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Assessment of air quality compliance in the City of Tshwane Metropolitan Municipality.

by

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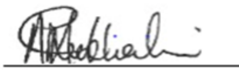
Declaration

I, Mphisedzeni Godwin Nemakhavhani, declare that the contents of this dissertation/thesis represent my work and that the dissertation/thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my opinions, not necessarily those of the Cape Peninsula University of Technology.

Signed  Date 29/09/2023

Abstract

Air pollution in metropolitan areas is a big problem, in developed and developing nations. Furthermore, in cities, it has been exacerbated by a growing urban population and increased vehicles on the road. Current estimations place more than 55% of the global population in urban areas by 2050, which is expected to climb to over 70%; and South Africa is not exempt from this reality. Studies have shown that air pollution is a substantial risk to humans health and has been linked to increased illness and mortality. Similarly, the World Health Organization (WHO) says that particulate matter, sulphur dioxide (SO_2), and nitrogen dioxide (NO_2) form part of the pollutants of concern with severe environmental health risks. The data pertaining to PM_{10}, NO_2, and SO_2, which are commonly monitored and considered to be of importance, was obtained from the SAAQIS database for the time period including 2016 to 2020. The provided data pertains to the network stations for ambient air monitoring within the City of Tshwane Metropolitan Municipality. The assessment of PM_{10}, NO_2, and SO_2 concentrations was conducted in accordance with the South African National Ambient Air Quality Standards (NAAQS). Therefore, the objectives of this study was to investigate the variations in NO_2, PM_{10}, and SO_2 levels across different seasons, evaluate the air quality within the City of Tshwane Metropolitan Municipality, and analyze the geographical patterns of these pollutants. The data analysis for this study was performed using Microsoft Excel and the Statistics Package for the Social Sciences (SPSS) techniques. In addition, the utilization of bar graphs and box and whisker plots was employed for the purpose of analyzing the obtained results. The research findings established that the City of Tshwane failed to comply with the National Ambient Air Quality Standards (NAAQS) in relation to the recorded annual levels of SO_2 (163.76 $\mu g/m^3$), NO_2 (60 $\mu g/m^3$) and PM_{10} (78.18 $\mu g/m^3$) at Booysens meighbourhood. The current findings is indicative of an area that is at risk of being declared a hotsport within the city should the current observation persists.

Keywords: Air quality compliance, Air pollution, Air quality assessment, City of Tshwane Metropolitan.

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Finally, I would like to express my gratitude to the divine entity for assisting with my various challenges. Daily, I have experienced the influence of your guidance. I attribute the successful completion of my degree to your assistance. To secure my future, I will persist in placing my confidence in your abilities.

Dedication

I dedicate this to my family:

- My wife for her unwavering support and motivation throughout this academic endeavour.
- My parents' unwavering support and encouragement during moments of discouragement have been instrumental in my academic journey. Their steadfast presence and guidance have played a pivotal role in shaping my current achievements.

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List of Acronyms

$\mu g/m^3$	Micrograms per cubic meter
AQI	Air Quality Index
CO	Carbon Monoxide
DEA	Department of Environmental Affairs
FEPA	Federal Environmental Protection Agency
H_2S	Hydrogen dioxide
INDAAF	International Network to study Deposition and Atmospheric chemistry in Africa
NAAQS	National Ambient Air Quality Standards
NEM: AQA	National Environmental Management Air Quality Act
NESREA	National Environmental Standards and Regulations Enforcement Agency
NO_2	Nitrogen dioxide
PM_{10}	Particulate matter aerodynamic diameter equal to or less than 10 $\mu g/m^3$
$PM_{2.5}$	Particulate matter aerodynamic diameter equal to or less than 2.5 $\mu g/m^3$
RQ	Risk Quotient
SAAQIS	South African Air Quality Information System
SO_2	Sulphur dioxide
US-EPA	United States Environmental Protection Agency
WHO	World Health Organisation

Dissertation Preface

The focus of the research was on the assessment of air quality compliance in the City of Tshwane Metropolitan Municipality.

This dissertation has Five (5) chapters, which are set out as follows;

Chapter 1 – Introduction: This chapter comprehensively overviews the research background, objectives, and significance. The chapter offers a concise overview of the air quality challenges encountered within the City of Tshwane Metropolitan Municipality.

Chapter 2 - Literature Review: This chapter conducts a comprehensive literature review focusing on the extent of exposure in various African urban areas, the variations observed across different seasons, and the existing air quality standards implemented in diverse African nations.

Chapter 3 - Research Design and Methodology: This chapter illustrates the research design and methodology employed in the study, encompassing aspects such as data collection, data analysis, and data presentation.

Chapter 4 – Results, Analysis and Interpretation: This chapter presents the findings, analysis, and interpretation of the data used in the research.

Chapter 5 - Conclusion and Recommendations: This chapter presents a summary and conclusion of the research findings, addressing the research questions and hypothesis. Additionally, recommendations are provided to address and mitigate the identified problem(s).

References: This chapter presents a comprehensive compilation of the research materials consulted to facilitate the execution of this study.

CHAPTER 1: INTRODUCTION

1.1 Background

Air pollution refers to chemicals or other pollutants that are either not ordinarily present in the air or in amounts that are detrimental to human health (Sharma et al., 2013). It primarily contributes to environmental effects such as acid rain (caused mainly by nitrogen and sulphur oxides in the atmosphere) (Ashfaq and Sharma, 2013). In addition, it can be caused by a vast number of emission sources, both natural and artificial (Sajjadi et al., 2018). The fact that some of these substances enter the atmosphere directly from their origins gives rise to the term "primary pollution". They frequently include sulphur dioxide, nitrogen oxides, carbon monoxide, lead, organic compounds, and particle matter (Sari et al., 2019; Tian et al., 2015; Fortin et al., 2005; Schwela, 2000). Additionally, air pollutants are produced by various sources, including industry and traffic, and are influenced by socioeconomic variables. Tian et al. (2019) found that urban land use patterns are closely related to air pollution. Land use distribution and shape impact air quality through spatial distribution and human activities (Wei et al., 2014). Previous studies (Misra et al., 2001; de Kok et al., 2006; Nyanganyura et al., 2007; Dionisio et al., 2010; Venter et al., 2012; Naidja et al., 2018) found that air pollution in Africa is caused by industry, transportation, home and commercial burning of living organisms, bush fires, live vegetation, sea spray, re-suspended dust from unpaved roads, and inadequate waste management. Air pollution disrupts the economy (Tian et al., 2019). It causes adverse health effects such as respiratory infections (Wei et al., 2014), heart disorders (Hassan et al., 2015), autoimmune disorders, lung cancer (Bereitschaft et al., 2013), and damages the ecosystem (both the atmosphere and the soil) (WHO, 2014; Yang et al., 2014).

