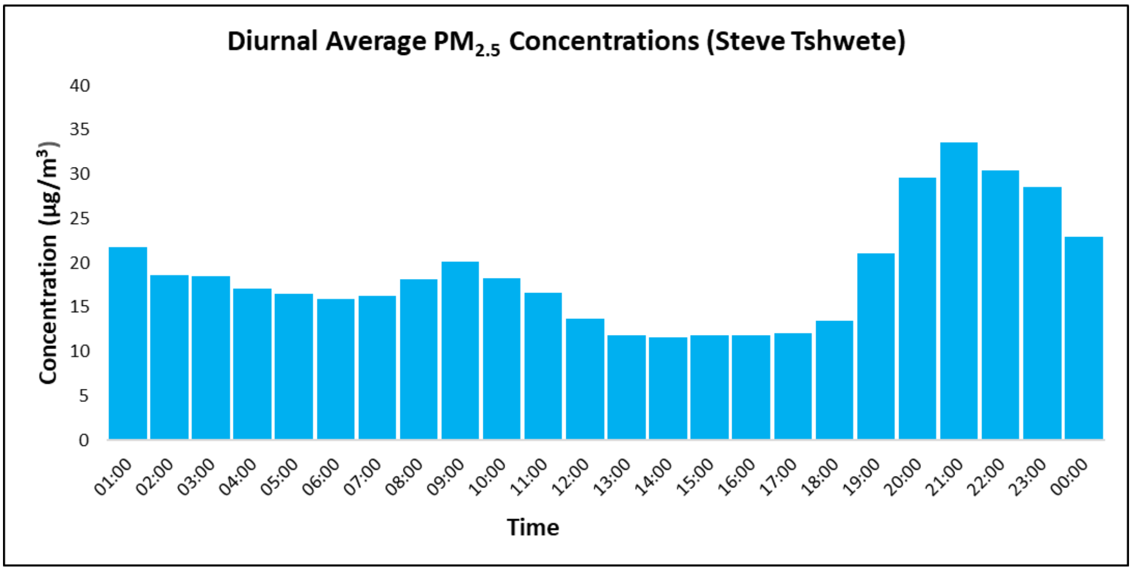


Figure 10: Diurnal patterns of $PM_{2.5}$ concentrations in Steve Tshwete for 2022.

Morning Peak

The observed peak in $PM_{2.5}$ concentrations during the early morning hours (between 07:00 and 11:00), as illustrated in Figure 10 is consistent with the findings of other studies (Melaniuk-Wolny & Widziewicz-Rzońca, 2024; Künn at al., 2023; Pala et al., 2022) that highlight the influence of both meteorological conditions and human activities on air quality during this time. The cooler ground temperatures in the morning, which lead to a temperature inversion, effectively trap air pollutants near the surface, restricting their dispersion. This atmospheric phenomenon has been well-documented, with studies confirming that temperature inversions, especially during the morning hours, contribute significantly to elevated concentrations of particulate matter, as seen in the current study. This is particularly relevant in urban areas, where temperature inversions are more likely due to the dense infrastructure and limited vertical air movement.

In addition to atmospheric conditions, one human activity that raises $PM_{2.5}$ concentrations is the use of solid fuels for heating during the cold morning hours. Burning coal and wood for warmth is one of the primary sources of particulate matter, particularly in low-income homes. This finding supports the findings of Wright et al. (2025), who point out that indoor air pollution—mainly from solid fuels and cookstoves—is responsible for millions of fatalities annually. This issue is especially prevalent during the winter months, when heating demand increases, further intensifying the morning peak in $PM_{2.5}$ levels. The current study's findings that solid fuel use exacerbates this peak are supported by a growing body of research emphasizing the significant public health risks associated with both indoor and outdoor air pollution.

Additionally, one of the main factors impacting $PM_{2.5}$ levels and contributing significantly to urban air pollution, especially during the morning rush hour, is vehicle emissions. According to Wallington et al. (2022), one of the main causes of the decline in urban air quality is car emissions. This issue is further exacerbated in South Africa, where the rise in private vehicle ownership has surpassed the use of public transportation, leading to higher traffic volumes and increased fuel consumption, as noted by Romero et al. (2024). Additionally, Shen et al. (2024) emphasize that motor vehicle emissions are a major contributor to the morning peak in $PM_{2.5}$ concentrations and are a prominent cause of urban air pollution. The findings of this study align with these conclusions, emphasizing that the surge in vehicular traffic during the morning commute, combined with lower atmospheric mixing heights, leads to the accumulation of pollutants near the surface, exacerbating air quality problems during this time.

