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Health Risk Assessment of Sulphur Dioxide Emissions in Mangaung, Bloemfontein, South Africa (2023)

RESEARCH REPORT

by

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DECLARATION

I Hlayisani Makhubele declare that this Thesis/Dissertation/Research Report is my own, unaided work. I have used Generative AI to assist me with paraphrasing my work. It is being submitted for the Degree of Master of Science in Medicine: Exposure Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

(Signature of candidate)

____**31**____day of_____**March**_____**2025**____in____**Johannesburg**_____

Dedication

This research is dedicated to my beloved mother, Tintswalo Ngobeni, whose unwavering love, sacrifices, and strength have shaped the person I am today. As a single mother, she faced countless challenges, yet her resilience, guidance, and endless support never wavered.

Mom, this achievement is as much yours as it is mine. Your faith in me has been my greatest motivation, and your hard work has been my inspiration. I am forever grateful for all that you have done to help me come this far.

With all my love and gratitude,
Hlayisani Makhubele

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Glossary of Terms

1. **Acid Rain** – Rainfall with high acidity resulting from atmospheric reactions involving pollutants like SO_2 and nitrogen oxides, which harm ecosystems, buildings, and human health.
2. **Air Pollution** – The presence of harmful substances in the air, including gases, particulate matter (PM), and biological molecules, which can pose health and environmental risks.
3. **Air Quality Monitoring** – The process of measuring pollutant concentrations in the air using specialized instruments, such as UV fluorescence analysers for SO_2.
4. **Ambient Air Quality** – The quality of the air in the surrounding environment, typically measured in terms of pollutant concentrations like sulphur dioxide (SO_2), nitrogen oxides (NOx), and particulate matter (PM10, PM2.5).
5. **Analysis of Variance (ANOVA)** – A statistical method used in this study to compare SO_2 levels across different seasons to determine significant differences.
6. **Chronic Daily Intake (CDI)** – A measure of long-term exposure to pollutants, expressed in micrograms per kilogram per day (µg/kg/day).
7. **Climate Change and Air Quality** – The interaction between global climate change and local air pollution, where increased temperatures can exacerbate the formation of secondary pollutants.
8. **Diurnal Patterns** – The daily fluctuations in pollutant concentrations due to factors such as traffic patterns, industrial operations, and temperature changes.
9. **Dose-Response Assessment** – The process of determining the relationship between the amount of exposure to a substance and the severity of health effects.
10. **Emission Factors** – Quantitative estimates of pollutant emissions from specific sources, used to assess contributions of different activities (e.g., industrial, vehicular) to air pollution levels.
11. **Environmental Justice** – The principle that all communities should have equal protection from environmental hazards, regardless of socio-economic status or geographic location.
12. **Exposure Assessment** – The measurement or estimation of the intensity, duration, and frequency of exposure to pollutants in specific populations.
13. **Gas Analyzers** – Instruments that measure concentrations of gaseous pollutants, such as SO_2, NOx, and CO, in real-time.
14. **Hazard Identification** – The first step in HRA, which involves recognizing environmental stressors (e.g., SO_2) and their potential health effects.

15. **Hazard Quotient (HQ)** – A numerical value used to assess whether exposure to a pollutant poses a health risk (HQ > 1 indicates potential risk; HQ < 1 suggests minimal risk).
16. **Health Risk Assessment (HRA)** – A systematic approach to evaluating the potential health effects of exposure to hazardous substances over different timeframes.
17. **Industrial Zoning and Air Pollution** – The placement of industrial activities near residential areas, often affecting low-income communities disproportionately due to historical planning decisions.
18. **Inhalation Exposure** – The process by which pollutants, such as SO_2, enter the body through breathing, impacting respiratory and cardiovascular health.
19. **National Ambient Air Quality Standards (NAAQS)** – Air quality limits set by South Africa to regulate concentrations of pollutants, ensuring protection of human health and the environment.
20. **Particulate Matter (PM)** – A mixture of solid and liquid particles in the air, classified by size (PM10, PM2.5), known to cause respiratory and cardiovascular diseases.
21. **Real-Time Air Quality Monitoring** – Continuous measurement of air pollutant levels using automated sensors, allowing for immediate data collection and analysis.
22. **Risk Characterisation** – The final step in HRA that integrates exposure, hazard, and dose-response information to estimate the overall risk to human health.
23. **Seasonal Variation** – The fluctuation of air pollution levels throughout the year, often influenced by heating, agricultural activities, and meteorological conditions.
24. **Socioeconomic Factors** – Social and economic conditions (e.g., income level, education, access to healthcare) that influence individuals' exposure to and vulnerability from pollution.
25. **South African Air Quality Information System (SAAQIS)** – A national database providing real-time and historical air quality data, used for air pollution assessment and policymaking.
26. **Sulphur Dioxide (SO_2)** – A toxic gas mainly produced from burning fossil fuels (coal, oil), industrial processes, and vehicle emissions, known to cause respiratory irritation and environmental harm.
27. **Temperature Inversion** – A weather condition where a layer of warm air traps pollutants near the ground, leading to high pollution concentrations.
28. **Time-Series Analysis** – A statistical approach used to examine trends and seasonal variations in SO_2 concentrations over time.

29. **Urban Resilience** – The ability of cities to withstand and adapt to environmental hazards like air pollution while maintaining the well-being of residents.
30. **UV Fluorescence Spectroscopy** – A method used to detect SO_2 in ambient air by measuring fluorescence emitted when SO_2 molecules absorb ultraviolet light.
31. **Vulnerable Populations** – Groups more susceptible to pollution-related health effects, such as toddlers (0–5 years), the elderly (60+ years), and individuals with preexisting conditions.
32. **Wind Speed and Direction** – Key factors affecting pollutant dispersion, with high winds dispersing pollutants and low winds leading to localized air pollution hotspots.
33. **World Health Organization (WHO) Air Quality Guidelines** – International standards recommending safe levels of pollutants in the air to minimize health risks, stricter than many national regulations.

List of Abbreviations

1. **ANOVA** – Analysis of Variance
2. **AQI** – Air Quality Index
3. **CDI** – Chronic Daily Intake
4. **COPD** – Chronic Obstructive Pulmonary Disease
5. **CO** – Carbon Monoxide
6. **FADD** – Field Average Daily Dose
7. **GIS** – Geographic Information System
8. **H_2S** – Hydrogen Sulphide
9. **HQ** – Hazard Quotient
10. **HRA** – Health Risk Assessment
11. **HREC** – Human Research Ethics Committee
12. **IEC** – International Electrotechnical Commission
13. **IQR** – Interquartile Range
14. **ISO** – International Organization for Standardization
15. **MLE** – Maximum Likelihood Estimation
16. **NAAQS** – National Ambient Air Quality Standards (South Africa)
17. **NEM** – National Environmental Management Act
18. **NOx** – Nitrogen Oxides
19. **O_3** – Ozone
20. **PEL** – Permissible Exposure Limit
21. **PM** – Particulate Matter
22. **PM_{10}** – Particulate Matter with a diameter of 10 micrometres or less
23. **$PM_{2.5}$** – Particulate Matter with a diameter of 2.5 micrometres or less
24. **RfC** – Reference Concentration
25. **RSA** – Republic of South Africa
26. **SAAQIS** – South African Air Quality Information System
27. **SADD** – Safe Average Daily Dose
28. **SANAS** – South African National Accreditation System
29. **SANS** – South African National Standards
30. **SO_2** – Sulphur Dioxide
31. **UNFCCC** – United Nations Framework Convention on Climate Change
32. **USEPA** – United States Environmental Protection Agency

33. **UV** – Ultraviolet
34. **VOC** – Volatile Organic Compounds
35. **WHO** – World Health Organization

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Abstract

Introduction: Air pollution poses serious environmental and public health challenges in many South African cities. In Mangaung, sulphur dioxide (SO_2) is one of the major pollutants linked to domestic fuel burning, traffic emissions, and meteorological conditions, especially during winter. Vulnerable groups such as children and the elderly are particularly at risk of adverse health outcomes from prolonged or high-level exposure. *Aim*: The study aimed to assess the health risks associated with ambient SO_2 emissions in Mangaung, based on 2023 data from the Pelonomi air quality monitoring station. *Methods*: A descriptive and quantitative approach was used, relying on secondary SO_2 concentration data obtained from the South African Air Quality Information System (SAAQIS). The data were analysed to determine hourly, daily, monthly, and seasonal trends. One-way ANOVA and Bonferroni post-hoc tests were applied to identify statistically significant seasonal SO2 differences. A scenario-based health risk assessment was conducted for toddlers and elderly populations using the USEPA's noncarcinogenic risk model. *Findings*: The results showed significant seasonal variation, with SO_2 concentrations peaking in winter and remaining lowest in summer. While all values were below the South African National Ambient Air Quality Standards (NAAQS), many exceeded the World Health Organization's 24-hour guideline of 20 $\mu g/m^3$. The calculated hazard quotient (HQ) values for both toddlers (0.0674) and the elderly (0.0824) were below 1, indicating low long-term health risk. However, repeated short-term peaks observed in the hourly and daily averages suggest potential health concerns for sensitive groups during colder months. *Conclusion*: Although long-term exposure to SO_2 in Mangaung does not currently pose a significant health risk, short-term exposure spikes—particularly during winter—may still lead to respiratory issues among vulnerable populations. The use of national standards alone may underestimate these risks. *Recommendations*: The study recommends aligning national air quality standards with WHO guidelines, expanding monitoring networks in high-risk areas, promoting clean energy alternatives for households, and improving public awareness of the health impacts of SO_2 pollution. These actions are necessary to safeguard public health and support sustainable urban air quality management in Mangaung.

CHAPTER 1: INTRODUCTION

1.1. Introduction

1.1.1 Background

Air pollution stems from a blend of processes introducing various pollutant gases or particulate matter from human activities, notably industrial and vehicular operations (1). Annually, air pollution is accountable for the deaths of 7 million individuals globally (1). Sulphur dioxide (SO_2) is a chemical compound in gas emissions capable of contaminating the surrounding air and contributing to air pollution (2). This chemical compound possesses distinct odorous qualities and does not ignite when airborne. Sulphur dioxide emissions arise from various human activities, including power generation, combustion processes, mining, and metal processing (3).

Research indicates that prolonged exposure to SO_2 has shown a threshold for health impacts, with effects observed after approximately 24 hours at concentrations ranging from 5 to 40 $\mu g/m^3$ (4). As per the Safety Data Sheets (SDSs), exposure to 20 parts per million (ppm) of SO_2 gas can lead to eye, nose, throat, and sinus irritation, along with pulmonary oedema and potentially death (4). Additionally, it can cause respiratory irritation and reduce lung function in people, leading to symptoms like coughing, difficulty breathing, and worsening asthma (2).

Sulphur dioxide exposure results in varying health outcomes across different age groups, with each group exhibiting distinct susceptibility and effects (5). Children are more vulnerable to the harmful effects of SO_2 on respiratory health due to factors such as increased mouth breathing, higher ventilation per body weight, time spent outdoors, and an immature, still developing respiratory system. Studies, including the Children's Health Study, have shown reduced lung growth in children exposed to poor air quality as well asthmatic symptoms. However, other scholars also found that lung growth improved when air quality improved (6). Elderly people are particularly susceptible to the adverse effects of sulphur dioxide (SO_2) exposure due to their typically compromised respiratory and cardiovascular systems (7). Increased airway sensitivity in older adults can lead to more pronounced respiratory symptoms such as coughing, wheezing, and shortness of breath. Sulphur dioxide exposure can exacerbate existing chronic respiratory conditions like asthma, chronic bronchitis, and chronic obstructive pulmonary disease, and can also increase cardiovascular stress, raising the risk of heart attacks

and other heart-related issues (8). The inclusion and exclusion criteria for this study refers to children as toddlers aged 0 – 5 years and elderly as people aged 60 and above.

This study delved into the SO_2 air quality guidelines and standards set by the World Health Organization (WHO), which stated that the 10-minute average should be 500 µg/m³ (micrograms per cubic meter) and the 24-hour average should be lower, i.e. 20 µg/m³ (9). The National Ambient Air Quality Standards (NAAQS) and the United States Environmental Protection Agency (USEPA) includes a 1-hour standard of 75 ppb (approximately 196 µg/m³), averaged over 3 years, and a 24-hour standard of 0.14 ppm, not to be exceeded more than once per year, also averaged over 3 years. The annual standard of 0.5 ppm was revoked in 2010 to conduct the health risk assessment (10). The air quality guideline is shown in annexure 1.

1.1.2. Rationale of the Study

The rationale for this study stemmed from the critical need to address the health impacts of SO_2 emissions in Mangaung, South Africa. Air pollution, driven by industrial and vehicular activities, has been linked to severe health issues and millions of deaths annually. Sulphur dioxide, a significant pollutant, is known for causing respiratory problems and exacerbating conditions like asthma and chronic bronchitis. Vulnerable populations, such as children and the elderly, are particularly at risk. Given the rising SO_2 levels in Mangaung, this study aimed to evaluate the health risks in the area by referencing WHO and USEPA guidelines, thus providing a foundation for effective air quality management strategies. By understanding the specific health outcomes of SO_2 exposure in this context, the study sought to contribute to the development of policies that could safeguard public health and improve the quality of life for residents.

1.1.3. Problem Statement

The city of Mangaung, located in Bloemfontein, South Africa, is confronted with a pressing environmental challenge due to the emission of SO_2 from various anthropogenic sources (including industrial sources) and natural activities sources (11). In Mangaung, there is a higher volume of vehicles on the road during peak hours, which can result in elevated SO_2 emissions (12). Sulphur dioxide emissions pose potential health risks to the residents of this area. Despite existing regulations, industrial and anthropogenic activities continue to contribute to the deterioration of air quality, resulting in elevated levels of SO_2 in the atmosphere (13).

Understanding the extent of exposure and its subsequent health implications is imperative for effective environmental management and public health intervention strategies (14). Therefore, the goal of this research was to conduct a comprehensive health risk assessment of SO_2 emissions in Mangaung, Bloemfontein, South Africa. The study characterized SO_2 emissions, analysed their temporal distribution, and evaluated potential health effects in the exposed local population. By identifying vulnerable groups and assessing the magnitude of health risks, this research provided valuable insights for policymakers, urban planners, and public health authorities to mitigate the adverse impacts of SO_2 emissions and safeguard the well-being of residents in this region.

1.1.4. Research Question

What is the health risk of continued exposure to ambient SO_2 emissions in different population sub-groups in Mangaung, using the 2023 data from the Pelonomi air quality station?

1.1.5. Research Aim

To assess the health risks of exposure to SO_2 in Mangaung in Bloemfontein, South Africa.