The country's economy is also energy- and carbon-intensive (OECD, 2013). Coal is an essential fuel for industrial activities in South Africa, and coal-fired power plants account for a significant portion of its consumption. The National Electricity Regulator (2000) says that 91 per cent of the power made in South Africa comes from coal. Even though the majority of power plants in South Africa burn low-grade coal, the resulting emissions of carbon monoxide (CO), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), and particulate matter (PM) have produced significant environmental and health concerns for communities located near industrial "hot spots" (Spalding-Fecher, 2003). Pollution levels in South Africa are often high and harmful to people's health (Spalding-Fecher, 2003). This is especially true in large industrial areas like the South Durban Industrial Basin and the Vaal Triangle (Terblanche, 1994).

Furthermore, Mathee and Von Schirnding (2003) indicated that most of the problems related to air pollution in South Africa are caused by increased industrialization, poor land-use planning, rapid urbanization, and poverty. Hence, it has been demonstrated that poor land-use planning led to the co-location of substantial industrial development and densely inhabited residential areas (WHO, 1996; Barnard, 1999). Formerly disadvantaged demographic groups predominantly populate residential neighbourhoods next to industrial projects, most of whom are low socioeconomic level (Scott et al., 2005). Even though some of these regions may have access to amenities such as power, clean water, and transportation, they still have to cope with environmental issues (such as air pollution and noise pollution) that can negatively impact their health and well-being.

1.2 **Statement of the research problem**

Air pollution in metropolitan areas is a big problem in developed and developing nations. Furthermore, in cities, it has been exacerbated by a growing urban population and increased vehicles on the road (WHO, 2014). Current estimates place more than 55% of the global population in urban areas by 2050, which is expected to climb to over 70% (United Nations, 2012). This phenomenon contributes to numerous public health problems, and South Africa is not exempt from this reality (Yang et al., 2014).

Furthermore, to this extent, studies have shown that air pollution is a substantial risk to humans and health and has been linked to increased illness and mortality (WHO, 2016). Similarly, the World Health Organization (WHO) says that particulate matter, ozone (O_3), sulphur dioxide (SO_2), and nitrogen dioxide (NO_2) form part of the pollutants of concern with severe environmental health risks (WHO, 2016).

Some of these pollutants' elevated exposure levels have been discovered in regions classified as hot spots or priority areas, demonstrating that South Africa's air pollution concerns are far from being remedied, especially in urban areas (SAAQIS, 2009; DEA, 2013).

Therefore, against this background, the City of Tshwane, one of the big agglomerations and the capital city of South Africa, is not exempt from issues related to poor air quality exposure. For instance, SO_2 and hydrogen sulphide (H_2S) odours have been detected in some regions of the City of Tshwane (Ngobeni, 2021). As a result, this is a source of concern for the populations that live in the affected areas and people who commute into the city. Thus, assessing air quality compliance in the City of Tshwane Metropolitan Municipality is urgent.

1.3 **Research questions**

- What are the concentrations of NO_2, PM_{10}, and SO_2 in the City of Tshwane Metropolitan Municipality?
- Is there a seasonal variability of the NO_2, PM_{10}, and SO_2 concentrations within the City of Tshwane Metropolitan Municipality?
- What is the a spatial variability of the pollutants between the areas of interest?
- Do NO_2, PM_{10}, and SO_2 concentrations in the Tshwane Metropolitan Municipality's comply with the National Air Quality Standards?

1.4 **Aims and Objectives of the study**

The following objectives will guide the study:

- To assess the NO_2, PM_{10}, and SO_2 concentrations and ascertain the spatial variability of pollutants in the City of Tshwane Metropolitan Municipality.
- To determine the seasonal variability of the NO_2, PM_{10}, and SO_2 concentrations in the City of Tshwane Metropolitan Municipality.
- To compare the NO_2, PM_{10}, and SO_2 concentrations in the City of Tshwane Metropolitan Municipality with the National Ambient Air Quality Standards.

1.5 **Delineation of the study**

The study will focus on the City of Tshwane Metropolitan Municipality. The City of Tshwane formed an ambient air monitoring network comprising seven (7) permanent stations and one (1) mobile station. The stations are Rosslyn, Pretoria West, Mamelodi, Booysens, Olievenhoutbosch, Bodibeng, Tshwane Mobile and Ekandustria. The air quality monitoring stations are strategically located to detect changes in ambient air quality caused by industrial, transportation, and residential activity. Data from the City of Tshwane Metropolitan Municipality for all available ambient air monitoring network stations (for the period 2016 - 2020) for PM_{10}, NO_2, and SO_2 will be obtained from the SAAQIS Website because they are common ones, and these will be the parameters of concern.

1.6 **Significance of the study**

This study is critical because it will assess the air quality of the City of Tshwane Metropolitan Municipality. Poor air quality affects human health. Therefore, knowing the air quality status will benefit the City of Tshwane Metropolitan Municipality community and surroundings.

1.7 **Expected outcomes of the study**

The City of Tshwane Metropolitan Municipality has established some air quality strategies to control air pollution in Tshwane. The National Environmental Management: Air Quality Act of 2004 requires the local authorities to take full responsibility for air quality management. The study will assess the air quality for the benefit of all. The findings will be published at accredited peer-reviewed local and international conferences and journals. The researcher would obtain a master’s degree in Environmental Management after completing this study.

CHAPTER 2: LITERATURE REVIEW

2.1 Preamble

The issue of air quality has emerged as a significant challenge in numerous large cities across the globe in the past decade, and this reality is not exclusive to African metropolises. This chapter will primarily concentrate on a comprehensive literature review to identify and analyse previous research on the present topic. The forthcoming chapter will encompass the subsequent subjects: The concentrations of pollutants in African cities that actively monitor air pollution, seasonal variability trends of PM_{10}, SO_2, and NO_2 in various African states, how African cities monitor the exposure of their populations to pollutants of concern; lastly, the standards employed in African cities to monitor and regulate air quality.

2.2 Concentrations of pollutants in African cities that monitor air pollution

Air pollution and its related adverse effects on the environment and ecosystems can be reduced through effective management of air quality (Burnett et al., 2014; Amegah and Jaakkola, 2016; Benaissa et al., 2016; Johansson et al., 2017; WHO, 2018). Nevertheless, this necessitates collecting data on air quality (Hsu et al., 2013; Kuklinska et al., 2015) to supply cities, regions and countries with specific information on the pollution level (Awe et al., 2017). However, most air monitoring stations across African countries have been dilapidated (Amegah and Agyei-Mensah, 2017). In addition, this has led to limited air quality data from monitoring stations across Africa (Petkova et al., 2013; Amegah, 2018; Bahino et al., 2018; Fayiga et al., 2018). Subsequently, there is limited data on air quality; thus, there is little understanding of the concentration levels, sources, and factors contributing to air pollution. Thus, table 2.1 below indicates the air quality concentration levels of NO_2, SO_2 and PM_{10} in different African cities.