The findings of the current study align with previous research in demonstrating how a combination of meteorological conditions and human activities, such as solid fuel use and vehicular emissions, contribute to the early morning peak in $PM_{2.5}$ concentrations. These results highlight the complex interplay between atmospheric stability and human behaviours in influencing urban air quality, particularly during the colder morning hours.

Midday Decline:

When comparing the observed decrease in $PM_{2.5}$ concentrations during the late morning and early afternoon (from approximately 11:00 to 16:00), as illustrated in Figure 10 with other research, it is evident that temperature plays a significant role in this trend. As noted by Yang et al. (2025), the rise in temperature during midday facilitates the vertical mixing of the atmosphere, which helps disperse air pollutants over a larger volume, thereby reducing $PM_{2.5}$ levels. This observation aligns with findings from other studies (Schnabel et al., 2025; Parra et al., 2024; Xin et al., 2024), which have shown that elevated temperatures promote vertical mixing, aiding in the dilution and dispersion of particulate matter.

Additionally, the role of wind speed and dispersion conditions during the daytime, as reported in this study, aligns with findings from (Parra et al., 2024). As temperatures rise and the sun is at its peak, wind speeds often increase, further promoting the dispersion and dilution of $PM_{2.5}$. This suggests that the observed reduction in $PM_{2.5}$ concentrations during this period may be a result of both temperature-induced atmospheric mixing and improved wind conditions.

Furthermore, the presence of solar radiation is noted in the study by Maghrabi et al. (2024), who found that solar radiation can lead to photochemical reactions, contributing to the breakdown of certain particulate matter components. This aligns with the current findings and reinforces the understanding that environmental factors, such as solar radiation and temperature, not only affect the dispersion of particulate matter but can also contribute to its chemical transformation.

Overall, these findings underscore the complex interaction between temperature, wind speed, and solar radiation in modulating $PM_{2.5}$ concentrations, and they are in agreement with other studies in the field that emphasize the importance of atmospheric conditions in determining air quality.

Evening Peak:

The observed peak in $PM_{2.5}$ concentrations during the late afternoon and evening (between 17:00 and 20:00), as illustrated in Figure 10, is consistent with findings from several studies, which identify the interplay of atmospheric conditions and human activities as key drivers of increased air pollution during this period. As temperatures drop in the evening, the cooling of the atmosphere and the reduction in wind speeds contribute to a diminished ability to disperse pollutants, as discussed by Piringer and Baumann-Stanzer (2024). This reduction in dispersion is compounded by the return of temperature inversion conditions, which trap particulate matter near the ground, leading to higher $PM_{2.5}$ concentrations. This phenomenon is well-documented in the literature and highlights how atmospheric stability, particularly temperature inversion, can exacerbate air pollution during evening hours.

In addition to atmospheric factors, the rise in evening home heating activities is a major contributor to the rising $PM_{2.5}$ levels. As temperatures decrease, more coal, wood, and other fuels are used for heating and cooking, which raises particulate matter concentrations in the air. This is especially noticeable in low-income areas, like those in South Africa, where solid fuel use is a major cause of urban air pollution (Frazenburg et al., 2025). Burning coal, wood, and paraffin releases a number of pollutants, such as sulfur dioxide, carbon monoxide, particulate matter, and volatile organic compounds (VOCs), according to Atafar et al.

(2025). These findings support the notion that domestic heating significantly contributes to the evening peaks in $PM_{2.5}$ concentrations.

Moreover, vehicular emissions add another layer of complexity to the rise in $PM_{2.5}$ levels during the evening. As Azhar et al. (2024) point out, car emissions can account for up to 95% of carbon monoxide and 70% of nitrogen oxides in urban areas. These pollutants significantly contribute to the creation of photochemical smog, particularly in regions with heavy traffic congestion. Hoekman and Welstand (2021) further elaborate on how increased traffic during evening commutes can exacerbate air pollution, especially in urban centers. The substantial contribution of traffic to the increase in $PM_{2.5}$ concentrations during this time is highlighted by the combination of higher vehicle emissions and decreased air dispersion in the evening.

Nighttime Stabilization:

The sustained elevation of $PM_{2.5}$ concentrations during the night, from 21:00 to early morning (around 01:00), observed in the current study, aligns with the findings of previous research that emphasize the role of both atmospheric conditions and continuous pollutant emissions in contributing to nighttime air quality issues. As highlighted by (Wang et al., 2022; Wang et al., 2021), reduced atmospheric mixing at night plays a significant role in maintaining elevated $PM_{2.5}$ levels. During this period, the lack of wind and cooling of the atmosphere limits the vertical dispersion of pollutants, effectively trapping them near the ground and preventing significant reductions in their concentration. This finding is consistent with the atmospheric dynamics that are often observed in urban areas, where the absence of significant wind or temperature variations creates stagnant conditions, leading to persistent pollution levels.