1.1.6. Research Objectives

1. To quantify ambient SO_2 emission factors prevalent in Mangaung, Bloemfontein, South Africa, using data from a stationary ambient air quality monitoring system.
2. To analyse diurnal seasonal variations of SO_2 concentrations in Mangaung, Bloemfontein, South Africa.
3. To assess the potential health risks of exposure to SO_2 emissions in different population groups (toddlers aged 0 – 5 years and elderly aged 60 and above) in the Mangaung, Bloemfontein, South Africa.

1.1.7 Justification and Rationale of the Study

Conducting a health risk assessment of SO_2 emissions in Mangaung, Bloemfontein, South Africa, is not only a scientific endeavour but also a moral and ethical imperative to protect public health, promote environmental justice, ensure regulatory compliance, inform policy decisions, and empower local communities. South Africa needs comprehensive studies that critically evaluate the health risks associated with airborne SO_2 emissions in regions hosting intensive industrial and power generation operations. The outcomes of such research endeavours would substantially enrich our understanding of exposure to ambient SO_2

emissions and the potential health risks to residents in Mangaung, South Africa. There is a lack of localized research focusing specifically on smaller urban centers like Mangaung. Most studies have concentrated on major metropolitan areas or regions with heavy industrial activity, leaving a gap in understanding the health risks in smaller, less-studied cities. Research in these areas is necessary to provide a more comprehensive picture of the health impacts of SO_2 across different contexts (13).

1.2. Overview of the study

- Chapter 1: Introduction

This chapter provides a comprehensive overview of the problem being investigated. It begins by detailing the background and significance of the research topic, including the context and relevance of the study. It outlines the research questions and objectives that the study aimed to address, setting the stage for the investigation. The chapter also includes a detailed action plan, describing the steps and strategies that were employed to achieve the research goals and ensure the successful completion of the study. This plan includes the methodology, data collection procedures, and timeline for the research activities.

- Chapter 2: Literature Review

The literature review chapter synthesises existing knowledge and perspectives related to the research topic. It provided a critical analysis of previous research and findings from various sources, including academic journals, articles, books, and dissertations. This review identified key themes, theories, and gaps in the literature, offering a comprehensive understanding of the subject matter. By examining the work of other researchers, this chapter establishes a foundation for the current study, highlighting how it builds upon or deviates from existing knowledge.

- Chapter 3: Research Methodology

This chapter details the research design and methods employed to gather data and obtain responses. It described the approach used for sampling respondents, including selection criteria and procedures. The chapter outlined the data collection techniques. Additionally, it covered the procedures for managing and analysing the collected data, ensuring that the findings are accurate and reliable. The methodology section also addresses ethical considerations and any limitations of the research methods used.

- Chapter 4: Results and Discussion of Findings

This chapter presents the results of the data analysis and interprets the findings in relation to the study's objectives and existing literature. It outlines the analytical methods used, highlights key trends in SO_2 concentrations, and discusses seasonal variations and health risks for vulnerable groups. The chapter also compares the results with previous studies, explaining any similarities or differences, and reflects on the implications for public health and air quality management in Mangaung.

- Chapter 5: Conclusion and Recommendations

The conclusion chapter summarised the key findings of the research and provided an assessment of whether the study successfully answered the research questions. It reflected on the overall success of the research in meeting its objectives and highlighted the contributions made to the field. Based on the findings, the chapter offered practical recommendations for addressing the identified issues or gaps. It suggested further research directions or policy changes to remedy the problems uncovered in the study.

2. Conclusion

In conclusion, this study is of significant importance due to its focus on assessing the health risks associated with sulphur dioxide (SO_2) emissions in Mangaung, South Africa. The background established the detrimental impact of air pollution, particularly from SO_2, on human health, highlighting its contribution to respiratory issues and exacerbation of existing health conditions among vulnerable populations such as children and the elderly. Motivated by the increasing SO_2 levels in Mangaung, the research aimed to bridge gaps in understanding by referencing WHO and USEPA guidelines to inform effective air quality management. The study's significance lies in its potential to influence public health policies and improve community well-being by providing data-driven insights into the health risks of SO_2 exposure. By addressing the problem of inadequate assessment of SO_2 health impacts in Mangaung, the research will offer valuable information to policymakers, urban planners, and public health authorities, thereby contributing to the development of strategies to mitigate adverse health effects and enhance air quality in the region.

CHAPTER 2: LITERATURE REVIEW

2.1. Introduction

Sulphur dioxide (SO_2) is a significant air pollutant primarily released from industrial processes, fossil fuel combustion, and vehicle emissions. As an irritant, SO_2 poses serious health risks, particularly affecting the respiratory system by aggravating conditions like asthma and bronchitis (25,26). In Mangaung, Bloemfontein, increasing urbanisation and industrial activities necessitate a thorough health risk assessment of SO_2 emissions to understand its impact on public health.

In urban areas, elevated concentrations of SO_2 are particularly concerning due to the dense population and high exposure levels. Health risk assessments play a crucial role in identifying vulnerable populations, assessing potential health impacts, and guiding policy decisions to mitigate these risks. These assessments are especially relevant in Mangaung, where urbanisation and industrial activities have led to increased SO_2 levels, posing potential threats to community health (27).

This study focuses on assessing the health risks associated with SO_2 emissions in Mangaung, Bloemfontein, South Africa. By conducting a comprehensive health risk assessment, the research seeks to provide insights into the extent of SO_2 exposure and its health implications for the local population, contributing to the development of strategies to reduce exposure and enhance public health (16).

2.2. Sources and emissions of SO_2

2.2.1. Primary Sources of SO_2 Emissions

Sulphur dioxide (SO_2) is primarily emitted from anthropogenic activities, with the main sources being industrial processes, particularly those involving the combustion of fossil fuels such as coal and oil. Industries like power generation, metal smelting, and the production of chemicals are significant contributors. Power plants that burn coal are especially notorious for releasing large quantities of SO_2 into the atmosphere due to the high sulphur content in the coal used. Additionally, petroleum refineries and industrial facilities that produce sulphuric acid are major sources of SO_2 emissions. Another notable source is the transportation sector, particularly diesel-powered vehicles and ships, which burn high-sulphur fuels. These sources collectively contribute to the bulk of SO_2 emissions globally, with industrial activities being the predominant (27,28,29).

2.2.2. Specific Sources Relevant to Mangaung, Bloemfontein

In Mangaung, Bloemfontein, the primary sources of sulphur dioxide emissions are largely related to industrial activities and vehicular emissions (16). Bloemfontein, being a central hub in the Free State Province, also experiences substantial vehicular emissions due to its role as a transportation nexus. Heavy-duty trucks, buses, and other diesel-powered vehicles that traverse the area contribute notably to the Sulphur dioxide levels in the atmosphere (30). Furthermore, local industries that engage in manufacturing and processing activities, albeit on a smaller scale compared to larger industrial cities, also add to the SO_2 emissions (31). These activities, combined with the transportation sector, make up the key sources of SO_2 in the Mangaung area.

2.2.3. Historical Context of SO_2 Emissions in the Region

Historically, the emission of sulphur dioxide in the Mangaung region has been influenced by the broader industrialisation trends in South Africa. During the apartheid era, industrial development was heavily promoted, leading to increased SO_2 emissions as coal-fired power plants and other industrial facilities were established to meet the growing energy demands (32). The post-apartheid period saw some regulatory improvements, but the legacy of high SO_2 emissions persisted, particularly from older, less efficient industrial facilities and vehicles. Over the years, with the growth of Bloemfontein as a key urban center, the contribution of vehicular emissions to SO_2 levels has also become more prominent (33). Although there have been efforts to monitor and manage air quality, the historical reliance on coal and fossil fuels, coupled with industrial and vehicular growth, has maintained a steady presence of SO_2 in the air, posing ongoing challenges for air quality management in Mangaung (34,35).

2.3. Health Impacts of Sulphur Dioxide Exposure

Sulphur dioxide (SO_2) is a significant air pollutant with considerable health implications, particularly in areas with high levels of industrial and vehicular emissions. Understanding the various health impacts associated with SO_2 exposure is essential for public health assessment and regulatory decision-making (36).

2.3.1. Short-term Health Effects

Short-term exposure to SO_2 primarily affects the respiratory system. When inhaled, SO_2 can irritate the mucous membranes in the nose, throat, and airways, leading to immediate symptoms such as coughing, throat irritation, and wheezing (37). It can also cause chest tightness and shortness of breath, particularly in individuals with asthma or other pre-existing respiratory

conditions (38). High concentrations of SO_2 can exacerbate asthma symptoms, leading to bronchoconstriction and increased use of rescue inhalers (39). These effects can occur within minutes of exposure, and even brief encounters with elevated SO_2 levels can trigger significant respiratory distress (40).

2.3.2. Long-term Health Effects

Long-term exposure to SO_2 is associated with the development and exacerbation of chronic respiratory diseases, such as chronic bronchitis and emphysema (41). Prolonged inhalation of SO_2 can lead to persistent inflammation of the airways, contributing to the progression of chronic obstructive pulmonary disease (COPD) (42). Additionally, long-term exposure has been linked to an increased risk of cardiovascular problems, including hypertension, heart attacks, and strokes. The inflammatory response triggered by SO_2 exposure can contribute to the development of atherosclerosis, thereby increasing the risk of cardiovascular events (43).

2.3.3. Vulnerable Populations

Certain populations are more vulnerable to the health impacts of SO_2 exposure. Children, whose respiratory systems are still developing, are particularly at risk, as they breathe more air per unit of body weight compared to adults, increasing their exposure to airborne pollutants(44). The elderly are also highly susceptible, as they are more likely to have preexisting cardiovascular or respiratory conditions that can be aggravated by SO_2 (45). Individuals with chronic conditions such as asthma, COPD, or cardiovascular diseases are at heightened risk, as their underlying health issues can be worsened by SO_2 exposure, leading to more severe health outcomes.

2.3.4. Mechanisms of SO_2 Toxicity and Pathophysiology

The toxicity of SO_2 arises from its ability to dissolve in the moisture present in the upper respiratory tract, forming sulfurous acid (H_2SO_3) (46). This acid can cause irritation and damage to the epithelial cells lining the respiratory tract, leading to inflammation and bronchoconstriction (38). In asthmatic individuals, SO_2 can directly stimulate the autonomic nervous system, leading to bronchospasm. Over time, repeated exposure to SO_2 can result in chronic inflammation, tissue remodeling, and fibrosis of the airways, contributing to the development of chronic respiratory diseases (47). Additionally, systemic inflammation caused by SO_2 exposure can lead to endothelial dysfunction, a precursor to atherosclerosis and other cardiovascular diseases (19).

2.3.5. Exposure Route of Sulphur Dioxide SO_2

Inhalation represents the primary means individuals are exposed to sulphur dioxide (19, 48). Its odour threshold is five times less than the OSHA Permissible Exposure Limit (PEL) of 5 parts per million (ppm). This means that even at concentrations below the OSHA limit, individuals may still be inhaling SO_2 without being able to detect its presence through smell. Consequently, there is a risk of unintentional exposure to SO_2, potentially leading to adverse health effects, particularly in occupational settings where workers may not realize they are being exposed to harmful levels of this gas. Most exposures stem from air pollution, posing immediate and long-term health risks, particularly for individuals with pre-existing lung conditions (48). Consequently, SO_2 gas fumes can evade the filtration process of the nasal passages, travel to the upper regions of the nasal cavity propelled by airflow, and subsequently disperse throughout the body via the respiratory system, resulting in enduring harm (49).

Humans can contact SO_2 through inhalation, skin contact, and ingestion as indicated in figure 2.2 below (50). Ocular effects resulting from exposure to the gas have also been documented (50). However, the primary route of exposure for humans is through inhalation, as SO_2 exists as a gas under typical conditions. Upon inhalation, the respiratory system may be exposed to various compounds, including SO_2, hydrogen ions (H+), H_2SO_4, or ions such as $SO^2{}_3^-$and $SO^2{}_4^-$ possibly in combination with ammonium ions or metal cations. Complicating matters further, some of these compounds may exist in particulate form or be adsorbed onto particles with varying chemical compositions (51).

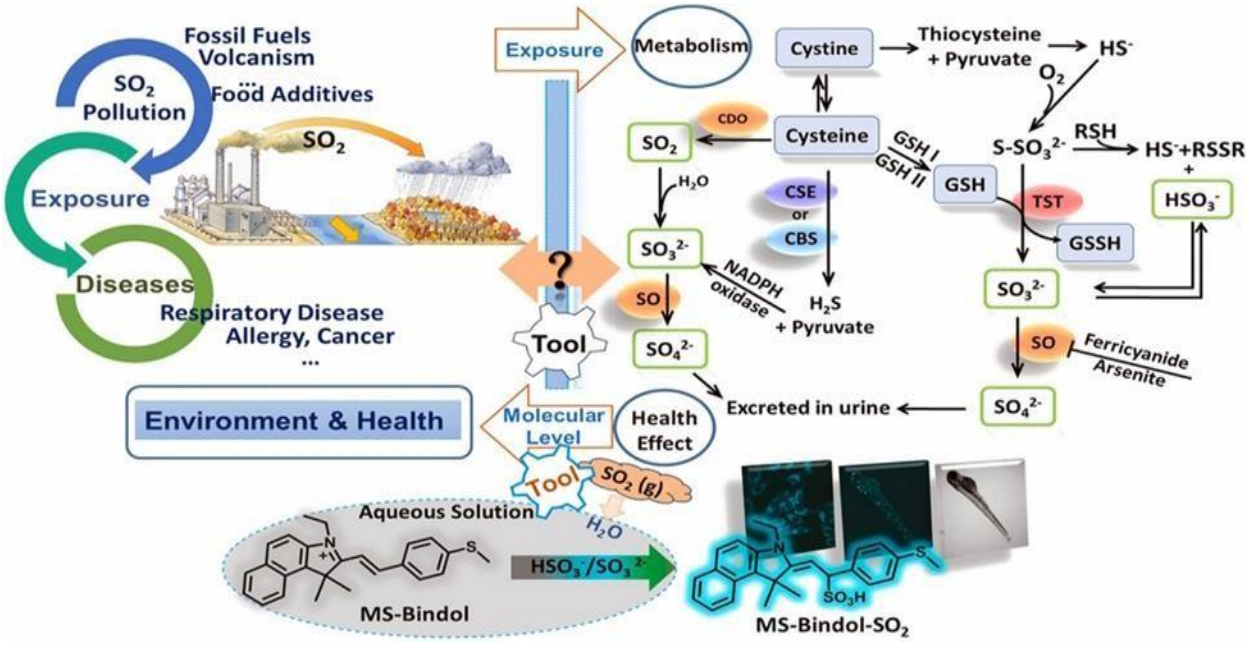

Figure 2.2: Pathways responsible for the generation and processing of SO_2 and its derivatives (52)

2.3.6. Effects of Environmental Conditions on SO_2 Levels

Environmental conditions significantly influence the levels of sulphur dioxide (SO_2) in the atmosphere. Weather patterns, such as wind speed and direction, play a crucial role in dispersing or concentrating SO_2 in specific areas (53). High winds can dilute SO_2 concentrations, while low winds or stagnant air conditions can lead to higher localised concentrations (31, 54). Temperature inversions, where a layer of warm air traps pollutants close to the ground, can increase SO_2 levels near the surface, heightening exposure risks (55). Humidity is another factor, as high humidity levels can enhance the formation of sulfuric acid from SO_2, contributing to acid rain, which impacts both the environment and human health (56).