Table 2.1 Air quality concentration levels of NO_2, SO_2 and PM_{10} in different cities in Africa

African authors	Morakinyo et al., 2017	Mujuru et al., 2012)	Kirenga et al., 2015	Nkhama et al., 2017	Kenneth et al., 2020
The method used for monitoring.	NO_X Analyser (Model T200; S/N: 1624) Fluorescence SO_2 Analyser (Model 100E; S/N: 2891)	Badge-type samplers by Krochmal and Gorski	Concentrations of NO_2 and SO_2 were measured with Combo diffusion tubes (NO_2 and SO_2, Ormantine, FL, USA)	2-µm pore, 47-mm Polytetrafluorethylene (PTFE) Teflon membrane filters (Pall, Ann Arbor, MI, USA).	The BOSEAN equipment
Mean Concentration levels	PM_{10} annual concentration 48.26 µg/m^3 SO_2 annual average 18.68 µg/m^3 NO_2 annual average11.50 µg/m^3	SO_2 5.0 µg/m^3 NO_2 pollution was 46.14 µg/m^3	NO_2-26.69 µg/m^3 SO_2 -3.7 µg/m3	PM_{10} 7.03 µg/m^3 to 68.28 µg/m^3	NO_2 0.32ppm - 0.50ppm SO_2 -0.37ppm
Air quality standards	National Ambient Air Quality Standard	WHO Ambient Air Quality Standards	World Health Organization (WHO) cut-off limits	WHO air quality guidelines	WHO standards
Sources	Industrialisation, urbanisation and modernisation, and its attendant increase in vehicular emissions and activities	Emissions from vehicles, emissions from industries.	Emissions from cars, re-suspended dust from unpaved roads, smoke from indoor biomass fuel use and garbage	Cement industry	Emissions from vehicles

			burning, and industrial sites		
Country of origin	Pretoria, South Africa	Harare, Zimbabwe	Kampala and Jinja, Uganda	Chilanga, Zambia	Nairobi, Kenya
African authors	**Feuyit et al., 2019**	**Campos et al., 2021**	**Arku et al., 2008**	**Adon et al., 2016**	**Njee et al., 2016**
Method used for monitoring	handheld Aeroqual Gas Sensor model S-500L, battery-operated, possessing an interchangeable sensor head.	Aeroqual Series 500 for NO_2 and SO_2 EPAM 5000 Particle Monitor for PM_{10}.	Sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) concentrations were measured using Ogawa passive samplers	INDAAF (http://indaaf.obs-mip.fr) passive samplers method	Harvard Impactors [21] mounted with 25mm diameter Teflon filters
Mean Concentration levels	PM_{10} 18.86 to114.45 µg/m^3 NO_2 94.07 µg/m^3 to 49.60 µg/m^3 SO_2 206.76 µmg/m^3 to 236.40 µg/m^3	Hourly concentration 46.67 to 130.21 µg/m^3	Weighted average concentrations at all four sites were 71.8 µg/m^3 for PM_{10}	NO_2 µg.m^3 to 175 µg.m^3 SO_2 0.2 µg.m^3 to 3,662 µg.m^3	PM_{10} ranged from 86 µg/m^3 Average NO_2 concentrations ranged from 8 µg/m^3 to 109 µg/m^3
Air quality standards	WHO standards	European Union through Directive, 2008/50/EC	US-EPA National Ambient Air Quality Standards (NAAQS)	World Health Organization	WHO standards
Sources	Landfill operations	Oil refining process, aircraft movements during the	Biomass combustion, in addition to transportation, industrial	Anthropogenic activities, road traffic, and industrial sector	Biomass combustion, traffic vehicles

		landing and take-off process, ground handling equipment, electrical generators, and vehicles.	pollution, and non-combustion sources		
Country of origin	Yaoundé´ Metropolis, Cameroon	Luanda, Angola	Kumasi, Ghana	Abidjan, Cote d'Ivoire	Dar es Salaam, Tanzania
African countries	**El Morabet et al., 2021**	**Bouchlaghem & Nsom, 2012**	**Nanaa et al., 2012**	**Doumbia et al., 2023**	**Abulude et al., 2021**
The method used for monitoring.	Meteorological station	Teledyne models are 200A, 400A, and 100A for NO_x, O_3, and SO_2, respectively	Passive diffusion tubes made by Passam ag (Passam, 2010) Thermo-Andersen ADR1200S PM_{10}	Automatic aerosol samplers	Hand-held particle counter Air Quality Egg
Mean Concentration levels	NO_2 reached 85–96 mg/m^3 (at 6 p.m., 2014), 96–104 mg/m^3 (7–9 p.m., 2015) and 102–117 (8–11 p.m., 2016).	PM_{10} concentration reached 90 µg/m^3 in Tunis	NO_2 - 22 to 27 µg m^3 SO_2 - 0.5 to 10.5 µg m^3 PM_{10} -	82 to 293 g.m^3 for PM_{10}	PM_{10} concentrations greater than 150µg/m^3

Air quality standards	(US EPA) standards WHO Ambient Air Quality Standards	EU standard	WHO standard	Senegalese daily national standard	Australian Standard AS2922
Sources	Combustion processes in automobiles and industries	High convective dynamics account for a high resuspension of dust	Vehicles on unpaved roads, dust from Sahara	Dust	Automobile exhaust, open solid waste burning, industrial emission and fugitive dust from non-tar road surfaces
Country of origin	Mohammedia city, Morocco	Tunis, Tunisia	Ouagadougou, Burkina Faso	Dakar, Senegal	Lagos State, Nigeria

Table 2.2 presents diverse NO_2, SO_2, and PM_{10} concentrations monitored in African cities and juxtaposed with various air quality standards or guidelines.

Numerous African nations monitor levels of air quality indicators, including NO_2, SO_2, and PM_{10}, primarily within urban areas. The World Health Organization (WHO) has identified gases such as PM_{10}, NO_2, CO, SO_2, and O_3 as the primary air pollutants with significant public health implications (WHO, 2014).