Furthermore, the continuous emissions from sources such as residential heating and industrial activities are key contributors to the elevated $PM_{2.5}$ concentrations during the night. As noted by (Wang et al., 2022), residential heating, particularly the use of solid fuels such as coal and wood, continues to be a significant source of particulate matter emissions during the nighttime, especially in colder months. Industrial emissions, which do not cease overnight, also contribute to the persistence of high $PM_{2.5}$ levels. This is consistent with the findings of the current study, which highlights how both domestic heating and industrial sources contribute to prolonged periods of elevated $PM_{2.5}$ concentrations.

Interestingly, while the atmospheric conditions can trap pollutants near the surface, (Wang et al., 2023) note that in the absence of significant wind or temperature variations, $PM_{2.5}$ concentrations may remain relatively constant or show slight reductions due to the settling of larger particles. This suggests that while the overall concentration of fine particulate matter remains high, there is a gradual decline in the concentration of larger particles as they settle out of the atmosphere. The current study concurs with this observation, as slight reductions in $PM_{2.5}$ concentrations may occur as larger particulate matter falls to the ground, but this effect is often insufficient to lead to significant improvements in air quality during the night.

In conclusion, the findings of the current study are in strong agreement with previous research, particularly the work of (Wang et al., 2021; Wang et al., 2022; Wang et al., 2023), which underscores the impact of reduced atmospheric mixing, continuous pollutant emissions, and the settling of larger particles on the persistence of elevated $PM_{2.5}$ concentrations during the night. This highlights the complex interaction between emissions, atmospheric conditions, and particle dynamics in shaping nighttime air quality.

4.3 To assess the health risks of exposure to $PM_{2.5}$ and risk characterization for different subgroups (children and adults) in the Steve Thswete Local Municipality:

The results in Table 4 present health risk assessment data for two age groups: children and adults. It includes parameters such as exposure time (ET), exposure frequency (EF), air quality standards (SA NAAQS and WHO Guidelines), and calculated hazard quotients (HQ).

Table 4: Air Quality and exposure data for different age groups.

Age group	ET (hr)	EF (days)	Cair (µg/m^3)	Cair_adj (µg/m^3)	HQ WHO Guidelines	HQ SA NAAQS	CR (unitless)
Children	18	350	14	10.07	2.014	0.504	6.9×10^{-3}
Adult	22	350	14	12.31	2.46	0.615	2.1×10^{-2}

CR assumes a life expectancy of 70 years for the 2 population subgroups and an exposure duration (ED) of 6 years for children and 15 years for the elderly.

The reported Cancer Risk (CR) values of 6.9×10^{-3} and 2.1×10^{-2}, as shown in Table 4, represent significantly higher probabilities of developing cancer due to exposure to $PM_{2.5}$ emissions. The CR values indicate a 6.9 in 1,000 chance for children and a 2.1 in 100 chance for elders of developing cancer over a lifetime due to long-term exposure to the recorded average $PM_{2.5}$ concentration of 14 $\mu g/m^3$. These levels are noticeably higher than what regulatory authorities typically consider acceptable. In most health and environmental risk assessments, cancer risk thresholds are set within a much lower range, often between 1×10^{-6} (1 in a million) and 1×10^{-4} (1 in 10,000). Such thresholds aim to ensure that the general public remains at low, acceptable risk levels for various health issues, including cancer.

In contrast, the reported CR values in this case are alarmingly high: A risk of 6.9×10^3 (6.9 in 1,000) is 1,000 times greater than the highest acceptable regulatory threshold (1×10^4). And a risk of 2.1×10^{-2} (2.1 in 100) is 100 times greater than the highest threshold. This significant discrepancy suggests that the affected population is exposed to a cancer risk that is far beyond what is considered acceptable by most environmental health standards. As such, these findings should raise immediate concern among health professionals, regulatory agencies, and the public. Urgent action is necessary to reduce exposure to $PM_{2.5}$ in the affected area, including investigating the sources of pollution, evaluating the effectiveness of current air quality control measures, and implementing more stringent emission standards or mitigation strategies to protect public health.

The Hazard Quotient (HQ) for the elderly is 2.46, and for children, it is 2.014, as illustrated in Table 4. HQ of 2 indicates that the estimated exposure to a pollutant is double the reference concentration that is considered safe for human health. The reference concentration is typically a value derived from extensive scientific studies, representing the level of exposure to a pollutant that is not expected to cause harmful effects to the majority of the population. In this case, an HQ of 2 suggests that the exposure levels in the population under study exceed the health-based threshold by a factor of two, which could indicate a potential risk for non-carcinogenic adverse health effects. These health effects may not be limited to cancer but could include a range of other health issues, such as respiratory problems, cardiovascular effects, or neurological impacts, especially for sensitive groups.