Geographic features like mountains and valleys also affect SO_2 dispersion, with valleys often trapping air pollutants and leading to higher concentrations, whereas open plains allow for greater dispersion. Sunlight can drive photochemical reactions involving SO_2, resulting in the formation of secondary pollutants such as sulphate aerosols, which have further environmental and health impacts (57). Seasonal variations also play a role; for instance, increased fossil fuel combustion for heating in winter can raise SO_2 emissions, while summer's enhanced photochemical activity can lead to different transformation products of SO_2 (53).

2.4. Air Quality Standards and Guidelines

2.4.1. World Health Organization (WHO) Guidelines for SO_2

The World Health Organization (WHO) provides global guidelines for sulfur dioxide (SO_2) concentrations to protect public health. According to the WHO, the 24-hour mean concentration of SO_2 should not exceed 20 µg/m³, and the 10-minute mean concentration should not exceed 500 µg/m³. These guidelines are designed to minimize the risk of acute and chronic health effects associated with SO_2 exposure (9).

2.4.2. South African National Ambient Air Quality Standards (NAAQS)

South Africa's National Ambient Air Quality Standards (NAAQS) are set to protect human health and the environment from harmful levels of air pollution. For SO_2, the NAAQS stipulates a 24-hour average limit of 125 µg/m³, not to be exceeded more than four times per year, and a

10-minute average limit of 500 µg/m³. These standards are aligned with international practices but take into account local environmental and economic factors (19,58).

2.4.3. Comparison with Other International Standards (HEA, EU)

When comparing South Africa's NAAQS with other international standards, such as those set by the United States Environmental Protection Agency (USEPA) and the European Union (EU), there are notable differences. The USEPA sets a 1-hour standard for SO_2 at 75 ppb (approximately 196 µg/m³), while the EU sets a 1-hour limit of 350 µg/m³ and a 24-hour limit of 125 µg/m³. Both USEPA and EU standards are comparable but slightly differ in their approach to averaging periods and exceedance allowances (59,60).

2.4.4. Historical Changes in Air Quality Standards

Over time, air quality standards for SO_2 have evolved to reflect new scientific evidence on the health impacts of air pollution. Historically, standards were less stringent, with higher permissible limits. However, as more research highlighted the health risks associated with even low levels of SO_2, organizations like WHO, USEPA, and national governments have progressively tightened their standards. For example, WHO's current 24-hour guideline of 20 µg/m³ is much stricter than previous limits, reflecting the growing understanding of SO_2's adverse effects on respiratory health (61,62).

2.5. Previous Studies on SO_2 and Health Risk Assessments

2.5.1. Global Studies on the Health Impacts of SO_2

Sulfur dioxide (SO_2) is a well-documented air pollutant with significant health implications. Globally, numerous studies have linked SO_2 exposure to various adverse health effects. For instance, the World Health Organization (WHO) has highlighted that short-term exposure to high levels of SO_2 can lead to respiratory symptoms and exacerbate asthma, while long-term exposure can contribute to cardiovascular diseases and chronic respiratory conditions (36).

A meta-analysis by Zhou et al. (2022) reviewed the effects of SO_2 on respiratory health and found consistent associations between SO2 exposure and increased hospital admissions for respiratory conditions across multiple countries (63,64). Additionally, a study by P Orellano, J Reynoso and N Quaranta et al. (2021) demonstrated that even low-to-moderate levels of SO_2 exposure were associated with an increased risk of mortality from respiratory and cardiovascular diseases (64).

2.5.2. Regional Studies within South Africa

In South Africa, research on SO_2's health impacts has been focused on both urban and industrial areas. For example, a study by DA Millar et al. (2017) investigated air quality and health outcomes in South Africa among adolescents living in the highveld and found significant associations between SO_2 levels and increased respiratory problems among residents (65). Similarly, research by M Matooane et al. (2003) in Durban highlighted that elevated SO_2 concentrations were linked to higher rates of respiratory hospital admissions (66). A more recent study by A Matyeni et al. (2021) focused on the impact of SO_2 emissions from industrial sources in the Gauteng province and reported that high SO_2 levels were strongly associated with chronic respiratory diseases and reduced lung function in exposed populations

(67).

2.5.3. Case Studies of Similar Urban Areas

Comparative case studies provide valuable insights into how SO_2 affects health in different urban settings. In Cape Town, a study by A Ojo et al. (2022) examined the effects of SO_2 emissions from vehicular traffic and found a significant correlation between high SO_2 levels and increased rates of respiratory ailments among children and the elderly (68). Another study in Lagos, Nigeria, by Kazeem et al. (2020), revealed that high SO_2 concentrations from industrial activities were linked to elevated incidences of asthma and bronchitis (69).

A research project conducted on behalf of Eskom by Scorgie et al. (2006) for the Mpumalanga and Gauteng province investigated the health impacts of SO_2 emissions in a predominantly residential area and found that exposure was associated with increased emergency room visits for respiratory issues (70).

2.5.4. Meta-Analyses and Systematic Reviews

Meta-analyses and systematic reviews provide comprehensive assessments of the health risks associated with SO_2 exposure. A systematic review and meta-analysis by P Orellano, J Reynoso and N Quaranta (2021) analysed data from various studies and concluded that SO_2 exposure was consistently linked to respiratory and cardiovascular health issues, with effects observed even at relatively low concentrations (71). Another meta-analysis by H Tran et al. (2019) confirmed that SO_2 exposure is associated with increased mortality from respiratory diseases, reinforcing the need for stringent air quality controls (72). The body of research highlights a robust association between SO_2 exposure and adverse health outcomes, including respiratory

and cardiovascular issues. Both global and regional studies, as well as case studies from similar urban areas, support these findings, with meta-analyses providing further evidence of the health risks posed by SO_2.

2.6. Air Quality Monitoring and Data Analysis

2.6.1. Methods for Measuring and Monitoring SO_2 Levels

Monitoring sulfur dioxide (SO_2) levels in the atmosphere is critical for assessing air quality and its impact on public health. The primary methods for measuring SO_2 include both manual and automated techniques. Manual methods, such as the Pararosaniline method, involve collecting air samples and analysing them in a laboratory setting. Automated techniques, such as UV fluorescence, are more commonly used in modern air quality monitoring stations. UV fluorescence is a widely accepted method that detects SO_2 by measuring the fluorescence emitted when SO_2 molecules absorb ultraviolet light. This method provides continuous realtime data, making it highly effective for monitoring fluctuations in SO_2 levels (59,73).

2.6.2. Tools and Technologies Used in Air Quality Monitoring

The tools and technologies used in air quality monitoring have advanced significantly over the years. At the Pelonomi monitoring station in Bloemfontein, state-of-the-art instruments such as gas analysers and meteorological sensors are employed. These instruments are capable of detecting and quantifying SO_2 concentrations with high precision. The station uses UV fluorescence analysers for SO_2 measurement, alongside meteorological sensors that record temperature, wind speed, and wind direction. These additional data points are essential for understanding the dispersion and transport of SO_2 in the atmosphere (74,75).

2.6.3. Data Sources for the Current Study

For the current study, SO_2 data were obtained from the Pelonomi monitoring station in Bloemfontein, which is part of the South African Air Quality Information System (SAAQIS). SAAQIS provides a comprehensive platform for accessing real-time and historical air quality data across South Africa (76). The data from the Pelonomi station include hourly measurements of SO_2 concentrations, along with meteorological data such as wind speed, wind direction, and temperature. These data are crucial for assessing the temporal variability of SO_2 levels and their potential health impacts in the Mangaung area (16).

2.6.4. Challenges in Air Quality Monitoring and Data Reliability

Air quality monitoring has significantly advanced, yet challenges persist in ensuring the accuracy and reliability of the data collected. The maintenance and calibration of monitoring equipment, such as UV fluorescence analysers, remain critical to obtaining accurate readings. Regular calibration is necessary to mitigate errors caused by sensor drift over time (77). Additionally, environmental factors like temperature fluctuations and humidity can affect the performance of sensors, leading to potential inaccuracies in the data (78). Data gaps due to equipment malfunctions, power outages, or maintenance downtime also pose significant challenges, as they can result in incomplete datasets and potentially skew the analysis (79). To draw reliable conclusions from air quality data, it is essential to carefully consider these potential sources of error and implement robust quality control measures.

2.7. Overview of Health Risk Assessment Methodologies

Health risk assessment (HRA) is a critical process used to evaluate the potential adverse health effects resulting from exposure to environmental hazards such as air pollutants. The methodologies used in HRA typically follow a structured approach that involves several key steps: hazard identification, dose-response assessment, exposure assessment, and risk characterization (80).

- Hazard Identification: This step involves identifying the pollutants or chemicals that may cause adverse health effects. In the case of Sulphur dioxide (SO_2), the health impacts, including respiratory and cardiovascular issues, are well-documented (81).
- Dose-Response Assessment: This step quantifies the relationship between the level of exposure to the pollutant and the incidence of adverse health effects. The dose-response relationship for SO_2 exposure is critical for understanding how varying levels of the pollutant impact health (81).
- Exposure Assessment: In this step, the extent of human exposure to SO_2 is evaluated. This includes determining the concentration of SO_2 in the air, the duration of exposure, and the characteristics of the exposed population (e.g., age, health status) (81).
- Risk Characterization: This final step integrates information from the previous steps to estimate the likelihood of adverse health effects in the exposed population. This process helps in determining the public health significance of the pollutant exposure (81).

2.7.1. Specific Methods Used in Previous Studies

Various methodologies have been employed in previous studies to assess health risks associated with SO_2 exposure. Epidemiological studies are a common approach, where researchers examine the relationship between SO_2 levels and health outcomes in populations. For example, time-series analyses have been used to assess the short-term effects of SO_2 on hospital admissions for respiratory conditions(82). Toxicological studies are also utilized to understand the mechanisms by which SO_2 causes harm at the cellular and molecular level (83). Another method involves the use of dispersion models to predict the concentration of SO_2 in the air and its potential health impacts. These models help simulate how SO_2 spreads in the atmosphere and affects different geographic areas (84).

2.7.2. Justification for Chosen Methodology in the Current Study

The choice of statistical methods and models in this study is driven by the specific objectives of understanding the seasonal variations in sulphur dioxide (SO_2) emissions, the temporal relationship between SO_2 levels and health outcomes, and the risk factors associated with exposure. The following methodologies were selected for their robustness, relevance, and ability to address the research questions effectively.

2.7.3. Statistical Methods and Models Used for Risk Assessment

In this study, several statistical methods and models are employed to analyse the data and assess health risks:

- Analysis of Variance (ANOVA): The ANOVA is used to determine if there are significant differences in SO_2 emissions across different seasons (summer, autumn,

- concentrations in $\mu g/m^3$) and the independent variable (season). Descriptive statistics (mean, median, standard deviation) are calculated for each season, and boxplots are created to visualize the distribution of emissions (85). Normality is tested using the Shapiro-Wilk test, and homogeneity of variances is checked using Levene's test (86). If the ANOVA indicates significant differences, a post hoc test like the Bonferroni test is performed to identify specific seasonal differences (87).

- Time-Series Analysis: The use of time-series analysis is justified by the need to explore the dynamic relationship between SO_2 levels and health outcomes over time. This method is essential for identifying trends, patterns, and potential lag effects in the data, which are crucial for understanding the impact of SO_2 exposure on public health. Time-series analysis is

particularly valuable in air quality studies as it accounts for confounding variables such as temperature and humidity, which can influence both pollutant levels and health outcomes. By adjusting for these factors, the analysis provides a more accurate and nuanced understanding of the relationship between SO_2 exposure and health risks (88).

2.8. Urban Resilience and Public Health

2.8.1. Concept of Urban Resilience in the Context of Air Pollution

Urban resilience refers to the capacity of cities to absorb, recover from, and adapt to various shocks and stresses, including those related to environmental hazards such as air pollution. In the context of air pollution, urban resilience involves the ability of a city's infrastructure, governance, and communities to mitigate the impacts of air pollution on public health, maintain air quality standards, and adapt to changing environmental conditions. This concept is increasingly important as cities face growing challenges from climate change, population growth, and industrialization, all of which can exacerbate air pollution levels (90).

Urban resilience to air pollution is multidimensional, encompassing structural, social, and institutional aspects. Structurally, it involves the design and implementation of green infrastructure, such as urban green spaces, that can absorb pollutants and improve air quality. Socially, it includes the capacity of communities to respond to air pollution through awareness, preparedness, and adaptation strategies. Institutionally, it requires the development and enforcement of policies and regulations that address the sources of air pollution and protect vulnerable populations (91).

2.8.2. Role of Public Health Policies in Mitigating Air Pollution Risks

Public health policies play a critical role in mitigating the risks associated with air pollution. These policies are designed to protect public health by setting air quality standards, monitoring pollution levels, and implementing interventions to reduce emissions from key sources such as transportation, industry, and residential heating. The development and enforcement of these policies are essential for reducing exposure to harmful pollutants like sulfur dioxide (SO_2), particulate matter (PM), and nitrogen dioxide (NO_2), which have been linked to respiratory and cardiovascular diseases (9).

Effective public health policies also involve collaboration between different levels of government, from local municipalities to national agencies, as well as partnerships with nongovernmental organizations and the private sector. For example, in many cities, low-

emission zones have been established to restrict the entry of high-polluting vehicles, thereby reducing the overall burden of air pollution. Additionally, public health campaigns that promote cleaner energy sources, such as solar and wind, and encourage the use of public transportation can significantly reduce air pollution levels and improve urban resilience (92).

2.8.3. Community Awareness and Engagement Strategies

Community awareness and engagement are vital components of building urban resilience to air pollution. Educating the public about the sources and health impacts of air pollution, as well as ways to reduce personal exposure, is crucial for fostering a culture of environmental responsibility. Public awareness campaigns can be conducted through various channels, including social media, community workshops, and school programs, to reach diverse audiences. Engaging communities in air quality monitoring and decision-making processes can also enhance urban resilience. Citizen science initiatives, where residents participate in monitoring air pollution levels using portable sensors, empower communities to advocate for cleaner air and hold policymakers accountable. Furthermore, involving community members in the development and implementation of local air quality action plans ensures that interventions are tailored to the specific needs and concerns of the population (93).