According to a study by Morakinyo et al. (2020), the mean concentrations of NO_2 and SO_2 in Pretoria West, South were recorded as 11.50 µg/m^3 and 18.68 µg/m^3, respectively, during the years 2014 and 2016. The concentrations of ambient air pollution that were measured in the urban area of Dar es Salaam were found to be significantly higher than the previously estimated levels. The levels of PM_{10} and $PM_{2.5}$ measured in this study were considerably higher than the thresholds known to cause adverse public health effects. Moreover, these levels surpassed the global interim standards established by the World Health Organization (WHO) for ambient particulate matter (Njee et al., 2016). The heightened levels of particulate matter have been linked to the resuspension of particles from unpaved roads, particularly in urban regions, and exhaust emissions (Njee et al., 2016).

Furthermore, Kirenga et al. (2015) did a study in which they measured the levels of particulate matter, nitrogen dioxide, and sulphur dioxide pollutants in two cities in Uganda, specifically Kampala and Jinja. Nevertheless, the levels of NO_2, SO_2, and O_3 were found to be lower than the recommendation thresholds set by the World Health Organization (WHO), namely 200 μg/m^3 for the average duration of one hour, 20 μg/m^3 for 24 hours, and 100 μg/m^3 for eight hours. The factors contributing to the observed low levels of pollutants in the present study and previous research conducted in Uganda have yet to be determined. SO_2 was measured at all specified study locations, which included diverse land use areas where NO_2 measurements were also carried out.

Out of the total of 27 monitoring sites, it was observed that the levels of SO_2 were below the detectable threshold at 20 of these sites (Kirenga et al., 2015). As determined by measurements, the detectable threshold was less than 0.03 μg/m^3. The mean concentration of SO_2 for two weeks at all monitoring locations was determined to be 3.79 ± 3.0 μg/m^3. The levels of NO_2 were assessed at multiple sampling sites, and an average concentration of 24.9 μg/m^3 was determined for two weeks. The study revealed that the average concentrations of PM were observed to be at their minimum 88.3 μg/m^3 in residential and office regions that exhibited the presence of paved roads (Kirenga et al., 2015).

The study conducted in Luanda, Angola, revealed that the average concentration of NO_2 varied between 46.67 and 130.21 μg/m^3 hourly. At a specific location, the concentrations of NO_2 ranged from 35.67 to 106.96 μg/m^3.

Following the human health legislation of the European Union, the prescribed limit for the average concentration of NO_2 per hour should not exceed 200 μg/m^3 for a maximum of 18 occurrences within a given year (Directive, 2008). Hence, the abovementioned limit was not surpassed at any monitoring site. The values observed at both locations exhibit similarities to the findings reported by the World Health Organization (2000). According to the WHO study, the average yearly concentrations of NO_2 in urban outdoor settings typically fall within the range of 20–90 μg/m^3, while the maximum hourly concentrations range from 75–1015 μg/m^3. No substantial variation is observed in the daily profiles of NO_2 at both locations. The daily maximum concentration exhibited higher values during daylight hours. The study involved comparing the average concentrations of SO_2 hourly and daily and the limits set by the EC Directive (2008) to safeguard human health. The average hourly concentrations of SO_2 at one of the areas varied between 0 and 584.39 µg/m^3. Therefore, the prescribed hourly limit value of 350 µg/m^3, which should not be surpassed on more than 24 occasions within a given calendar year, was reached on 19 events throughout the campaign.

Conversely, the daily mean concentrations ranged from 42.42 to 164.12 µg/m^3. The prescribed daily threshold established to safeguard human health is 125 µg/m^3, with a maximum of three occurrences per calendar year exceeded on ten occasions. At a specific location, the mean concentrations of SO_2 hourly varied between 0 and 122.75 micrograms per cubic meter (µg/m^3). Consequently, there were no occurrences in which the hourly threshold was surpassed. The mean daily concentration remained below 25 µg/m^3, not exceeding the legal threshold for protecting human health. During the 28-day monitoring period, it was observed that the PM_{10} concentrations at a particular site exceeded the daily limit value established by the EC Directive (2008) for protecting human health by a factor of 26. The maximum allowable concentration, which should not surpass more than 35 instances within a calendar year, is 50 µg/m^3. The average daily concentrations of PM_{10} in other regions were below the recommended threshold values set to protect human health.

In the city of Accra, located in Ghana, the concentrations of sulphur dioxide SO_2 were below the National Ambient Air Quality Standards (NAAQS) set by the United States Environmental Protection Agency (USEPA). These standards specify that the annual average concentration of SO_2 should be below 0.03 parts per million (ppm), and the daily average concentration should be below 14 ppm (EPA, 2021).

This observation was consistent across all 29 measurement sites in Accra and throughout the measurements, indicating minimal variability in SO_2 levels across different locations. This observation aligns with the evidence indicating that the imported vehicle fuels utilized in Ghana have diminished sulphur content. The concentrations of NO_2 were lower than the National Ambient Air Quality Standards (NAAQS) annual average threshold of 0.053 parts per million (ppm) at all measurement sites, except for two locations. Except for the outlier mentioned above, there was no discernible pattern concerning the type of road (primary and secondary roads; alley), potentially due to the ubiquitous presence of biomass and transportation sources contributing to NO_2 levels throughout the neighbourhood. The concentrations of PM_{10} at all four sites were calculated to have a weighted average of 71.8 $\mu g/m^3$.

In the Zambian community, the recorded values ranged from 7.03 $\mu g/m^3$ during warm, wet times to 68.28 $\mu g/m^3$ during the hot season. The concentrations were also variable, changing from a low of 2.26 $\mu g/m^3$ during the mild, rainy times to a high of 8.82 $\mu g/m^3$ during the hot, dry seasons. Throughout the 42-day follow-up, the average daily concentrations of PM_{10} and $PM_{2.5}$ were higher than the thresholds set by the WHO. Furthermore, on day 21, PM levels were up to five times higher than acceptable (Nkhama et al., 2017). Based on the findings of the investigation, it was observed that there were increased levels of particulate matter (PM), specifically PM_{10} and $PM_{2.5}$, with recorded values ranging from 3.6 to 168 $\mu g/m^3$ and 0.4 to 54 $\mu g/m^3$, respectively. Nevertheless, a study by Nkhama et al. (2017) documented a notable increase in particulate matter (PM) concentrations within communities near cement factories.

The study conducted in Yaoundé Metropolis, Cameroon, has provided findings regarding the average daily concentrations of $PM_{2.5}$ and PM_{10}. The results indicate that the levels of the concentrations of PM_{10} varied from 28.84 $\mu g/m^3$ to 97.69 $\mu g/m^3$. Similarly, the average daily concentrations in different sites of PM_{10}, precisely 91.34 µg/m3, 97.69 $\mu g/m^3$, and 82.91 $\mu g/m^3$, exceeded the recommended daily threshold of 50 $\mu g/m^3$ established by the World Health Organization (WHO, 2006). Multiple studies have presented compelling evidence that exposure to elevated levels of particulate matter (PM) is associated with an increased risk of developing cardiopulmonary disease (CPD) and mortality from ischemic heart disease (IHD) (Laden et al., 2006). NO_2 was solely observed at two monitoring stations. The substance's hourly and daily mean levels varied between non-detectable (ND) and 94.07 $\mu g/m^3$ and between 35.92 and 49.60 $\mu g/m^3$.