An HQ greater than 1 does not automatically mean that harm will occur; it simply indicates that the exposure is higher than the threshold considered safe, signaling a need for closer evaluation. While the risk may be manageable for some individuals, it remains important to consider that vulnerable populations could face more serious risks even at lower levels of exposure. In environmental health assessments, an HQ of 2 is viewed as a significant concern, as it suggests that people are being exposed to levels of a pollutant that exceed the safe limits. This is particularly alarming in areas where long-term exposure could lead to chronic health effects or where cumulative risks (from multiple pollutants) could compound the danger.

The HQ SA NAAQS values below 1 indicate that non-cancer health effects are unlikely under current exposure conditions. However, the high cancer risk suggests that long-term exposure may still pose a significant health threat, particularly for vulnerable populations

The higher HQ for adults is attributed to longer exposure times, as adults generally have extended periods of exposure to pollutants, leading to a higher cumulative risk. Furthermore, adults may engage in activities such as spending more time outdoors or in environments with elevated pollutant levels, increasing their exposure to pollutants compared to children; this is also highlighted by Khan et al. (2023). Additionally, physiological differences between children and adults, such as body weight, metabolic rate, and potential underlying health issues, contribute to the variation in HQ values. Adults' higher metabolic rates and larger body mass may result in different absorption, distribution, and elimination of pollutants, influencing the overall risk. The increased vulnerability of adults may also be compounded by pre-existing health conditions, as highlighted by (Manisalidis et al., 2020). In contrast, children tend to have shorter exposure times, lower adjusted pollutant concentrations, and differences in activity patterns and physiology, all of which contribute to their lower HQ values than adults. These findings are consistent with those reported by Radua et al. (2024), who also observed that children tend to have lower exposure and risk compared to adults due to their developmental stages and activity patterns.

Lastly, if the standard for $PM_{2.5}$ remains high according to the WHO and South African National Ambient Air Quality Standards (SA NAAQS), it could pose a complex challenge for developing countries. While elevated $PM_{2.5}$levels harm public health, leading to higher healthcare costs and reduced workforce productivity, many industries that contribute to air pollution, such as manufacturing, mining, and energy production, play a significant role in strengthening the economy. These industries provide jobs, stimulate infrastructure development, and contribute to national GDP growth. However, the economic benefits of these industries may be offset by the long-term health costs associated with pollution, including increased healthcare expenditures, premature deaths, and reduced economic output due to illness. In developing countries, where resources are already stretched, balancing economic growth with environmental and health considerations becomes even more critical. Therefore, while polluting industries can drive economic progress in the short term, failing to address air quality and health risks may undermine the country's long-term development and economic stability

5. *CHAPTER FIVE: CONCLUSION & RECOMMENDATIONS*

5.1 **Conclusion**

This study highlights significant air quality challenges in Steve Tshwete, where $PM_{2.5}$ concentrations often surpass both WHO and NAAQS guidelines. These elevated levels pose substantial health risks, underscoring the necessity for effective pollution mitigation strategies to protect public health. Continuous air quality monitoring and informed management are essential to address these issues.

Seasonal variations in $PM_{2.5}$ concentrations were evident, with peaks in July and troughs in January. Higher July levels are linked to dry conditions, increased agricultural burning, and possible wildfires. In contrast, January's lower concentrations result from higher precipitation, increased humidity, and reduced human activities during the holiday season. Understanding these patterns is vital for developing targeted interventions, especially during July's high-risk period.

Diurnal patterns showed elevated $PM_{2.5}$ levels during daytime, correlating with peak human activities like transportation, industry, and energy use. This finding emphasizes the need for policies addressing peak pollution times.

The study also examined wind patterns' impact on $PM_{2.5}$ levels. Monitoring stations that record wind direction, speed, and $PM_{2.5}$ concentrations offer valuable insights into pollution sources, aiding in identifying areas needing targeted control measures. Such monitoring is crucial for enhancing air quality management effectiveness.

Exposure to $PM_{2.5}$ presents a significant health risk, particularly in areas where air quality standards are not adequately enforced. The fine particulate matter can lead to severe respiratory and cardiovascular issues, increased mortality, and long-term chronic diseases, disproportionately affecting vulnerable populations such as children, the elderly, and those with pre-existing health conditions. While industries contributing to $PM_{2.5}$ emissions may boost economic growth, the long-term health consequences of such exposure present a serious public health challenge. Addressing these risks is crucial to safeguarding both the well-being of individuals and the sustainable development of affected communities.