2.8.4. Case Studies of Urban Resilience in Other Cities

Several cities around the world have implemented successful strategies to enhance urban resilience to air pollution, providing valuable lessons for other urban areas.

2.8.4.1. London, United Kingdom:

London has been at the forefront of efforts to reduce air pollution through a combination of public health policies, community engagement, and technological innovation. The introduction of the Ultra Low Emission Zone (ULEZ) in 2019 significantly reduced emissions from vehicles, particularly diesel engines, which are a major source of nitrogen dioxide. London's air quality strategy also includes measures to increase green spaces, promote cycling and walking, and reduce emissions from residential heating (94).

2.8.4.2. Los Angeles, United States:

Los Angeles has historically struggled with air pollution due to its high levels of vehicle traffic and industrial activity. However, the city has made significant progress in improving air quality through stringent regulations on vehicle emissions, the promotion of electric vehicles, and the

expansion of public transportation networks. Community-based initiatives, such as the Clean Up Green Up program, have also played a key role in addressing pollution in the most affected neighborhoods, demonstrating the importance of community engagement in building urban resilience (95).

2.8.4.3. Beijing, China:

Beijing has faced severe air pollution challenges due to rapid industrialization and urbanization. In response, the city has implemented a comprehensive air pollution control plan that includes strict limits on coal use, the closure of polluting factories, and the promotion of clean energy. Public health campaigns have raised awareness about the health risks associated with air pollution and encouraged behavioral changes, such as wearing masks on high-pollution days and using air purifiers indoors (96).

2.9. Policy and Regulatory Framework for Air Quality in South Africa

2.9.1. Existing Policies and Regulations on Air Quality in South Africa

South Africa has a well-defined policy and regulatory framework aimed at controlling air pollution and protecting public health. The key legislation governing air quality in the country is the National Environmental Management: Air Quality Act (NEMAQA) (Act No. 39 of 2004). National Environmental Management: Air Quality Act (NEMAQA) replaced the outdated Atmospheric Pollution Prevention Act (APPA) of 1965, shifting the focus from merely controlling emissions to managing air quality through an integrated approach. The Act empowers the government to set national ambient air quality standards (NAAQS) for various pollutants, including sulfur dioxide (SO_2), and mandates the creation of air quality management plans at the national, provincial, and municipal levels (74).

Under NEMAQA, the South African government has established NAAQS for SO_2, which are designed to protect human health and the environment. These standards are aligned with the World Health Organization (WHO) guidelines but have been adapted to reflect the local context, including industrial activities and prevailing environmental conditions (9). The NAAQS specify permissible limits for SO_2 concentrations over different time frames, such as hourly, daily, and annually, to mitigate both acute and chronic exposure risks.

2.9.2. Role of Local and National Governments

The implementation of air quality regulations in South Africa involves a multi-tiered governance structure. At the national level, the Department of Forestry, Fisheries and the Environment (DFFE) is responsible for setting air quality standards, developing policies, and overseeing compliance. The DFFE also maintains the South African Air Quality Information System (SAAQIS), which monitors air quality across the country and provides real-time data to the public (97).

Provincial governments play a crucial role in coordinating air quality management efforts within their jurisdictions, ensuring that local municipalities comply with national standards and regulations. Local municipalities, including those in Mangaung, are tasked with developing and implementing air quality management plans, conducting air quality monitoring, and enforcing local bylaws related to air pollution (16). Municipalities also have the authority to issue licenses for activities that may contribute to air pollution, such as industrial operations, under the framework provided by NEMAQA.

2.9.3. Gaps and Challenges in the Current Regulatory Framework

Despite the robust regulatory framework, there are significant challenges and gaps in air quality management in South Africa. One of the primary challenges is the uneven enforcement of air quality regulations across different regions. Resource constraints, including limited technical capacity and financial resources at the municipal level, often hinder effective monitoring and enforcement (74). This is particularly problematic in industrial areas where emissions may exceed permissible limits, posing a risk to public health.

Another significant gap is the lack of comprehensive data on air pollution sources and their health impacts, particularly in smaller municipalities and rural areas. While SAAQIS provides valuable data, the network of monitoring stations is not evenly distributed, leading to potential underreporting of air quality issues in less monitored areas (98). Furthermore, there is a need for greater integration of air quality management with other environmental and public health policies, to ensure a more holistic approach to addressing air pollution.

2.9.4. International Policies and Their Implications for Local Governance

South Africa's air quality policies are influenced by international agreements and guidelines, particularly those set by the World Health Organization (WHO) and the United Nations Framework Convention on Climate Change (UNFCCC). The WHO's air quality guidelines serve as a benchmark for setting national standards, while the UNFCCC's Paris Agreement has

implications for national policies aimed at reducing greenhouse gas emissions, which are often co-pollutants with air pollutants like SO_2 (99).

International policies also encourage the adoption of best practices in air quality management and promote the use of cleaner technologies and renewable energy sources. For local governance, this means a need to align local policies with international commitments, which may require updating regulations, enhancing monitoring capabilities, and investing in sustainable infrastructure (30). The challenge lies in balancing these international obligations with local socio-economic realities, particularly in a developing country context where industrial activities are crucial for economic growth.

2.10. Socioeconomic and Environmental Factors

2.10.1. Socioeconomic Factors Affecting Exposure and Vulnerability to SO_2

Socioeconomic factors play a significant role in determining both exposure to and vulnerability from sulfur dioxide (SO_2) emissions. Communities with lower socioeconomic status often face greater exposure to air pollutants, including SO_2, due to several intertwined factors such as inadequate housing, poor urban planning, and proximity to industrial areas (100). These populations are often less able to afford cleaner, well-ventilated housing, and may live closer to sources of pollution like factories, power plants, and major highways (16). Therefore, Mangaung being an area with higher poverty rates, it is more likely to experience elevated SO_2 levels due to the proximity to industrial zones and the use of coal, wood, or paraffin or other solid fuels for heating and cooking (101)

Furthermore, these communities often have limited access to healthcare and other resources that could mitigate the health impacts of air pollution. For instance, children and the elderly in lower-income households are more vulnerable to respiratory and cardiovascular diseases linked to SO_2 exposure. Education levels also influence how well individuals can protect themselves from air pollution, as less-educated populations may have limited knowledge of the risks associated with SO_2 and how to reduce exposure (101).

2.10.2. Environmental Justice Issues Related to Air Pollution

Environmental justice concerns are closely related to the unequal distribution of environmental hazards and the disproportionate impact of air pollution on marginalized communities. In South Africa, historical factors such as apartheid-era spatial planning have led to the concentration of industrial activities near predominantly black, low-income neighborhoods, exacerbating

exposure to pollutants like SO_2 (102). These communities often lack the political power and resources to advocate for stricter enforcement of air quality regulations or the relocation of polluting industries.

Environmental justice also involves ensuring that all communities, regardless of socioeconomic status, have equal access to clean air and a healthy environment. However, in many cases, the benefits of pollution control measures are not equally distributed. Wealthier neighborhoods may see quicker improvements in air quality due to more effective advocacy and enforcement, while poorer communities continue to suffer from high pollution levels (103).

2.10.3. Impact of Urban Planning and Industrial Activities on SO_2 Levels

Urban planning and industrial activities significantly impact SO_2 levels in urban areas like Mangaung. Poor urban planning can lead to the development of residential areas in close proximity to industrial zones, resulting in higher exposure to SO_2 and other pollutants. The placement of industries, transportation routes, and waste management facilities without adequate consideration of environmental impacts contributes to localized increases in SO_2 levels (102).

Industrial activities, particularly those involving the burning of fossil fuels, are major sources of SO_2 emissions. In Mangaung, industries such as metal processing, chemical manufacturing, and power generation are significant contributors to SO_2 levels. The type and scale of industrial activities, along with the technologies used, determine the amount of SO_2 released into the atmosphere. For example, older plants that use outdated technologies may emit more SO_2 compared to newer facilities that employ cleaner technologies (74).

Urban sprawl and the expansion of industrial activities without adequate environmental controls further exacerbate air pollution issues. Effective urban planning, including the implementation of green buffers, zoning laws, and stricter emission controls, is essential to mitigating the impact of industrial activities on air quality (9).

2.11. Key Findings from the Reviewed Literature

2.11.1. Health Impacts of SO_2 Exposure

Numerous studies have established that exposure to sulfur dioxide (SO_2) is associated with adverse health effects, particularly respiratory and cardiovascular conditions. SO_2 exposure is known to exacerbate asthma, bronchitis, and other respiratory ailments, while also being linked

to cardiovascular problems, such as increased risk of heart attacks and strokes. The toxicological effects of SO_2, especially at higher concentrations, make it a significant pollutant of concern in urban environments (9,104).

- Vulnerable Populations

Research has identified children, the elderly, and individuals with pre-existing health conditions as particularly vulnerable to SO_2 exposure. For instance, children exposed to high levels of SO_2 are more likely to develop respiratory issues, which can have long-term consequences on their health. Similarly, elderly individuals and those with conditions like chronic obstructive pulmonary disease (COPD) are at greater risk of adverse effects from SO_2 (105).

- Geographical and Temporal Variations

SO_2 concentrations often vary geographically and temporally, with urban and industrial areas typically showing higher levels. Seasonal variations also play a role, with certain periods (e.g., winter) seeing elevated SO_2 levels due to increased heating and industrial activities. These variations are crucial for understanding exposure patterns and tailoring public health interventions accordingly (106).

- Methodological Approaches

The literature highlights the use of various methodologies to assess health risks from SO_2 exposure, including epidemiological studies, time-series analyses, and air quality modeling. These methodologies are employed to quantify the relationship between SO_2 exposure and health outcomes, and to predict future health risks based on current exposure levels (106).

2.11.2. Identified Gaps and Areas for Further Research

- Longitudinal Health Studies

While many studies have explored the short-term effects of SO_2 exposure, there is a scarcity of longitudinal studies that track the long-term health impacts of chronic exposure. Longitudinal research is essential for understanding the cumulative health effects and for developing interventions aimed at reducing long-term exposure risks (108).

- Socioeconomic and Environmental Justice Considerations

There is limited research on how socioeconomic status, race, and environmental justice issues intersect with SO_2 exposure. Understanding these dimensions is critical for addressing

disparities in health outcomes and for ensuring that public health interventions are equitable and effective (106).

2.11.3. Relevance of the Current Study to Fill These Gaps

- Regional Focus

The current study's focus on Mangaung, Bloemfontein, addresses the gap in localized research. By providing detailed insights into SO_2 exposure and its health risks in this specific urban center, the study contributes valuable data that can inform local public health policies and interventions (109).

- Longitudinal Approach

By including seasonal and year-long monitoring of SO_2 levels, the study captures temporal variations in exposure, which is essential for understanding the long-term health impacts. This approach helps to address the need for more longitudinal data on chronic exposure and its health effects (107).

- Integrated Assessment

The study's methodology includes an integrated risk assessment that considers the effects of multiple pollutants in addition to SO_2. This comprehensive approach provides a more accurate estimate of health risks and helps in the development of targeted interventions to mitigate these risks.

- Socioeconomic Analysis

By exploring the socioeconomic dimensions of SO_2 exposure, the study contributes to the understanding of how factors like income, access to healthcare, and environmental justice issues affect vulnerability and health outcomes. This analysis is crucial for developing interventions that address disparities in health risks, making the study highly relevant for public health policy (113).

2.12. Conclusion

The health risk assessment of Sulphur dioxide (SO_2) emissions in Mangaung, Bloemfontein, South Africa, is a critical undertaking given the considerable health risks associated with this pollutant. SO_2 is a prominent air contaminant with well-documented adverse effects on respiratory and cardiovascular health, especially in densely populated urban areas. In

Mangaung, where industrial activities and traffic contribute to elevated SO_2 levels, understanding these health impacts is essential for implementing effective public health strategies.

This study seeks to provide a thorough evaluation of SO_2 exposure and its health effects specific to Mangaung. By analysing local SO_2 emission data and correlating it with health outcomes, the research will contribute significantly to the field of environmental health. The findings are expected to offer evidence-based insights that will assist local and national policymakers in formulating and refining air quality management strategies. Additionally, this study will help in identifying vulnerable populations and developing targeted health interventions to mitigate the adverse effects of SO_2.

Furthermore, the research will enhance our understanding of the broader implications of SO_2 exposure in similar urban contexts, offering a valuable reference for other cities with comparable industrial and traffic-related pollution challenges. The insights gained will be instrumental in advancing urban resilience by integrating environmental health considerations into urban planning and development.

Looking ahead, future research should focus on longitudinal studies to track the long-term health impacts of SO_2 exposure and evaluate the effectiveness of implemented mitigation measures. Additionally, incorporating studies that examine the interactions between SO_2 and other pollutants will provide a more holistic view of air quality impacts. Policy development should leverage findings from such comprehensive research to establish and enforce robust air quality standards and health protection regulations. Collaborative efforts involving researchers, policymakers, and community stakeholders will be crucial in driving forward effective air quality management and enhancing public health outcomes in Mangaung and other similar urban environments

CHAPTER 3: RESEARCH METHODOLOGY

3.1. Introduction

This research investigated the health risks associated with SO_2 emissions in Mangaung, Bloemfontein, South Africa, for the year 2023. The study adopted a descriptive and quantitative approach to assess the concentrations of SO_2 and their potential health impacts. By utilizing secondary data from the South African Air Quality Information System (SAAQIS) and focusing on the Pelonomi Hospital monitoring station, the research intended to provide a detailed analysis of SO_2 levels across different seasons and evaluate the associated health risks.

Mangaung, with its semi-arid climate and diverse topographical features, offers a unique context for this study. The research area spans approximately 6,263 square kilometers and is characterized by flat terrain with rolling hills, varying elevations, and a climate that experiences distinct seasonal changes (16). The methodology included analysing hourly averaged SO_2 data, assessing seasonal variations, and conducting health risk assessments based on an established exposure scenario. This comprehensive approach was intended to enhance understanding of SO_2's impact on public health and inform relevant policy and health strategies in similar urban environments.

3.2. Study Design

The study employed a descriptive and quantitative research design to comprehensively assess the health risks associated with sulfur dioxide (SO_2) emissions in Mangaung, Bloemfontein. The descriptive component of the research aimed to provide a detailed characterization of SO_2 emission levels and their temporal variations throughout the year 2023. This involved systematically documenting and describing SO_2 concentration patterns, which are essential for understanding the environmental exposure to this pollutant within the study area. By utilizing a range of secondary data source from the South African Air Quality Information System (SAAQIS), the descriptive analysis will illustrate how SO_2 levels fluctuate over different seasons and under various meteorological conditions.

The quantitative aspect of the study was designed to evaluate the potential health risks associated with these SO_2 emissions. This involved applying statistical methods to analyse the relationship between SO_2 concentrations and health outcomes. Specifically, the research employed scenario-based exposure assessments to estimate the potential health impacts on the

local population. These assessments considered chronic exposure scenario to quantify the risks for various age groups, including children (0-5 years) and adults (60+ years).