Furthermore, it is worth noting that the concentrations of O_3 and NO_2 were found to be significantly below the maximum emission limits established by the World Health Organization (WHO) (WHO, 2000; WHO, 2006), respectively. Compared to other locations, the relatively elevated CO and NO_2 concentrations observed at monitoring stations and other areas could be attributed to their proximity to the highway. The concentration of SO_2 ranged from non-detectable (ND) to 206.76 µg/m3, ND to 236.40 µg/m^3, and ND to 28.56 µg/m^3, respectively. The daily average concentrations varied from 14.49 to 32.25 µg/m^3, 8.74 to 28.06 µg/m^3, and 1.05 (RA9) to 4.18 µg/m^3 in different monitored sites.

A study conducted in Ouagadougou, Burkina Faso, revealed that nitrogen dioxide (NO_2) concentrations remained below the limit established by the World Health Organization (WHO) standard for the city as a whole. However, certain downtown areas with high vehicular traffic exhibited levels of NO_2 that exceeded this threshold value. The concentrations of SO_2 in the city are consistently low. The levels of PM_{10} particles indicate an increase during the dry season and a decrease during the rainy season. In urban areas, the concentration of PM_{10} particles surpasses the threshold established by the World Health Organization (WHO). The PM_{10} concentrations observed in Ouagadougou are comparable to those recorded in the broader Sahel region, as reported by Nanaa et al. (2012).

Additionally, the concentrations of PM_{10} and $PM_{2.5}$ exceeded the Senegalese daily national standard of 150 and 75 µg/m^3, respectively, by up to two times and 3.4 times. As mentioned above, the limit is two to three times greater than the corresponding values stipulated by alternative international standards. The latest data on $PM_{2.5}$ levels in Dakar indicates that, from 2018 to 2019, the average daily concentrations ranged from 280.6 to 302.7 µg/m^3 (Kebe et al., 2021). These findings suggest a notable rise in concentration compared to the preceding decade. The observed phenomenon can be attributed to the rapid urbanization and concurrent population growth, exemplified by the substantial increase of approximately one million inhabitants in Dakar between 2007 and 2017.

In Lagos state, Nigeria, most of the observations on PM_{10} in this investigation exceed the threshold of 150 µg/m^3 (Abulude et al., 2021). Furthermore, it is worth noting that the levels of NO_2 exceed the recommended 1-hour mean of 0.5µg/m^3 set by the Federal Ministry of Environment (FMEnv) Nigeria. However, these levels remain below the recommended 24-hour limit of 40µg/m^3 established by the World Health Organization (WHO) (Abulude et al., 2021). The measured concentrations of SO_2 were below the 24-hour guideline limit recommended by the World Health Organization

($500\mu g/m^3$). Airborne contaminants in various cities worldwide are primarily caused by the combustion of fossil fuels, vehicular activities, population growth, accelerated economic progress, and the re-suspension of soil dust (Abulude et al., 2018).

According to El Morabet et al., 2021, the highest recorded concentration of the substance in Mohammedia city, Morocco, was observed to be between 85 and 96 mg/m^3 at 6 p.m. in the year 2014, between 96 and 104 mg/m^3 from 7 to 9 p.m. in the year 2015, and between 102 and 117 mg/m^3 from 8 to 11 p.m. in the year 2016. The Air Quality Index (AQI) exhibited a 0-50 mg/m^3 range during elevated NO_2 concentrations, indicating good air quality. However, during peak hours, the AQI increased to a range of 51-100 mg/m^3, indicating air quality deemed unhealthy for individuals sensitive to such conditions (El Morabet et al., 2021). The risk quotient (RQ) was determined for the mean daily and mean hourly exposure to NO_2. The calculated RQ values for all three years were determined to be less than one, indicating the absence of any potential health risks in terms of lifetime exposure and hourly exposure (El Morabet et al., 2021). Nevertheless, the observed rise in the RQ value from 0.84 in 2014 to 0.98 in 2016 suggests a corresponding increase in the potential health risk. Therefore, it is imperative to implement policies and measures aimed at mitigating potential health risks (El Morabet et al., 2021). African cities are confronted with many sources of air pollution, which will be further examined in the subsequent discussion.

Coal is an essential energy source for industrial applications in South Africa, primarily employed by power plants that rely on coal combustion. Coal is the predominant source of electricity in South Africa, constituting approximately 91% of the overall electricity production (National Electricity Regulator (NER), 2000). Using low-grade coal in most power stations in South Africa has produced emissions such as CO, NO_2, SO_2, and particulate matter (PM). These emissions have posed considerable environmental and health issues for nearby communities (Spalding-Fecher and Matibe, 2003).

The investigation conducted on the elemental composition of particulate matter in Dar es Salaam has unveiled heightened concentrations of bromine. This discovery suggests that biomass combustion could substantially affect the observed levels. As mentioned, the data has been documented in multiple scholarly investigations

(Koleleni, 2002; Bennet et al., 2005). A study conducted ten years ago by Mbuligwe and Kassenga (1997) forecasted a notable escalation in potential emissions from traffic vehicles in Dar Es Salaam. One area of concern relates to the significant increase in the number of cars, accompanied by elevated emissions originating from older vehicles and diesel engines, specifically those employed for commuting, such as minibuses.

Human activities are responsible for most air pollution in cities, including Abidjan (Cote d'Ivoire), where high quantities of gaseous and particle pollutants have been detected in recent studies of the urban atmosphere (Kampa and Castanas, 2008).

Cement manufacturing is responsible for a sizeable fraction of worldwide PM emissions (Abu-allaban and Abu-qudais, 2011; Shiravan, 2014). The cement factory's production process generates vast quantities of particulate matter in dust. Furthermore, this begins with the raw materials' quarrying and continues through the packing (Abdul-Wahab, 2006). Particulate matter is emitted as fugitive dust within the vicinity of cement facilities. In Chilanga, Zambia, there have been instances of particulate matter concentrations derived from cement dust exceeding the minimum allowable levels within the manufacturing facility and in the neighbouring towns.