In conclusion, addressing $PM_{2.5}$ pollution in Steve Tshwete requires proactive measures. Strategies should include stricter controls on agricultural burning, enhanced industrial emission monitoring, and public awareness campaigns to reduce exposure. Understanding seasonal and daily $PM_{2.5}$ variations and assessing health risks enable policymakers to take informed actions, aiming to improve air quality and protect community health. Implementing these measures will foster a healthier environment and enhance residents' quality of life.

5.2 Recommendations

Several important suggestions are made in light of the study's findings to lessen Steve Tshwete's exposure to $PM_{2.5}$ and the resulting health hazards. These suggestions focus on enforcing stricter emission controls, improving air quality monitoring, raising public awareness, incorporating green infrastructure, and implementing preventive actions to reduce particulate matter pollution.

Stricter Emission Controls are crucial to addressing the elevated levels of $PM_{2.5}$ in the region. It is important to enforce stricter regulations on industrial emissions to limit the release of $PM_{2.5}$ and other harmful pollutants. Regular monitoring and compliance checks should be carried out to ensure that industries follow emission standards. Additionally, promoting cleaner fuels and advanced emission control technologies in vehicles is essential to reduce vehicular pollution. Policies designed to alleviate traffic congestion and encourage the use of public transportation could also contribute to lower $PM_{2.5}$ levels by reducing the number of vehicles on the road.

Enhancing Air Quality Monitoring is another vital measure for improving air quality in the region. A comprehensive network of air quality monitoring stations should be established throughout Steve Tshwete to continuously measure $PM_{2.5}$ levels. Real-time data will help pinpoint pollution hotspots, evaluate the effectiveness of mitigation strategies, and inform future air quality policies. Public access to this data is crucial as it will enable residents to take precautionary actions during periods of elevated pollution.

Raising Public Awareness is essential for encouraging collective action to reduce pollution. Educational campaigns should be launched to inform the public about the health risks of $PM_{2.5}$ exposure and the importance of pollution control. These campaigns should also offer practical tips for minimizing exposure, such as staying indoors during high pollution events or reducing personal contributions to pollution, such as limiting car usage. Engaging local communities in air quality improvement initiatives is also important. Encouraging community-driven projects will foster a sense of responsibility and motivate residents to actively reduce air pollution.

Integrating Green Infrastructure plays a critical role in enhancing air quality. Expanding green spaces and urban vegetation helps absorb pollutants, effectively acting as natural air filters. Trees and plants, in particular, can significantly reduce $PM_{2.5}$ concentrations. Additionally, incorporating green roofs and walls into buildings can improve air quality while providing other environmental benefits, including energy savings and increased biodiversity.

Lastly, Implementing Preventive Measures is essential to target specific sources of $PM_{2.5}$. One such measure is promoting sustainable agricultural practices that minimize the burning of crop residues, a major contributor to air pollution. Farmers should be encouraged to adopt alternatives, such as composting or using crop residues for bioenergy production. Furthermore, dust control strategies at construction sites should be put in place, including using water sprays and covering materials, to prevent the release of particulate matter into the air.

By implementing these recommendations, the Steve Tshwete Local Municipality can effectively lower $PM_{2.5}$ levels, mitigate health risks, and improve air quality for its residents. Continuous monitoring, public involvement, and proactive strategies are crucial to achieving long-term improvements in air quality, ultimately protecting the health and well-being of the community.

5.3 Recommendations for future research

Future studies should examine the long-term health impacts of $PM_{2.5}$ exposure in a range of age groups, paying special attention to vulnerable groups like children, the elderly, and people with underlying medical disorders. Understanding these long-term effects can help develop focused health interventions and legislation to lessen unfavorable health consequences.

Determine and measure the main sources of $PM_{2.5}$ in the area, such as natural sources like wildfires, automobile traffic, industrial emissions, and agricultural activities. Source apportionment can inform more effective regulatory measures and pollution control strategies by targeting the most significant contributors to $PM_{2.5}$ levels.

Examine the impact of meteorological factors, including temperature, humidity, wind patterns, and precipitation, on $PM_{2.5}$ concentrations. Gaining insights into how weather conditions influence $PM_{2.5}$ levels can enhance air quality forecasting and support the development of adaptive measures to safeguard public health during unfavorable weather events.

Evaluate the effectiveness of various interventions and mitigation strategies, such as green infrastructure, emission control technologies, and public awareness campaigns. Assessing the outcomes of these strategies can provide valuable information for policymakers to implement the most effective actions to reduce $PM_{2.5}$ levels and protect public health.

Examine cumulative exposure to $PM_{2.5}$ and other pollutants, accounting for multiple sources and exposure pathways. A comprehensive assessment of cumulative exposure can offer a deeper understanding of the overall health risks and contribute to the development of holistic risk management strategies.