The inclusion of toddlers (0-5 years) and the elderly (60+ years) in the health risk assessment for exposure to harmful air pollutants like SO_2 was crucial due to their heightened vulnerability. They are generally considered vulnerable groups, as toddlers have higher breathing rates and tend to spend time outdoors, where they may come into contact with harmful stressors. The elderly often have underlying health conditions and spend more time indoors. Both groups are more susceptible to respiratory and cardiovascular impacts from SO_2, which can exacerbate existing health issues and lead to severe health outcomes, including hospitalizations and premature mortality. Considering these vulnerable populations ensured that health standards and interventions are inclusive and protective across all age groups, reflecting ethical responsibility and public health equity in environmental policies (15).

The use of quantitative methods facilitated a rigorous assessment of health risks, allowing for precise measurements and comparisons of the potential adverse effects of SO_2 exposure in Mangaung. This comprehensive approach was aimed to ensure that the study not only describe the emission patterns but also provides valuable insights into their implications for public health.

3.3. Study Area

3.3.1. Location

Mangaung, a metropolitan municipality situated in Bloemfontein, the capital city of the Free State Province in South Africa, spans approximately 6,263 square kilometers. The municipality is positioned at approximately 29.0858° S latitude and 26.1596° E longitude (16).

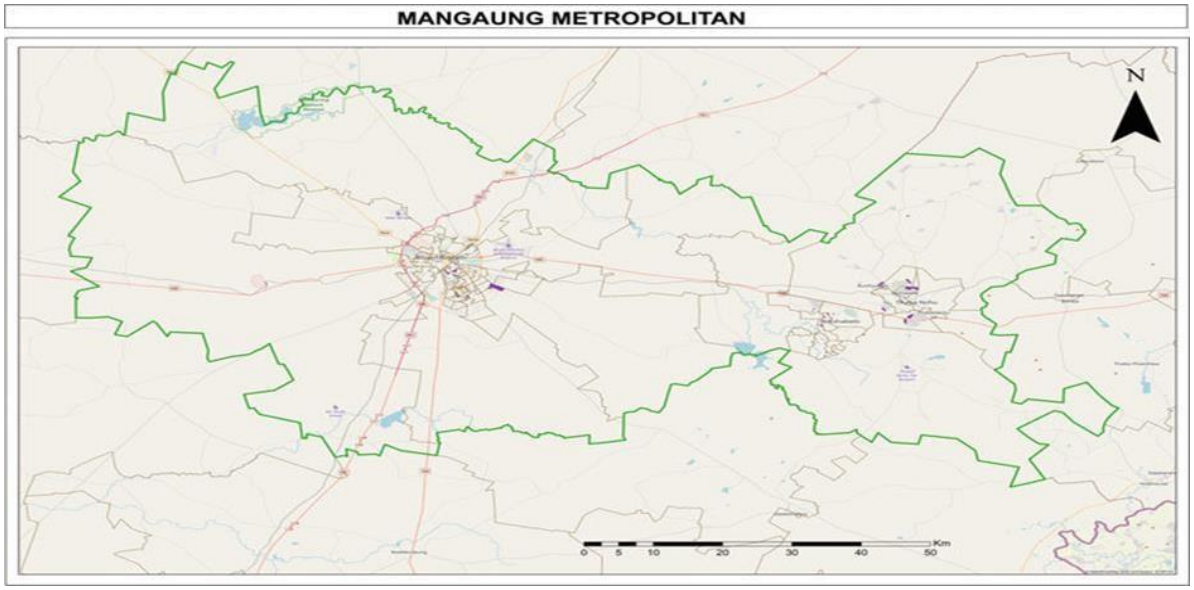

Figure 3.1: Map of Mangaung Metropolitan Municipality, South Africa (16)

3.3.2. Topography

The terrain of Mangaung is characterized by a combination of flat areas and gently rolling hills. Elevations within the municipality range from about 1,300 meters (4,265 feet) to 1,400 meters (4,593 feet) above sea level. The landscape's variety supports diverse land uses, including residential, industrial, commercial, and institutional areas (16).

3.3.3. Climate: Mangaung experiences a semi-arid climate with distinct seasonal variations (16):

- Summer (December to February): The weather is hot and moderately humid, with average daytime temperatures ranging between 25°C and 35°C (77°F to 95°F). Heatwaves can push temperatures even higher.
- Autumn (March to May): Temperatures gradually decrease, averaging between 20°C and 30°C (68°F to 86°F).
- Winter (June to August): Conditions are cool and dry, with daytime temperatures between 5°C and 20°C (41°F to 68°F). Nighttime temperatures can fall below freezing, particularly in July.
- Spring (September to November): A warming trend occurs, with average daytime temperatures ranging from 15°C to 30°C (59°F to 86°F).

3.3.4. Rainfall

Mangaung receives annual rainfall of approximately 500 to 600 mm (20 to 24 inches), with most precipitation occurring between October and March in the form of afternoon thunderstorms. The dry season from April to September experiences very little rainfall, contributing to dry conditions (16).

3.3.5. Wind Patterns

The wind patterns in Mangaung are influenced by its semi-arid climate and regional topography. Prevailing winds generally blow from the northwest to the southeast, with average speeds ranging between 10 to 20 km/h (6 to 12 mph). Wind speeds can increase during thunderstorms or frontal systems. These patterns affect the dispersion of air pollutants, with winds helping to carry pollutants away from the city center towards the southeast (16). Temperature inversions during winter can trap pollutants close to the ground, leading to higher concentrations of SO_2 and other pollutants, while summer thunderstorms may help to clear the air by washing out pollutants (17).

3.4. Data Collection and Quantification of Sulphur Dioxide Emissions (Objective 1)

For the purpose of this study, the data collection and quantification of sulfur dioxide (SO_2) emissions are centered on secondary data sourced from the South African Air Quality Information System (SAAQIS). This data repository provides comprehensive air quality information that is crucial for assessing the levels of SO_2 and understanding their implications for public health.

3.4.1. Source

The primary source of data for this research is the South African Air Quality Information System (SAAQIS), which offers a robust database of air quality metrics across various locations in South Africa. SAAQIS aggregates data from multiple monitoring stations, ensuring a wide coverage of air quality conditions.

3.4.2. Monitoring Station

Data was specifically obtained from the Pelonomi Hospital monitoring station located in Bloemfontein. This station is strategically positioned to provide representative air quality measurements for the Mangaung metropolitan area. It records various pollutants, including SO_2, and is equipped to capture meteorological parameters such as temperature and wind speed, which are essential for a comprehensive analysis of air quality.

3.4.3. Data Period

The data spans from January 1, 2023, to December 31, 2023. This one-year period provided a comprehensive view of SO_2 emissions throughout different seasons, allowing for an in-depth analysis of temporal variations and trends.

3.4.4. Calculation Method

To quantify SO_2 emissions, the study utilized average daily concentrations derived from diurnal averages. This method involves aggregating the hourly SO_2 measurements recorded by the monitoring station to calculate daily averages. These daily averages are then used to analyse trends, seasonal variations, and overall patterns in SO_2 concentrations. This approach ensures that the data reflects typical daily exposure levels and facilitates a detailed assessment of air quality throughout the year.

3.5. Seasonal Variation of Sulphur Dioxide (Objective 2)

To assess the seasonal variation of SO_2 emissions, the study focuses on analysing hourly averaged SO_2 data collected throughout the year 2023. This approach enabled a detailed examination of how SO_2 concentrations fluctuate across different seasons and under varying climatic conditions.

3.5.1. Data Retrieval

The analysis utilizes hourly averaged SO_2 data obtained from the Pelonomi Hospital monitoring station. This granular data provided insight into the diurnal patterns of SO_2 concentrations, which are crucial for understanding seasonal variations. By focusing on hourly data, the study captures the temporal dynamics of SO_2 levels more precisely, allowing for a thorough assessment of how these levels change throughout the year.

3.5.2. Seasons:

- Summer: Comprising December, January, and February, summer is characterized by hot and moderately humid conditions. The analysis examined SO_2 levels during this period to identify any potential increase in concentrations due to higher temperatures and increased atmospheric activity.
- Autumn: Covering March, April, and May, autumn is marked by cooling temperatures. The study evaluated how SO_2 concentrations adjust during this transitional period as temperatures decrease and weather patterns change.

- Winter: Including June, July, and August, winter in Mangaung is cold and dry. The analysis focused on this season to assess the impact of lower temperatures and reduced rainfall on SO_2 concentrations. Winter conditions, such as temperature inversions, may lead to higher pollutant levels near the ground.
- Spring: Encompassing September, October, and November, spring experiences warming temperatures. This period was analysed to determine how increasing temperatures and shifting weather patterns influence SO_2 levels.

3.5.3. Analysis of Data Retrieved

To determine seasonal variations, the study constructed seasonal datasets by grouping hourly SO_2 data according to the four defined seasons. This grouping allowed for the calculation of seasonal averages, which were used to analyse trends and variations in SO_2 concentrations. The seasonal averages provided a clear picture of how SO_2 levels differ across seasons and helped identify any significant patterns or anomalies. This analysis was crucial for understanding the seasonal dynamics of SO_2 emissions and their potential impact on air quality and public health throughout the year.

3.6. Health Risk Assessment (Objective 3)

Hazard identification entails identifying the stressor of interest, SO_2, and its potential adverse effects on human health and the environment. Exposure to SO_2 can irritate the respiratory system, causing symptoms such as coughing, shortness of breath, and chest tightness, particularly in individuals with pre-existing respiratory conditions (19). Prolonged exposure to high levels of SO_2 may lead to more severe respiratory issues and exacerbate cardiovascular diseases. Additionally, SO_2 emissions contribute to air pollution, forming acid rain, which can harm ecosystems, damage infrastructure, and affect water quality (3). The hazard identification for SO_2 emissions in Mangaung aimed to understand the risks associated with its release into the environment and implement measures to mitigate exposure and protect public health and environmental integrity.

The health risk assessment for sulfur dioxide (SO_2) emissions in Mangaung aimed to identify and evaluate the potential health impacts associated with exposure to this pollutant. This assessment was structured around several key components: hazard identification, dose-response assessment, and exposure assessment.

3.6.1. Hazard Identification

- Stressor: The primary stressor under investigation is sulfur dioxide (SO_2), a common air pollutant known for its adverse effects on human health and the environment.
- Health Effects: SO_2 exposure is associated with several health concerns. It can cause respiratory irritation, leading to symptoms such as coughing, wheezing, and shortness of breath. Prolonged exposure may exacerbate existing cardiovascular conditions, contributing to increased morbidity and mortality among vulnerable populations. Additionally, SO_2 contributes to the formation of acid rain, which can indirectly impact human health by affecting water and soil quality (38).

3.6.2. Dose-Response Assessment

- Approach: Due to resource constraints, a detailed dose-response assessment was not included in this study. Instead, the health risk evaluation relied on existing literature and established guidelines to infer potential health effects based on the observed SO_2 concentrations. This approach draws on previous research and exposure-response relationships documented in the scientific literature to estimate potential health risks associated with different levels of SO_2 exposure.

3.6.3. Exposure Assessment

- Method: The study employed a scenario-assessment methodology to estimate health risks associated with SO_2 exposure. This method involves evaluating different exposure scenarios to understand potential health impacts under varying conditions and age groups (children and the elderly).
- Scenario: The assessment of chronic exposure scenarios:
    - Chronic scenarios: Considers (annual) exposures to assess the potential impact of high levels of SO_2 exposure.
- Age Categories: The analysis was conducted for two distinct age groups:
    - Elderly (60+ years): This category encompasses the general adult population and is used to evaluate risks associated with typical and high SO_2 exposure levels.

- Children (0–5 years): This group represented a vulnerable population that may be more sensitive to SO_2 exposure. The assessment includes considerations for children's exposure patterns and potential health impacts.

3.6.4. Risk Characterisation where:

- C represents the average annual concentrations of the pollutant, also referred to as the field average daily dose (FADD)
- RfC represents the legislated ambient air quality limits or the safe average daily dose (SADD)

In non-carcinogenic risk assessments, it is standard practice to assume that the exposure duration (ED) and averaging time (AT) are the same, because non-cancer health effects are expected to occur during or immediately after the exposure period. This approach is recommended by the USEPA and is commonly used in chronic inhalation risk calculations. Moreover, Keretetse et al. 2023 utilized a probabilistic assessment framework employing Monte Carlo simulations to quantify both non-carcinogenic and carcinogenic risks, including the use of consistent exposure parameters (ED = AT) (20). Similarly, Thabethe et al. (Nomsa Duduzile Lina Thabethe, et al., 2025) applied a probabilistic human health risk assessment model that explicitly incorporated ED and AT as equivalent exposure parameters using Monte Carlo methods (81). Therefore, the air concentration must be adjusted to account for time-activity pattern variations between the vulnerable groups (80).

$$C_{air_adj} = C \times \left(\frac{ET}{24}\right) \times \left(\frac{EF}{365}\right) \times \left(\frac{ED}{AT}\right) \qquad \text{Equation 1}$$

where:

Table 3.1: Variables used

Variable	Symbol	Definition	Units	Children (0–5 years)	Elderly (60+ years)	Source

Pollutant concentration	C	Annual average SO_2 concentration in ambient air	µg/m³	Site-specific	Site-specific	Computed
Exposure Time	ET	Time spent in exposure area daily	hours /day	18 hours	22 hours	(21)
Exposure Frequency	EF	Number of days per year exposed	days/ year	350 days	350 days	(20, 21,80,81)
Exposure Duration	ED	Years of exposure	years	6 years	25 years	(21)
Averaging Time	AT	Period over which exposure is averaged (equal to ED for non-carcinogenic)	years	6 years	25 years	(22)
Reference Concentration	RfC	Safe Average Daily Dose or air quality limit for SO_2	µg/m³	20 (WHO or NAAQS)	20 (WHO or NAAQS)	(74)
Adjusted Air Concentration	Cair_adj	Exposure concentration adjusted for ET, EF, ED, and AT	µg/m³	Computed using Eq. 1	Computed using Eq. 1	Computed using Eq. 1
Hazard Quotient	HQ	Risk indicator: HQ = Cair_adj ÷ RfC	Unitless	Computed using Eq. 2	Computed using Eq. 2	Computed using Eq. 2

To account for variations in time activity patterns, it is assumed that the ET for children is 18 hours and that for the elderly is 22 hours, while EF is 350 days for the two groups (20), which accounts for the time they do not spend in the receiving environment. When assessing noncarcinogenic risks, it is assumed that ED equals AT, and as such, they cancel out in the equation above. The adjusted air concentration is divided by the Rfc to determine the HQ (80).