Marticorena et al. (2010) found that the lowest concentration of PM_{10} aligns with the highest levels of precipitation, which hinders the release of dust by enhancing soil moisture and vegetation growth. This observation also implies that the wet scavenging process may reduce dust concentration. During the dry season in Burkina Faso, the levels of PM_{10} concentrations consistently surpass the established national standard for PM_{10}, except for February, specifically at the background site. The concentrations exhibit a greater proximity to the standard limit during the wet season, particularly at the peak site. The air concentrations of PM_{10} in Ouagadougou's urban area exceed the standard set by the World Health Organization (WHO, 2005), which is 20 $\mu g/m^3$.

The studies conducted on African cities have identified several sources of particulate air pollution. These sources commonly include emissions from vehicles, dust that is stirred up from unpaved roads, smoke resulting from the indoor use of biomass fuel and the burning of garbage, as well as industrial sites (Arku et al., 2008; Ofosu et al., 2013; Gaita et al., 2014). Elevated levels of particulate matter (PM) in residential neighbourhoods characterized by unpaved roads and heavy traffic suggest that the re-suspension of dust particles significantly contributes to the observed high PM concentrations. On the other hand, it can be deduced that there is a correlation between increased levels of particulate matter (PM) in regions with commercial land use, heavy traffic flow, and extensive road infrastructure. In addition, this suggests that vehicle emissions contribute significantly to the overall PM concentration in these places. The dispersion of dust that originates from unpaved roads in suburban areas of cities is reported to be enhanced by human activity, resulting in its deposition in regions characterized by paved roads (Arku et al., 2008; Ofosu et al., 2013; Gaita et al., 2014).

Biomass fuels continue to be a prevalent energy source among urban populations in Sub-Saharan Africa (Bailis et al., 2005; Barnes et al., 2005). The rise in urban population utilizing biomass, along with the concurrent escalation of traffic and industrial emissions associated with economic evolvement, is anticipated to result in heightened levels of air pollution in African cities. This trend aligns with observations made in major cities across Asia (Smith and Ezzati, 2005). Moreover, this necessitates the development of technological and policy advancements aimed at mitigating the escalating levels of air pollution, particularly in low-income and marginalized communities. Additionally, it underscores the importance of regular air quality monitoring, explicitly focusing on pollution levels within local neighbourhoods.

The origins of air pollutant emissions vary depending on the specific pollutant. The emission of significant amounts of sulphur dioxide into the atmosphere is attributed to the chemical industries, vehicular traffic, and petroleum refineries. Vehicular emissions have been recognized as an essential contributor to air pollution in Lagos, Nigeria, specifically in the emission of SO_2 and NO_2. Pandey et al. (2014) posit that SO_2 has the potential to cause direct chemical deterioration of architectural structures. The combustion of fossil fuels at elevated temperatures leads to the generation of nitrogen oxides, making vehicular emissions the primary contributor of NOx. Nevertheless, numerous megacities, including Lagos, suffer from insufficient air quality monitoring systems. The evident potential contributors to air pollution in Lagos encompass motor vehicles, industrial operations, open dump incineration, dust emissions from highways, domestic heating practices, power generators, and coal combustion in commercial zones. Numerous studies have demonstrated that automobiles constitute the primary contributor to air pollution in most urban areas

(Elbir et al., 2000; Yannis et al., 2006; Pandey et al., 2014). The elevated level of vehicular emissions can be attributed to several factors, including the substantial volume of vehicles on heavily congested roadways, incomplete combustion processes within engines, substandard fuel quality and maintenance systems, and inadequate transport management strategies. These reasons are apparent in the city of Lagos. Nevertheless, the emission patterns of air pollutants exhibit daily variations, particularly in areas near highways or roadsides.

The study's findings in Mohammedia City, Morocco, suggest that traffic-related factors predominantly influence the concentration of NO_2 in the urban area of Mohammedia. Industrial pollution persists for extended periods (Morakinyo et al., 2017). Furthermore, this is primarily attributed to the fact that work shifts in industries typically span 6 to 8 hours. Therefore, the concentration of NO_2 will remain relatively constant. Nevertheless, the rise in NO_2 levels is inconsistent and exhibits intermittent surges that can be attributed to the escalation in traffic volume during specific hours within the urban area.

While several African nations have made progress in assessing the levels of priority pollutants in urban areas, a significant amount of work remains to be accomplished in this field. Certain countries, such as Uganda, have been documented as experiencing a deficiency in air quality data. Thus, there is a permanent lack of air quality monitoring stations. It should be noted that the lack of continuous air quality monitoring has significant implications for both the environment and human health. Furthermore, the lack of knowledge regarding the concentration levels of pollutants has a considerable impact. The literature suggests that air quality standards are not uniformly established for other African countries, thereby constraining the overall compliance level of these nations. The implementation of air quality standards in South Africa has been observed. However, there exists a deficiency in monitoring and adherence to these standards. The present investigation aims to evaluate the concentration levels of pollutants to determine their compliance with the South African National Ambient Air Quality Standards.

2.3 Seasonal variability trends of PM_{10}, SO_2 and NO_2 in African states

Assessing pollution levels in the lower atmosphere has traditionally been considered the seasonality variable. The presence of hazardous pollutants, including but not limited to SO_2, CO, NO_2, PM_{10}, and chlorofluorocarbons (CFCs), due to both natural phenomena and anthropogenic activities, has the potential to compromise air quality significantly and, consequently, the well-being of organisms (WHO, 2000). The seasonal fluctuations were observed in the concentrations of NO_2 in the ambient environment. The study's findings indicate that the concentration levels were higher during the winter than during the summer at various sites in Egypt, including Tabbin, Assyut, Suez, and Alexandria (WHO, 2000). The recorded concentration levels during the winter season were 29 µg/m^3 and 37 µg/m^3 at Tabbin and Assyut, respectively, while the levels during the summer season were 23 µg/m^3 and 23 µg/m^3, respectively. Similarly, the concentration levels during the winter season were 55 µg/m^3 and 46 µg/m^3 at Suez and Alexandria, respectively, while the levels during the summer season were 19 µg/m^3 and 37 µg/m^3, respectively.

In contrast, the variance between the two values in Abbasseya was insignificant, measuring at 71 and 74 µg/m^3 (WHO, 2000). Comparable findings were reported in the Cape Town, Western Cape region of South Africa, where the recorded concentration of particulate matter was 28 µg/m^3, compared to 16 µg/m^3. These results were documented in Elminir's (2007) and Saucy et al. (2018) studies. According to studies conducted by Raheem et al. (2009), Adon et al. (2016), and Adeleke et al. (2011), the concentration of NO_2 during dry seasons was observed to be significantly higher than during wet seasons at various sites in Dakar, Senegal and Lagos, Nigeria. The mean concentration of NO_2 during dry seasons was approximately 2 to 4 times larger than during wet seasons, with values ranging from 5.9 µg/m^3 to 67 µg/m^3, depending on the location.