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Annexure 1: Plagiarism declaration

PLAGIARISM DECLARATION TO BE SIGNED BY ALL HIGHER DEGREE STUDENTS

SENATE PLAGIARISM POLICY: APPENDIX ONE

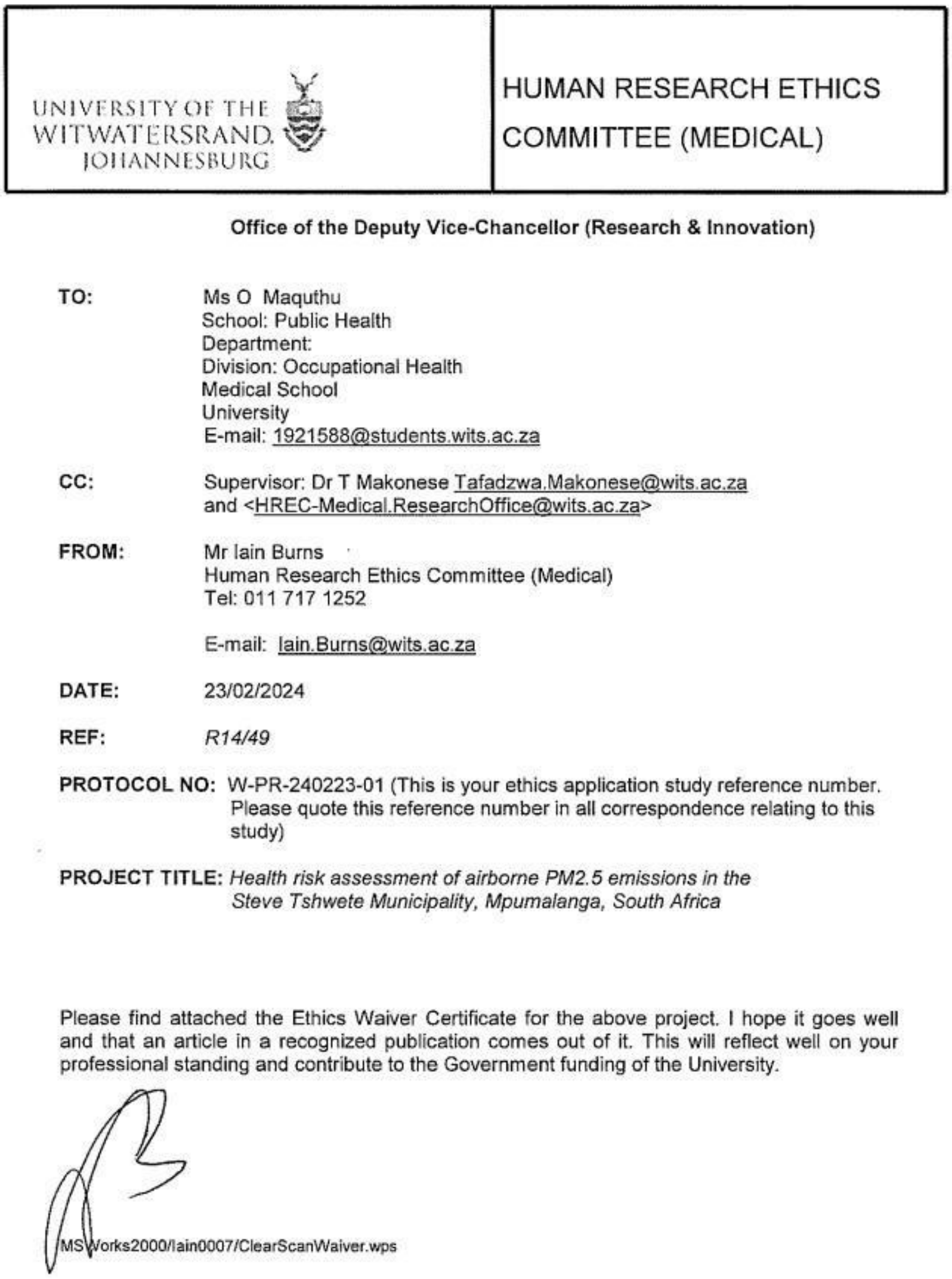
I Odwa Maquthu (Student number: ___1921588) am a student registered for the degree of Master of Science in Medicine (Exposure Science)_____in the academic year ___2023___.

I hereby declare the following:

- I am aware that plagiarism (the use of someone else's work without their permission and/or without acknowledging the original source) is wrong.
- I confirm that the work submitted for assessment for the above degree is my own unaided work except where I have explicitly indicated otherwise.
- I have followed the required conventions in referencing the thoughts and ideas of others.
- I understand that the University of the Witwatersrand may take disciplinary action against me if there is a belief that this is not my own unaided work or that I have failed to acknowledge the source of the ideas or words in my writing.
- I have included as an appendix a report from "Turnitin" (or other approved plagiarism detection) software indicating the level of plagiarism in my research document.