$HQ = C_{air_adj} / Rfc$ Equation 2

The resultant HQ values (A numerical value used to assess whether exposure to a pollutant poses a health risk (HQ > 1 indicates potential risk; HQ < 1 suggests minimal risk) are then

compared to 1, the safety benchmark (23). HQ values below 1.0 suggest that the pollutant is unlikely to cause adverse health effects, while those exceeding 1.0 indicate a heightened risk level associated with potential adverse effects.

3.7. Data Management

The data was transferred to Microsoft Excel for processing. A revalidation procedure was carried out to identify and rectify negative values and data spikes that had been previously overlooked. Spike detection algorithms were employed to identify these spikes within the dataset. A predefined threshold was established to identify outliers, which were subsequently excluded from the dataset. Identified outliers were manually reviewed for validation and either excluded from further analysis or corrected if necessary. An iterative check ensured no outliers remained undetected, and the entire process was documented for transparency. Google Cloud Storage was utilized to store the data due to its redundancy, backup, and disaster recovery features. Graphical representations of trends were generated using pivot tables for enhanced visualization.

3.8. Data Analysis

The data analysis for this study employs Analysis of Variance (ANOVA) to investigate the variations in sulfur dioxide (SO_2) concentrations across different seasons and to determine if these variations are statistically significant. This method provides a robust framework for comparing means and assessing the influence of seasonal changes on SO_2 levels.

3.8.1. Method:

Analysis of Variance (ANOVA)**:** was conducted to determine whether the seasonal differences in SO_2 concentrations were statistically significant. The null hypothesis (H_0) assumed that there is no significant difference in SO_2 levels across the seasons. This statistical method helps identify whether the observed differences in SO_2 levels are due to seasonal effects or if they occur by random chance (85; 86; 87)

3.8.2. Steps: In this study, variables were carefully defined to ensure a clear understanding of the analysis. The dependent variable in this research is SO_2 concentrations, which serve as the primary focus of the study. These concentrations represent the outcome being measured and analyzed across different seasons. The independent variable, on the other hand, is the season, which categorizes the data into four distinct periods: summer, autumn, winter, and spring. This classification allows for an investigation into the potential effects of seasonal variations on SO_2

levels. To provide a comprehensive summary of the data, descriptive statistics were calculated for SO_2 concentrations in each season. These statistical measures included the mean, median, standard deviation, and interquartile range, which together offer insights into the central tendency and dispersion of the data. Additionally, boxplots were generated to visually represent the distribution of SO_2 concentrations across the seasons. These graphical representations helped in identifying patterns, trends, and potential outliers within the dataset, thereby providing a clearer picture of seasonal variations. Before proceeding with inferential statistical tests, it was necessary to assess whether the data followed a normal distribution. To achieve this, the Shapiro-Wilk test was conducted. This test plays a crucial role in determining the suitability of parametric statistical tests such as ANOVA, as it checks whether the distribution of SO_2 concentrations aligns with the assumptions of normality.

Ensuring normality is essential for the reliability of subsequent analyses.

In addition to normality testing, it was also important to verify whether the variances of SO_2 concentrations were consistent across the different seasons. This was achieved using Levene's test for homogeneity of variances. Homogeneity of variance is a key assumption in ANOVA, as it ensures that the variability of data across groups remains comparable. If the assumption is violated, alternative statistical methods may be required to adjust for the differences in variance.

Following these preliminary checks, ANOVA (Analysis of Variance) was performed using Microsoft Excel. ANOVA is a powerful statistical method that allows for the comparison of means across multiple groups. In this case, it was used to determine whether significant differences exist in SO_2 concentrations across the four seasons. The results of ANOVA included F-statistics and p-values, which indicated whether seasonal variations had a statistically significant impact on SO_2 levels (88).

If ANOVA results suggested significant differences among the seasons, posthoc tests were conducted to further explore these variations. One commonly used posthoc test is the Bonferroni test, which helps identify specific pairs of seasons that exhibit significant differences in SO_2 concentrations. This additional analysis provided a more detailed understanding of how SO_2 levels varied between seasons, allowing for precise conclusions regarding the impact of seasonal changes on air quality (89).

3.9. Quality Control

The air quality monitoring station in Pelonomi rigorously maintains the accuracy and reliability of its measurements through meticulous instrument usage, calibration, and handling procedures. Manual bi-weekly calibration sessions by trained air quality specialists from the South African Weather Services (SAWS) uphold measurement precision, supplemented by annual comprehensive calibrations conducted at accredited independent laboratories (24). Monthly assessments performed by air quality specialists from SAWS comprising of routine inspections, machine performance audits and comparative data analysis address deviations in sensor readings and guarantee data integrity. Verification procedures follow the South African National Accreditation System Technical Requirement 07-02 (SANAS TR07-02) guideline, ensuring an 80% verification rate per parameter, while compliance with the South African National Standard (SANS 17025): General Requirements for the Competence of Testing and Calibration Laboratories guarantees adherence to regulatory requirements and international best practices. With the support of the South African Weather Service (SAWS), the monitoring station upholds its accreditation status under the Department of Forestry, Fisheries, and the Environment (DFFE), SANAS TR07-02, and SANS 17025, reinforcing its commitment to public health protection and environmental quality in Pelonomi (110).

3.10. Ethical Considerations

This research did not involve human or animal subjects, and no surveys were administered. It utilized publicly available air quality data from SAAQIS and reference values from USEPA to assess the health risks associated with ambient sulphur dioxide emissions. The study employed SO_2, temperature, wind direction, and wind speed data from the Pelonomi air quality station collected in 2023. Data security measures included encryption of electronic data during storage and transmission, restricted access to authorized personnel only, and adherence to institutional data management policies. Access to the data was limited to researchers involved in the study and complied with data sharing agreements and ethical guidelines. After submitting the study protocol, ethical clearance waiver certificate (W-PR-240821-02) was obtained on the 21/08/2024 from the University of the Witwatersrand Human Research Ethics Committee (HREC).

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CHAPTER 4: RESULTS AND DISCUSIONS OF FINDINGS

4.1. Introduction

This chapter presents the findings of the study on sulphur dioxide (SO_2) concentrations in Mangaung, as recorded at the Pelonomi monitoring station during the year 2023. The chapter includes both descriptive and statistical analyses of SO_2 levels across various time scales—hourly, daily, monthly, seasonal, and diurnal patterns. It also includes a health risk assessment focused on vulnerable population groups, particularly toddlers and the elderly.

The purpose of this chapter is to link the monitored SO_2 data with potential health impacts and to compare the results with established air quality standards from both South African legislation and international guidelines, such as those set by the World Health Organization (WHO). The findings are discussed in relation to previous research and existing literature on air pollution trends and human exposure risks in urban and semi-urban environments. This chapter also explores contributing factors to the observed SO_2 patterns, such as domestic fuel use, meteorological conditions, and socio-economic realities of Mangaung residents.

4.2. SO_2 Hourly average Concentrations

Figure 4.1 shows the hourly average levels of sulphur dioxide (SO_2) recorded at the Pelonomi monitoring station for the year 2023. The graph shows clear spikes throughout the year, with several periods where SO_2 concentrations rise above 30 $\mu g/m^3$. These spikes are more common during the first half of the year, especially between March and July, which falls in the autumn and winter seasons. During these months, the air is usually colder and more stable, making it easier for pollutants like SO_2 to build up in the atmosphere. Towards the end of the year, in spring and early summer, SO_2 levels are generally lower, though there are still a few sharp increases.

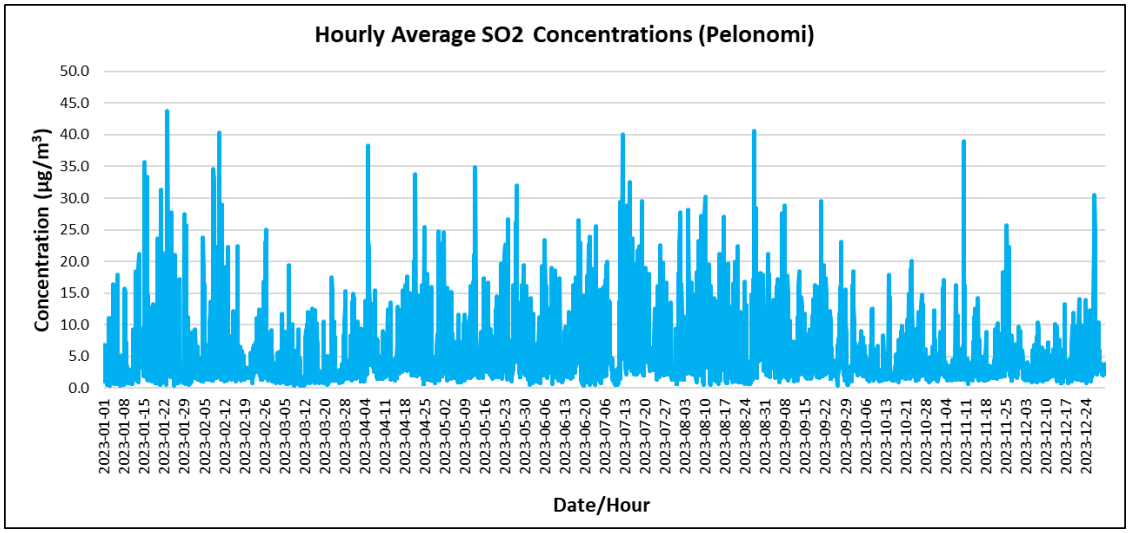

Figure 4.1: Hourly Average SO_2 Concentrations at Pelonomi Monitoring Station (2023)

These trends support what is found in the literature. For example, studies by Mukherjee and Agrawal (29) explain that cold weather conditions can trap air pollutants close to the ground, especially during winter. This leads to higher SO_2 levels. Naidoo et al. (101) also found similar patterns in other South African cities, where people often use more coal, wood, or paraffin for heating in winter, which adds to air pollution. In Mangaung, this could explain the higher SO_2 levels in winter, especially in residential areas.

The World Health Organization (WHO) warns that short-term exposure to SO_2 levels above 20 µg/m³ can cause breathing problems, especially for children, elderly people, and those with asthma or other lung conditions. Although visible spikes in ambient SO_2 concentrations were observed across the monitoring period, none exceeded the applicable air quality standards. This suggests that short-term fluctuations may be notable but remain within regulatory limits. The finding highlights the importance of considering both concentration magnitude and temporal persistence when assessing potential health risks.

4.3. SO_2 Daily Average Concentrations

Figure 4.2 shows the daily average sulphur dioxide (SO_2) concentrations recorded at the Pelonomi monitoring station over the full year of 2023. The black line represents the SO_2 levels measured each day, while the red line marks the National Ambient Air Quality Standard (NAAQS) for South Africa, which is 125 µg/m³. From this figure, it's clear that SO_2 concentrations in Mangaung stayed below the NAAQS threshold throughout the year. Most days recorded SO_2 levels between 5 and 20 µg/m³, with only a few days reaching up to around 30 µg/m³. Not a single day in 2023 went above the legal limit of 50 µg/m³.

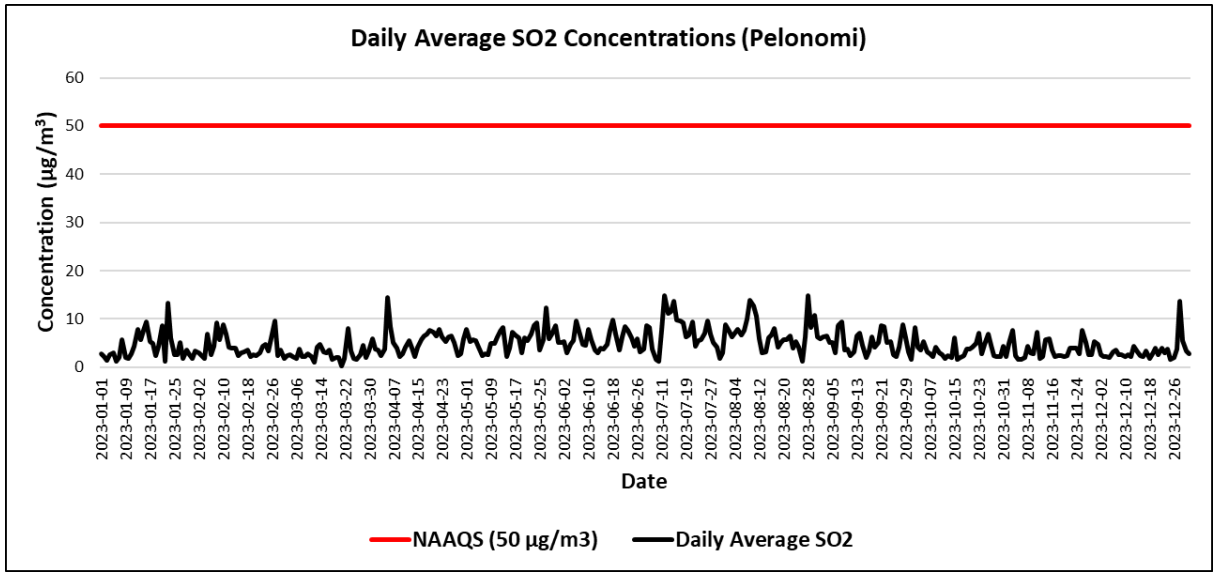

Figure 4.2: Daily Average SO_2 Concentrations at Pelonomi Monitoring Station (2023)

Although this might suggest that the air quality in Mangaung is generally acceptable, a closer look at the literature shows that even lower concentrations of SO_2 can still be harmful to human health. According to the World Health Organization (9), the recommended 24-hour average guideline for SO_2 is 20 µg/m³. This is more than twice as strict as the South African standard. In this context, many of the daily averages shown in the graph would actually be considered unhealthy by WHO standards. Research by Naidoo et al. (2013) (101), on air pollution in South African townships showed that communities are still exposed to harmful pollution even when official standards are met. This is especially true for low-income households that rely on solid fuels like coal or wood for cooking and heating.

What's also noticeable in the graph is that the daily SO_2 concentrations show more activity (more spikes and higher values) during the colder months, especially from May to August. This trend matches the seasonal pattern discussed in the literature. Mukherjee and Agrawal (29) found that SO_2 levels tend to rise during winter due to increased emissions from domestic burning and because cold air traps pollution close to the ground – a phenomenon called temperature inversion. Similarly, Zunckel et al (2006). (31) observed that during winter in parts of southern Africa, pollution levels increase due to low wind speeds and the use of coal-based heating.

In Mangaung, many residents still rely on informal heating sources during winter, which may explain why the SO_2 levels increase during that season. While the spikes do not go over the 50 µg/m³ mark, they still indicate possible short-term health risks. It is important to remember that

the graph only shows daily averages. It does not show hourly peaks, which, as we saw in the previous figure, can be much higher. Short-term exposure to SO_2, even over a few hours, can cause coughing, shortness of breath, and worsen conditions like asthma – especially in children and the elderly (9,98). In addition, the Department of Environmental Affairs pointed out that South Africa's air quality standards are sometimes outdated and may not fully protect vulnerable populations (74). That's why Department of Forestry, Fisheries and the Environment (DFFE) State of Air Quality Report (98), have recommended aligning local standards with WHO guidelines and improving pollution monitoring in urban and peri-urban areas (9).