Adon et al. (2016) reported no significant contrast between the two seasons was detected in Bamako, Mali, with a recorded value of 29 versus 31 µg/m^3. Previous studies noted that elevated concentrations of NO_2 during winter months can be attributed to increased heating demands, decreased photochemical activities, and reduced atmospheric mixing (Bouchlaghem and Nsom,2012; Laakso et al., 2012;

Mentz et al., 2018; Muttoo et al., 2018). Adon et al. (2016) have identified that high average levels of NO_2 during the dry season in Dakar and Bamako can be attributed to amplified biomass burning and heavy traffic activities during this period. In addition to seasonal variations, diurnal oscillations are noted primarily due to the predominant human actions during the observation period. Tunis exhibits a distinct daily fluctuation in the average hourly concentration of NO_2, with higher levels recorded during the morning (75 to 122 μg/m^3) and lower levels during the afternoon (56 to 85 μg/m^3). This pattern corresponds with the peak traffic hours, as Azri et al. (2009) reported, that vehicular activities significantly contribute to the elevated pollution levels during these periods in Tunis. The concentrations of NO_2 in the cooking areas surpass the appropriate World Health Organization (WHO) and Air Quality Guidelines (AQG) levels, set at 200 μg/m^3.

According to Laakso et al. (2012), the concentration of SO_2 exhibited seasonal variations, with elevated ambient levels typically observed during seasons characterized by reduced rainfall and limited air circulation caused by inversion. According to Elminir's (2007) study, the average concentration of SO_2 in Egypt exhibits a seasonal variation, with higher levels observed during the winter months compared to the summer months. Specifically, Shoubra El-Kheima and Assyut sites recorded mean concentrations of 63 and 52 μg/m^3 and 52 and 27 μg/m^3 during the winter and summer, respectively. Raheem et al. (2009) and Adon et al. (2016) reported that the average SO_2 concentration in Dakar, Senegal and Ilorin, Nigeria, respectively, were higher during dry seasons compared to wet seasons. Specifically, the mean SO_2 concentrations were 54 μg/m^3 and 18 μg/m^3 in Dakar during dry and wet seasons, respectively, while in Illorin, the mean SO_2 concentrations were 8 μg/m^3 and 0.7 μg/m^3 during dry and wet seasons, respectively. In some areas of Egypt, there is a potential for the concentration of ambient SO_2 to be twice as high during the winter compared to the summer (Raheem et al., 2009; Adon et al., 2016).

Similarly, in Dakar and Illorin, the concentrations of ambient SO_2 can be three (3) to eleven (11) times higher during the dry season than in the wet season. The elevated concentrations of SO_2 during winter and dry seasons are linked to limited air circulation caused by the inversion and heightened emission intensities (Raheem et al., 2009; Adon et al., 2016). The statement mentioned above stands in opposition to the summer or wet season, which exhibits a heightened occurrence of precipitation and air movements, as noted by Josipovic et al. (2011), Adon et al. (2010, 2016), Bouchlaghem and Nsom (2012), and Laakso et al. (2012). According to Jafta et al. (2017), the average concentration of SO_2 in indoor (living/sleeping room) environments in Durban, South Africa, over two weeks is 0.6 ± 0.7 μg/m^3, with a maximum recorded value of 3 μg/m^3. According to Ana et al. (2013), the average concentration of indoor SO_2 at cooking sites in the Olurunda community of Nigeria ranges from 79 to 3404 μg/m^3 (with a 1-hour average), while the daily mean is 1544 ± 759 μg/m^3. The average value is 87 times greater than the air quality guideline (AQG) of 20 μg/m^3 established by the World Health Organization (WHO) for 24 hours. McCord et al. (2017) reported that the concentration level of SO_2 during cooking over a firewood stove in Kampala, Uganda was 350 μg/m^3. This finding highlights the high exposure and risk of SO_2 in the rural kitchens of Africa.

The PM concentrations in the air may be influenced by seasonal variations in atmospheric conditions, as noted by Gaita et al. (2014) and Salvador et al. (2016). Between November and March, the African region experiences a strong Northeast trade wind known as Harmattan (Oluleye and Jimoh, 2018). This wind causes the entrainment of Saharan dust, which is loaded with significant quantities of mineral aerosols, into the atmosphere over Africa (Elminir, 2007; Aboh et al., 2009; Stuut et al., 2009; De Longueville et al., 2010; Klose et al., 2010; Kchih et al., 2015; Terrouche et al., 2016; Middleton, 2017; Dimitriou and Kassomenos, 2018; Donateo et al., 2018). The transportation of aerosols towards the southern region results in increased concentrations of $PM_{2.5}$ and PM_{10}, particularly in the winter and dry seasons (Akinlade et al., 2015; Aklesso et al., 2018).

Bouchlaghem and Nsom (2012) examined the impact of atmospheric pollutants on the air quality in Tunisia. The findings revealed that the high PM_{10} concentrations in major Tunisian cities were attributed to the substantial dust load of the Saharan air masses. The findings revealed that the hourly mean levels during Saharan dust events in Tunis, Bizerte, Sfax Centre, and Sousse were significantly higher than before or after the events period (Bouchlaghem and Nsom's, 2012). Specifically, the hourly mean levels were 30 (307 versus 10 μg/m^3), 94 (378 versus 4 μg/m^3), 14 (399 versus 27 μg/m^3), and 5 (130 versus 23 μg/m^3) times larger in the areas mentioned above, respectively (Bouchlaghem and Nsom's, 2012). According to Mkoma et al. (2010), the mean PM_{10}

concentration levels in Tanzania were found to be higher during the dry season in Dar es Salaam (76 μg/m^3) compared to the wet season (52 μg/m^3).

Similarly, in Morogoro, the mean PM_{10} concentration levels were reported to be higher during the dry season (61 μg/m^3) compared to the wet season (36 μg/m^3) (Mkoma et al., 2013). Additionally, Mkoma et al. (2013) reported similar findings regarding the mean PM2.5 levels in Dar es Salaam (26 μg/m^3) and Morogoro (39 μg/m^3) compared to the respective levels of 19 μg/m^3 and 28 μg/m^3. The authors attributed these results to the prevalence of temperature inversions, which hinder air mixing and minimal precipitation, leading to little or no scavenging. Additionally, the authors suggested that reduced vegetation in dry seasons may contribute to increased soil dust dispersal, as previously discussed in Mkoma et al. (2010, 2010, 2013). According to Tahri et al. (2017), photochemical activity during summer may lead to generating a greater number of secondary particles. According to Bouchlaghem and Nsom (2012), PM levels are higher in winter or dry than in summer or wet seasons. Furthermore, this is attributed to lower dispersion during winter and reduced mixing. According to Gebre et al. (2010), the concentration of TSP in Addis Ababa, Ethiopia, was found to be four times higher during the dry season (305 μg/m3) compared to the wet season (75 μg/m^3).