Signature: _____ _______Date: _06 June 2025________

Annexure 2: Ethics



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Office of the Deputy Vice-Chancellor (Research & Innovation)

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FROM: Mr Iain Burns
Human Research Ethics Committee (Medical)
Tel: 011 717 1252

E-mail: Iain.Burns@wits.ac.za

DATE: 23/02/2024

REF: *R14/49*

PROTOCOL NO: W-PR-240223-01 (This is your ethics application study reference number. Please quote this reference number in all correspondence relating to this study)

PROJECT TITLE: *Health risk assessment of airborne PM2.5 emissions in the Steve Tshwete Municipality, Mpumalanga, South Africa*

Please find attached the Ethics Waiver Certificate for the above project. I hope it goes well and that an article in a recognized publication comes out of it. This will reflect well on your professional standing and contribute to the Government funding of the University.

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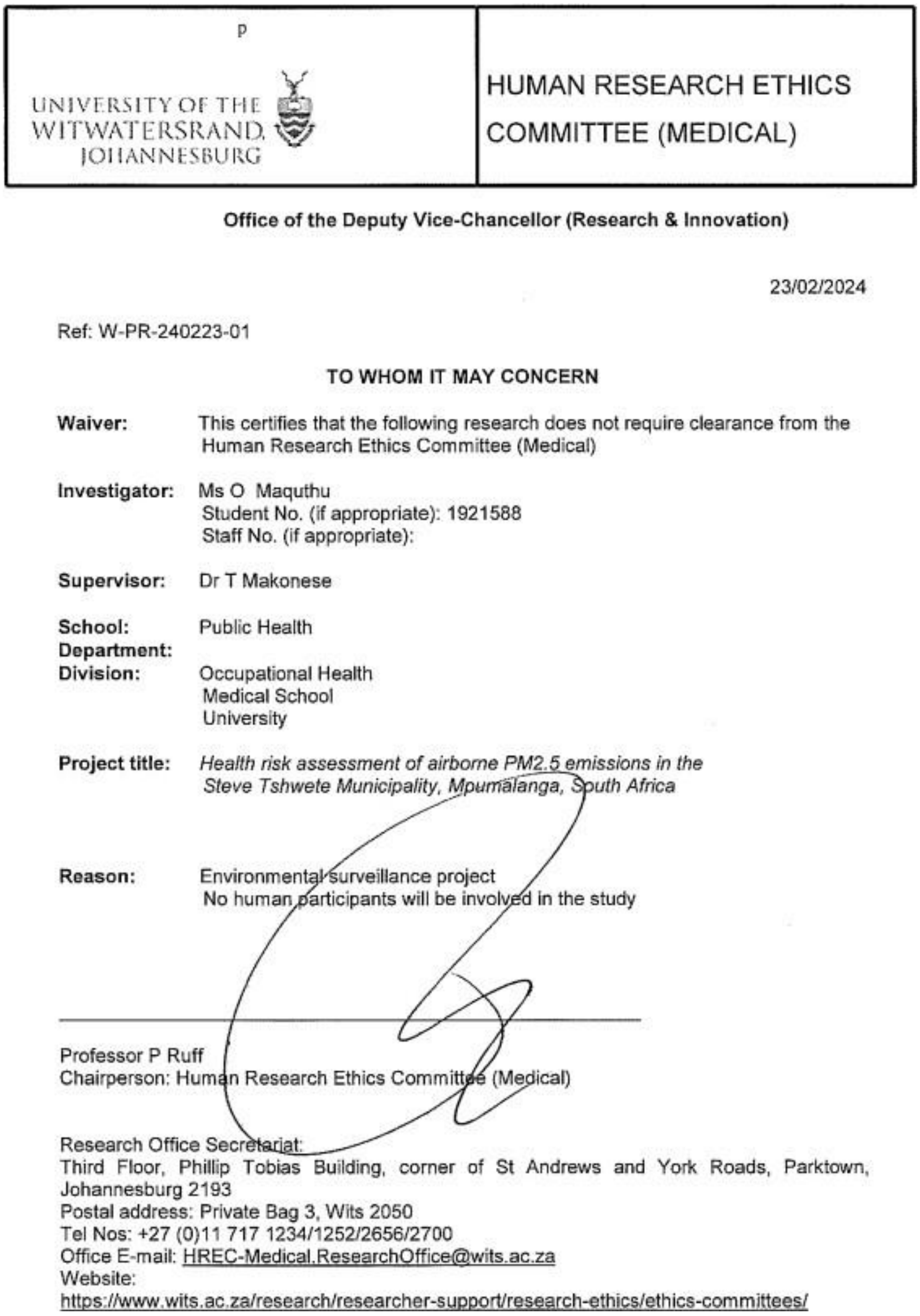