While the daily SO_2 concentrations recorded at the Pelonomi station in 2023 were within the South African legal limits, a deeper analysis shows that air quality may still pose health risks, particularly in winter. The results also highlight the importance of using both national and international guidelines when assessing health impacts. Decision-makers should consider more proactive interventions such as promoting cleaner energy alternatives, improving public awareness, and enhancing monitoring to capture both daily and short-term exposure risks.

4.4. SO_2 Monthly averages Concentrations

Figure 4.4 shows the monthly average concentrations of sulphur dioxide (SO_2) recorded at the Pelonomi monitoring station for the year 2023. From the graph, SO_2 levels were the highest during the winter months, especially in August (7.0 µg/m³) and July (6.1 µg/m³). The lowest concentration was observed in March (2.8 µg/m³). Generally, the colder months (May to August) had higher SO_2 levels compared to the warmer months (October to March), where concentrations remained below 5 µg/m³.

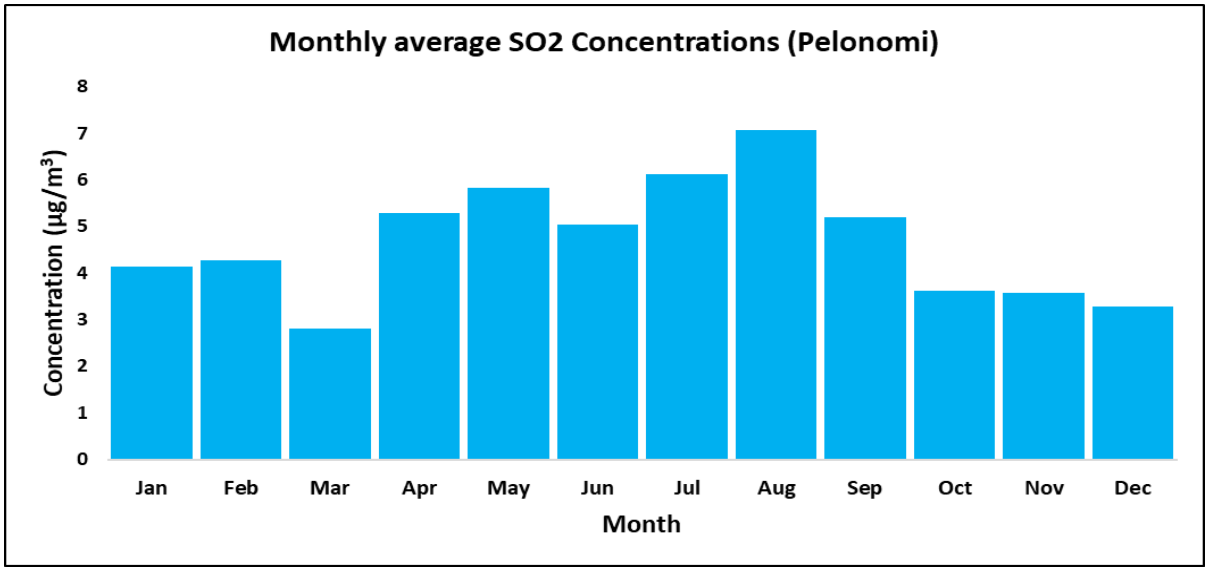

Figure 4.4: Monthly average sulphur dioxide (SO_2) concentrations recorded at Pelonomi monitoring station in 2023

These results reflect clear seasonal variation, where winter months show increased SO_2 pollution. This is in line with findings by Lourens et al. (2011), who observed that domestic burning of coal and wood for heating in colder seasons is a major contributor to increased air pollution in South African urban areas (12). In Mangaung, similar activities likely contribute to higher SO_2 levels in winter, especially in communities with lower access to electricity and alternative heating methods. The results also support what was noted in the South African Air Quality Information System (SAAQIS) reports, where SO_2 peaks were found to be linked to both domestic fuel burning and atmospheric conditions like temperature inversions that trap pollutants near the surface during winter (76).

Although none of the monthly average concentrations exceeded the South African National Ambient Air Quality Standard (NAAQS) daily limit for SO_2 (125 µg/m³ for 24 hours) (74), the consistent elevation in winter months is still concerning. Prolonged exposure, even to moderate levels, can impact vulnerable groups such as children, the elderly, and people with asthma or other respiratory issues (9, 98). The data shows that seasonal changes, domestic burning, and weather conditions play a big role in influencing SO_2 levels in Mangaung. These findings stress the need for better energy access, clean heating alternatives, and public awareness campaigns, especially before winter, to reduce SO_2 exposure and its related health risks

4.5. SO_2 Diurnal average Concentrations

Figure 4.5 shows how sulphur dioxide (SO_2) concentrations changed throughout the day at the Pelonomi monitoring station. The data reveals that SO_2 levels were generally higher in the early morning and evening hours. The highest peaks were recorded around 08:00 and again between 20:00 and 22:00, with concentrations reaching up to about 6.8 µg/m³. The lowest levels were observed in the early afternoon, around 16:00 to 17:00, where concentrations dropped to around 3.5 µg/m³.

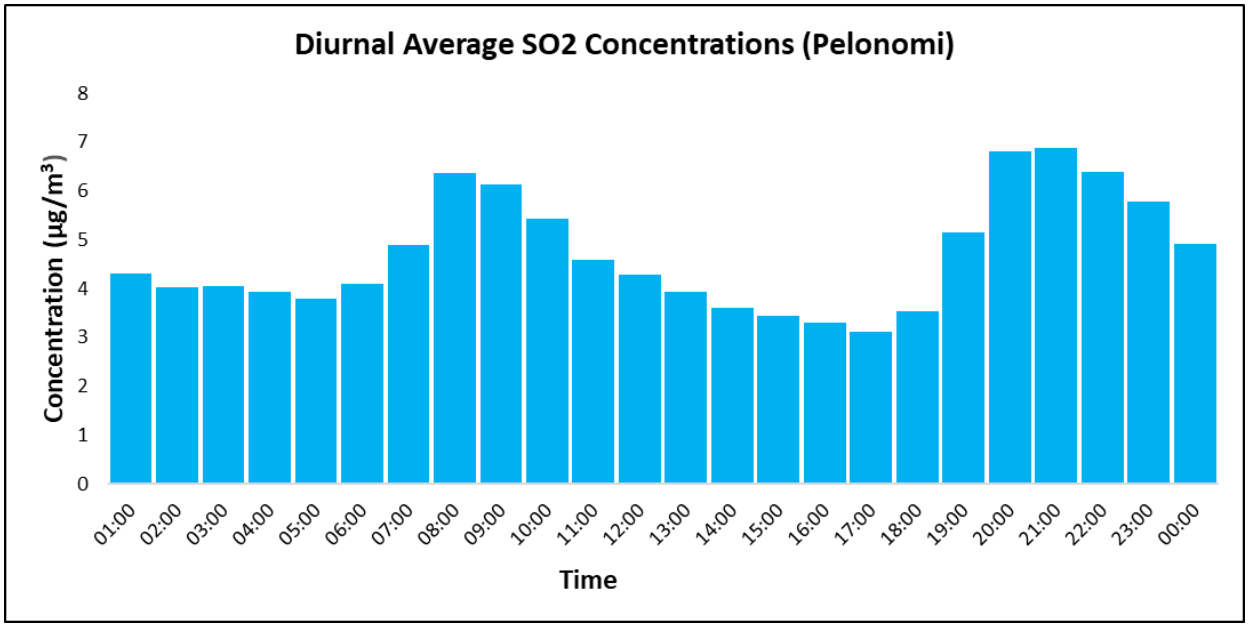

Figure 4.5: Diurnal Average SO_2 Concentrations (Pelonomi)

These patterns can be explained by both human activities and atmospheric conditions. The morning peak likely reflects increased vehicle emissions and industrial activity as people travel to work and businesses open for the day. In the evening, another spike occurs, possibly due to evening traffic, residential heating, and cooking emissions during peak usage times. These findings are consistent with the literature, where studies have shown that SO_2 levels often rise during rush hours due to traffic-related and domestic emissions (29).

Temperature inversion during the early morning and late evening can trap pollutants close to the ground, making concentrations higher at those times (98). Midday usually brings stronger sunlight and wind, which help to disperse pollutants, leading to lower SO_2 concentrations, as also noted in regional air quality assessments (12).

According to the WHO guideline of 20 µg/m³ for 24-hour exposure, the values recorded here remain below the limit, but the diurnal peaks still matter—especially for sensitive groups like children, the elderly, and people with respiratory conditions (9). Even short-term exposure to elevated SO_2 levels during these peak hours can trigger asthma and other health effects, as supported by previous studies in South Africa and internationally (29, 74).

4.6. Seasonal Variation

4.6.1. Probability Testing

Results in Table 4.1 indicate a statistically significant difference in SO_2 concentrations between the seasons ($p < 0.05$). This means that post-hoc testing is necessary to find out which seasons differ from each other.

Table 4.1: ANOVA Summary Table

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	251.4907181	3	83.83024	12.01244	1.63333E-07	2.629638
Within Groups	2519.281444	361	6.978619			
Total	2770.772162	364				

4.6.2. Post-hoc Testing

Figure 4.6 shows the seasonal distribution of sulphur dioxide (SO_2) concentrations across Summer, Autumn, Winter, and Spring. The boxplot reveals that Winter has the highest median and the widest spread of SO_2 values, followed by Spring and Autumn, while Summer shows the lowest levels overall. To assess whether these differences are statistically significant, a oneway ANOVA was conducted. The results indicate a statistically significant variation in SO_2 concentrations between the seasons ($F = 12.01$, $p < 0.0001$), which means that at least one season differs significantly from the others regarding SO_2 levels.

Table 4.2: Pairwise comparison of seasons

The results show statistically significant differences in SO_2 levels between most seasonal pairs, except for Summer vs Autumn ($p = 0.207$) and Winter vs Spring ($p = 0.315$), where p-values exceed the common significance threshold of 0.05. Significant differences are observed between

Group	**P Value (T Test)**	**Significance?**
Summer vs Autumn	0.20718467	No
Summer vs Winter	0.000000976	Yes
Summer vs Spring	0.000029737	Yes
Autumn vs Winter	0.000127224	Yes
Autumn vs Spring	0.002517570	Yes
Winter vs Spring	0.314633052	No

The results from the pairwise t-tests in Table 4.2 highlight clear seasonal variations in sulphur dioxide (SO_2) concentrations across Mangaung in 2023. Statistically significant differences

were found between most seasonal pairs, with p-values below 0.05 indicating a meaningful variation in SO_2 levels.

The comparison between Summer and Winter (p = 0.000000976), Summer and Spring (p = 0.000029737), Autumn and Winter (p = 0.000127224), and Autumn and Spring (p = 0.002517570) all show significant differences. This suggests that there are substantial shifts in SO_2 emissions and/or atmospheric dispersion mechanisms during these seasonal transitions. Winter consistently stands out in these comparisons, likely due to increased fossil fuel combustion for heating, reduced atmospheric dispersion, and temperature inversions common in colder months, which trap pollutants closer to the ground (53).

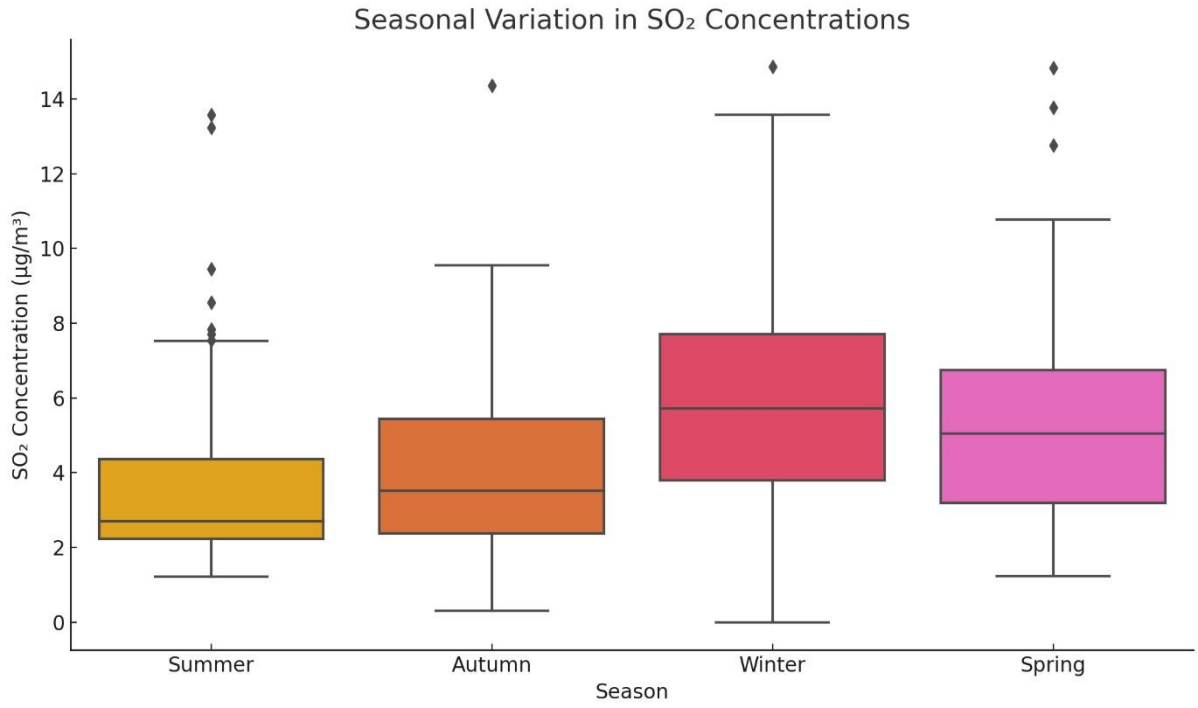

Figure 4.6: Seasonal Variation in SO_2 Concentrations Recorded at Pelonomi Monitoring Station in 2023

The boxplot illustrates the seasonal variation in SO_2 concentrations in Mangaung for 2023, revealing notable fluctuations across the four seasons. SO_2 levels were significantly higher during winter, with the median concentration peaking at nearly 6 µg/m³ and the upper quartile extending well beyond 10 µg/m³. This seasonal peak in winter can be attributed to anthropogenic and meteorological factors. In low-income and informal settlements prevalent in Mangaung, the demand for domestic heating rises during winter, leading to the increased combustion of solid fuels such as coal, wood, and paraffin. These sources are known

contributors to elevated SO_2 emissions, especially when used in poorly ventilated or open combustion settings.

Meteorological conditions in winter also exacerbate pollution levels. Temperature inversions—common in the Highveld regions during colder months—trap pollutants close to the surface, reducing vertical dispersion and accumulating SO_2 near breathing level (29; 102). Calm wind conditions, longer nights, and lower atmospheric mixing heights further contribute to the stagnation of air pollutants in urban atmospheres during this period (44,91).

In contrast, the summer season recorded the lowest SO_2 concentrations, with an interquartile range (IQR) around 2.5 $\mu g/m^3$. This trend aligns with the presence of stronger solar radiation, enhanced atmospheric mixing, and generally improved pollutant dispersion. Additionally, reduced reliance on fossil fuels for heating contributes to lower SO_2 emissions in summer. The observed decline in air pollutant levels during warmer months is consistent with studies in similar urban and periurban settings in South Africa and other developing regions.

From a public health perspective, the World Health Organization (WHO) has emphasized that even moderate increases in ambient SO_2 can trigger respiratory symptoms, particularly among vulnerable populations such as children, the elderly, and individuals with pre-existing respiratory conditions (98). Repeated exposure to elevated SO_2, even below short-term peak levels, has been linked to bronchoconstriction, reduced lung function, and increased hospital admissions for respiratory illnesses (104). The winter season, therefore, poses the highest risk for adverse health outcomes, necessitating proactive interventions from local authorities.

Targeted public health strategies and regulatory action should prioritize the winter months, incorporating both preventative measures and responsive health support. These might include community education on cleaner heating alternatives, subsidies for less polluting fuels, enhanced monitoring during high-risk periods, and emergency response plans for pollution spikes.

The observed seasonal pattern in SO_2 concentrations in Mangaung reflects broader socioenvironmental dynamics, where human activity and atmospheric processes intersect. These findings show that it's important to have air quality policies that change with the seasons and take into account the living conditions and challenges faced by local communities.

4.7. Risk Assessment

Table 4.2 shows the results of a health risk assessment for two sensitive age groups in Mangaung: toddlers and the elderly. These two groups are usually more at risk from air pollution because their bodies are either still developing (in the case of toddlers) or becoming weaker (in the case of the elderly). The method used to calculate the risk in this study looks at how much sulphur dioxide (SO_2) is in the air (C_air), how many hours per day people are exposed (ET), and how often they are exposed in a year (EF). From that, calculation of an adjusted concentration (C_air_adj) that takes into account the behaviour and daily habits of each age group.

The study then compared this adjusted concentration to a Reference Concentration (RfC), which is a safe level of SO_2 set by the World Health Organization (WHO) and the US Environmental Protection Agency (US EPA). By dividing the adjusted concentration by the RfC, this gives something called the Hazard Quotient (HQ). If the HQ is below 1, the risk is considered low or acceptable. If it's higher than 1, it may mean there is a possible health concern.

Table 4.3: Non-Carcinogenic Health Risk Assessment of SO_2 Exposure for Toddlers and the Elderly in Mangaung (2023)

Age Group	Cair (ug/m3)	ET (hrs/day)	EF (days/year)	Cair_adj (ug/m3)	Rfc (ug/m3)	HQ
Toddler	4,69	18	350	3.37	50	0.0674
Elderly	4,69	22	350	4.12	50	0.0824

The HQ for toddlers was 0.0674, and the HQ for the elderly was 0.0824. Both are well below 1, which means that under current SO_2 levels in Mangaung, there is no expected harmful health risk from long-term exposure for these two groups.

These results are similar to what other South African researchers have found. For example, a study by Naidoo et al. (2013) in Durban showed HQ values below 1 for most population groups exposed to ambient air pollution. However, they did note that people with asthma and children might still feel some health effects from short-term spikes in pollution (101). In another study by Millar et al. (2022) in the Highveld Priority Area, HQ values for children were also below 1, but they recommended close monitoring because the region had repeated exceedances of hourly SO_2 limits during winter (65). This shows that even when the long-term risk is low,

short-term peaks in pollution can still pose problems — especially for people with breathing issues.

However, in more polluted or industrial areas in other countries, some studies found HQ values greater than 1, meaning there might be a risk. For example, Omotayo Laro et al. (2018) in Lagos, Nigeria, reported HQ values higher than 1 for children living near oil refineries (69). Similarly, a study in Beijing, China, by Zhou et al. (2022) found high HQ values during winter due to coal combustion and traffic emissions (63). In both cases, the main reasons for the high HQ values were very high air pollution levels (especially during winter); The use of the maximum recorded concentration (not the average) to calculate risk; and sometimes more conservative methods where researchers assume people are exposed 24 hours a day, every day of the year.

Compared to these studies, the method used in this is more realistic. The researcher used average adjusted concentrations based on the local data from Pelonomi station and realistic exposure time (not assuming people are exposed 24/7). This makes the study results more reflective of actual living conditions in Mangaung. However, some might say it's less conservative, meaning it might not fully account for worst-case scenarios, like pollution spikes during cold winter nights when people burn a lot of coal or wood. The study approach also adjusted exposure based on the age group, which is very important and aligns with US EPA exposure assessment guidelines (2011). Children breathe faster and are more active, and the elderly often have weaker lungs. So, adjusting the air concentration (C_air_adj) for these groups makes the risk assessment more accurate and meaningful.

Although the results show no immediate health risk, it's important to note that SO_2 pollution in Mangaung is higher in winter due to domestic fuel burning and weather patterns that trap pollution near the ground (9, 98). Even if the HQ is below 1 now, those values could rise if fuel use increases or air quality worsens. Also, as seen in the WHO air quality guidelines (2021), even short-term exposure to SO_2 can cause coughing, shortness of breath, and worsen asthma, especially in young children and the elderly (9). This study gives valuable evidence for local policymakers. It shows that while the current risk may be acceptable, there is still a need to improve access to clean energy, reduce reliance on coal and paraffin, and educate communities about the health risks of air pollution — especially during the colder months.

4.8. Limitation of the Study

The findings of this study depended greatly on the quality of SO_2 concentration data obtained from SAAQIS. Firstly, the accuracy of measurement devices could have varied, affecting the reliability of the collected data. Secondly, missing data points due to instrument failure and power outages could have led to gaps in the assessment, potentially underestimating the actual health risks. Moreover, environmental concentrations of SO_2 might not have directly correlated with the effective dose absorbed by individuals, complicating risk estimation, meaning that there may be a level of uncertainty to the risk estimation. Lastly, relying solely on the hazard quotient (HQ) as a measure of risk could overlook potential health outcomes, as an HQ<1 does not guarantee immunity from adverse health effects due to chronic exposures. These limitations highlighted the importance of using strong research methods and collecting comprehensive data to accurately assess the health risks linked to SO_2 emissions. While many studies have explored the short-term effects of SO_2 exposure, there is a scarcity of longitudinal studies that track the long-term health impacts of chronic exposure.

4.9. Conclusion

The results presented in this chapter reveal important patterns in SO_2 pollution levels in Mangaung throughout 2023. While SO_2 concentrations mostly remained within the South African National Ambient Air Quality Standards (NAAQS), there were several short-term spikes—particularly during the colder months—that could pose potential health risks. These spikes were observed in both the hourly and daily average data and were most prominent in winter, a trend consistent with other studies conducted in South Africa and globally.

The findings show that SO_2 concentrations are influenced by seasonal factors, especially the increased use of coal, wood, and paraffin for heating during winter, and atmospheric conditions like temperature inversions that trap pollutants near the surface. The ANOVA and post-hoc analyses confirmed that SO_2 levels differ significantly between seasons, with winter recording the highest levels and summer the lowest. The health risk assessment showed that toddlers and the elderly in Mangaung are not currently at significant risk from long-term SO_2 exposure, as both HQ values were well below 1. However, the findings also suggest that even at low or moderate SO_2 levels, short-term exposure during pollution peaks can still harm sensitive individuals, especially those with pre-existing respiratory conditions.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1. Introduction

This chapter presents the conclusions and recommendations based on the findings from the study on the health risk assessment of sulphur dioxide (SO_2) emissions in Mangaung, Bloemfontein, during the year 2023. The chapter summarises the key insights drawn from the data analysis in Chapter 4, discusses the implications of the results in light of national and international standards, and proposes actionable strategies to reduce air pollution and protect vulnerable communities. By focusing on pollutant trends and health risk outcomes, this chapter contributes toward developing evidence-based responses for air quality management in semiurban environments like Mangaung.

5.2. Key Findings

One of the major findings from the study was that SO_2 concentrations in Mangaung displayed clear seasonal variations. The highest concentrations were recorded during winter, while the summer experienced the lowest levels. This seasonal pattern aligns with national and international literature, pointing to increased domestic fuel burning and temperature inversion phenomena as key drivers of elevated air pollution during colder periods. The analysis also showed that SO_2 concentrations were generally within the South African National Ambient Air Quality Standards (NAAQS), which set the 24-hour limit for SO_2 at 125 $\mu g/m^3$. However, several daily and hourly concentrations exceeded the World Health Organization's (WHO) more stringent guideline of 20 $\mu g/m^3$ for 24-hour exposure, especially during winter.

Another key finding was that although national standards were met, vulnerable groups such as toddlers and the elderly remain at risk of exposure to unhealthy air. The health risk assessment indicated that both groups had hazard quotient (HQ) values below 1, with toddlers at 0.0674 and the elderly at 0.0824. This suggests no significant risk of long-term non-carcinogenic health effects under the current average exposure conditions. However, the analysis also found that short-term spikes in SO_2, especially during early morning and evening hours, may lead to health concerns, particularly for people with respiratory conditions such as asthma. These hourly variations were evident in the diurnal analysis, which showed peaks around 08:00 and again between 20:00 and 22:00.

Furthermore, the study found that while Mangaung is not heavily industrialised compared to areas like eMalahleni, domestic sources of air pollution, such as coal, wood, and paraffin for

cooking and heating, are still significant contributors. The consistent rise in SO_2 levels during winter suggests that localised emissions in residential areas play a major role in overall air quality.

5.3. Study Conclusion

This study aimed to assess the health risks of sulphur dioxide (SO_2) exposure in Mangaung using the United States Environmental Protection Agency (USEPA) health risk assessment framework based on 2023 data from the Pelonomi air quality station. The results show that while SO_2 levels sometimes spiked during the study, none went above South Africa's air quality limits. This means short-term changes can be noticeable but still within legal limits, highlighting the need to look at both how high and how long the levels last when assessing health risks.

The health risk assessment revealed that the hazard quotient (HQ) values for toddlers and the elderly were both below 1, indicating that there is currently no significant long-term health risk from SO_2 exposure in these population sub-groups. However, the presence of seasonal and hourly peaks suggests a potential for short-term health effects, especially for individuals with pre-existing respiratory conditions. Therefore, although the overall health risk remains low, continued monitoring and targeted interventions are necessary to protect vulnerable communities in Mangaung from potential exposure-related health impacts.

5.4. Recommendations

Considering the findings and conclusions, this study proposes several recommendations to improve air quality and reduce health risks associated with SO_2 emissions in Mangaung. Firstly, there is a need for policy and regulatory reform. South Africa's air quality legislation should incorporate the WHO air quality guidelines, particularly the more protective 24-hour and shortterm limits for SO_2. Aligning local standards with international health evidence will better protect vulnerable populations.

Secondly, air quality monitoring should be enhanced. The current network should be expanded to include more monitoring stations in high-density residential areas and informal settlements where pollution exposure is most likely. These stations should provide real-time data to support early warning systems for pollution spikes and help track seasonal changes more effectively. Thirdly, a stronger focus should be on public health surveillance and preparedness. Regular respiratory health screenings should be offered in clinics, schools, and old-age homes,

especially during winter. Training healthcare professionals in environmental health issues will improve the diagnosis and treatment of pollution-related conditions.

Fourthly, clean energy alternatives must be promoted. Households should be supported through subsidies and incentives to transition from coal and paraffin to cleaner energy sources such as LPG, electricity, and solar heating. Municipal programmes that provide access to affordable, reliable, and safe energy technologies can reduce household emissions and improve indoor and ambient air quality. Fifth, community education and awareness campaigns are essential. Public education efforts should focus on the health risks of SO_2 and the importance of reducing household emissions. These campaigns should be inclusive, using local languages and culturally relevant messages to ensure community engagement and behaviour change.

Lastly, urban planning and emissions control strategies should be strengthened. Zoning laws must ensure that residential areas are not located near pollution hotspots. At the same time, emissions from small industries, transport, and informal businesses should be monitored and regulated to prevent them from contributing excessively to local pollution.

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8. Annexures

8.1. **Annexure 1**: WHO guidelines and the standards proposed by the South African National

Ambient Air Quality Standards (NAAQS) and the United States Environmental Protection Agency (USEPA) (AMETSOC).

Organization	**Time Period**	**Standard Level**	**Notes**
WHO	10-minute	500 µg/m³	-
WHO	24-hour	20 µg/m³	-
South African NAAQS	1-hour	75 ppb (approximately 196 µg/m³)	Averaged over three years
South African NAAQS	24-hour	0.14 ppm (approximately 365 µg/m³)	Not to be exceeded more than once per year, averaged over three years
USEPA	1-hour	75 ppb (approximately 196 µg/m³)	Averaged over three years
USEPA	24-hour	approximately 125 µg/m³	Not to be exceeded more than once per year, averaged over three years
USEPA	Annual	0.5 ppm	Revoked in 2010 for health risk assessment

8.2. **Annexure 2**: Ethical Waiver Clearance Certificate

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG	HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

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

TO: Mr H Ngobeni
School: Public Health
Department:
Division: Occupational Health
Faculty of Health Sciences

E-mail: hngobeni@yahoo.com

CC: Supervisor: Dr T Makonese, et al Tafadzwa.Makonese@wits.ac.za
and <HREC-Medical.ResearchOffice@wits.ac.za>

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

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

DATE: 21/08/2024

REF: *R14/49*

PROTOCOL NO: W-PR-240821-02 (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 Sulphur Dioxide emissions in Mangaung, Bloemfontein, South Africa (2023)*

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.

MSWorks2000/Iain0007/ClearScanWaiver.wps

UNIVERSITY OF THE WITWATERSRAND, JOHANNESBURG	HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL)

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

HUMAN RESEARCH ETHICS COMMITTEE (MEDICAL) ETHICS WAIVER

21/08/2024

Ref: W-PR-240821-02

TO WHOM IT MAY CONCERN

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

Investigator: Mr H Ngobeni
Student No. (if appropriate): 2449911
Staff No. (if appropriate):

Supervisor: Dr T Makonese, et al

School: Public Health
Department:
Division: Occupational Health
Faculty of Health Sciences

Project title: *Health risk assessment of Sulphur Dioxide emissions in Mangaung, Bloemfontein, South Africa (2023)*

Degree: MSc

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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