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23/02/2024

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TO WHOM IT MAY CONCERN

Waiver: This certifies that the following research does not require clearance from the Human Research Ethics Committee (Medical)

Investigator: Ms O Maquthu
Student No. (if appropriate): 1921588
Staff No. (if appropriate):

Supervisor: Dr T Makonese

School: Public Health
Department:
Division: Occupational Health
Medical School
University

Project title: *Health risk assessment of airborne PM2.5 emissions in the Steve Tshwete Municipality, Mpumalanga, South Africa*

Reason: Environmental surveillance project
No human participants will be involved in the study

Professor P Ruff
Chairperson: Human Research Ethics Committee (Medical)

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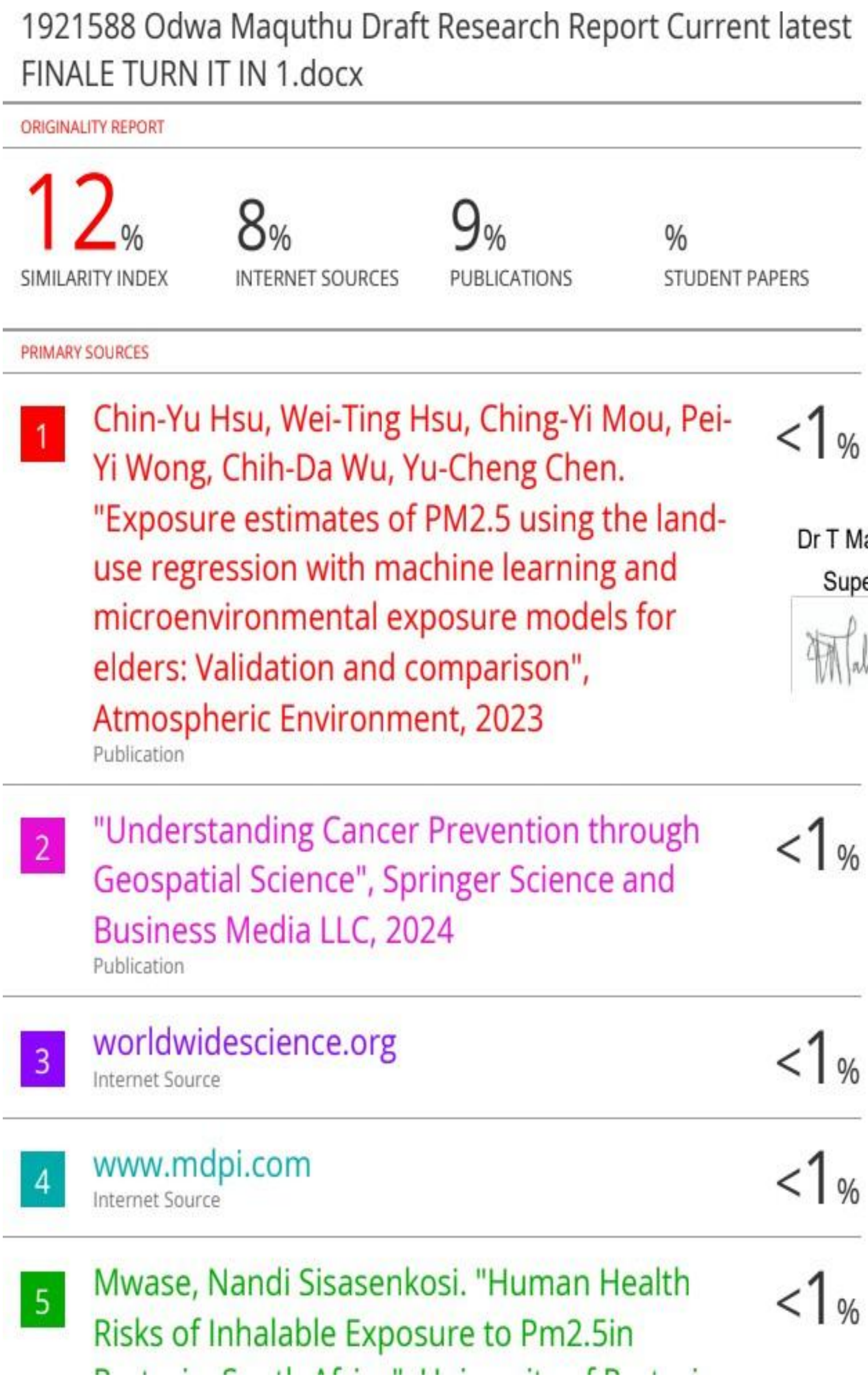
Annexure 3: Turnitin report



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