The composition and origin of PM_{10} in Cape Verde was investigated by Salvador et al. (2016). Salvador et al. (2016) discovered that the weighted mean concentration levels of PM_{10} in Cape Verde exhibited a seasonal variation, with the lowest levels observed in spring at 37 μg/m^3, followed by summer at 41 μg/m^3, autumn at 65 μg/m^3, and the highest concentration recorded in winter at 98.0 μg/m^3.

According to a study conducted by Laid et al. (2006), the average PM_{10} concentration in Algiers was found to be higher during the winter season (74 ± 35 μg/m^3) as compared to the summer season (48 ± 21 μg/m^3). The decreased PM levels observed during the summer or wet seasons can be attributed primarily to wet deposition caused by increased precipitation, as noted by Lowenthal et al. (2014) and Saucy et al. (2018). Within a shorter time frame than the seasonal period, there is evidence of daily fluctuations in PM concentration levels that depend on time or human activities. According to Azri et al. (2009), bimodal peaks were observed in the morning (140-200 μg/m^3) and afternoon (100-140 μg/m^3) at traffic sites in Tunis, with the levels of PM_{10}

being dependent on traffic density. The study findings indicate the presence of a distinct daily pattern in the concentration of PM_{10} in Gaborone, Botswana and Ouagadougou, Burkina Faso. Specifically, the concentration of PM_{10} was observed to be higher in the morning and late afternoon or night time in Gaborone, Botswana (100 versus 10 μg/m^3) and Ouagadougou, Burkina Faso (approximately 5000 versus 120 μg/m^3), respectively (Azri et al., 2009). Nonetheless, it has been documented by Eliasson et al. (2009) that the absence of night peaks could occur in Dar es Salaam, Tanzania, due to the delayed stabilization of air.

2.4 Air quality Standards used in African cities to monitor air quality

The National Environment Management: Air Quality Act (2004) of South Africa stipulates the attainment of implementation objectives by establishing diverse standards. These standards include national and provincial ambient air quality standards, national, provincial, and local emission standards, emission standards for specific industrial activities (listed activities), emission standards for appliances and activities, such as motor vehicle emissions (controlled emitters), and standards for planning, reporting, and monitoring (Department of Environmental Affairs and Tourism, 2005). Zambia's regulatory framework encompasses a range of pollutants, including but not limited to Sulphur Dioxide, Arsenic, Cadmium, Copper, Lead, Mercury, Particulates- Smelter, and Particulates from other sources. Zimbabwe's Environmental Management Act (EMA) contains environmental quality standards for various biophysical components, such as air quality (Sections 63-68).

The publication titled "Ambient Air Quality - Limits for Common Pollutants (BOS 498:2012)" was released by the Botswana Bureau of Standards. The present Standard outlines threshold levels for prevalent atmospheric contaminants to mitigate or averter their detrimental impact on human health and the environment. The limit values for prevalent air pollutants in Botswana exhibit a favourable comparison with those of its neighbouring country, South Africa, except for the PM_{10} one-year limit value. This value is 100% higher than the South African value of 50 μg/m^3, as stipulated by the South African National Standard of 2011. Notwithstanding, it may be imperative for the Botswana authorities to contemplate reducing certain pollutants, particularly SO_2. As mentioned earlier, the viewpoint is based on the IEMA Environmental Impact Assessment conducted on the Selebi Phikwe mining region. The assessment established a connection between the atmospheric concentration of SO_2 (100 µg/m^3) and the area's reduction in plant growth and foliar damage (IEMA 2012).

The year 2007 marked the adoption of air quality standards in Tunisia, which aimed to guarantee the populace's entitlement to a healthful environment and sustainable progress (as per Law No. 2007-34 of 4 June 2007 on air quality). Daily and annual limit values for health and well-being were established per the standards set for airborne particles, specifically PM_{10} (Bouchlaghem and Nsom, 2009, 2012). The air quality standards in Tunisia establish a yearly limit value of 80 µg/m^3 concerning health. This value is twice as high as the European air quality standards for PM_{10} (40 µg/m^3) and four times higher than the air quality guidelines for PM_{10} set by the World Health Organization (20 µg/m^3) (WHO, 2006). In Tunisia, the second air quality standard daily stipulates that the concentration limit concerning health should not surpass 260 µg/m^3 more than once annually.

Nigeria has a plethora of policies and standards. The Public Health Act of 1917 initiated air quality preservation, and subsequent legislation was enacted after the nation's independence in 1960, many of which remain in effect to this day (Ladan, 2013). Environmental legislation persisted in the subsequent decades, ultimately establishing the Federal Environmental Protection Agency (FEPA) in 1988. In 1991, the institution promulgated National Air Quality Standards; however, no guidelines were established for $PM_{2.5}$, as noted by Fagbeja et al. (2008) and Aliyu and Botai (2018). According to Yakubu (2017), the Environmental Impact Assessment Act of 1992 represented a significant measure aimed at compelling industries to undertake environmental impact assessments to guarantee adherence to environmental regulations. In 1999, the Federal Ministry of the Environment took over the role previously held by the FEPA. The matter of inadequate enforcement and overall non-adherence to current regulations had emerged as a significant apprehension, given that pollution levels had already surpassed the regulations set by both FEPA and WHO at that particular juncture (Aliyu and Botai, 2018). The National Environmental Standards and Regulations Enforcement Agency (NESREA) was instituted in 2007 to enhance the implementation and enforcement of environmental regulations in Nigeria.

It operates under the purview of the Federal Ministry of the Environment, with the primary objective of ensuring the attainment of regulatory goals (Aliyu and Botai, 2018)

Furthermore, from 2009 to 2011, the NESREA released a total of 24 regulations at the national level. Among these regulations, one pertained to bushfires and open burning, while another focused on vehicle emissions. However, it is noteworthy that these two regulations address the air quality issue in Nigeria, as Schwela (2012) and the Federal Republic of Nigeria (2011) reported. In 2014, the NESREA introduced new regulations about air quality control in Nigeria (Federal Republic of Nigeria, 2011).

Installing the monitoring stations mentioned above is part of Ghana's Air Quality Management Plan, including revising National Air Quality Standards and National Motor Vehicle Emissions Standards. Before their promulgation, efforts to control air quality were concentrated on enforcing prevailing fuel quality standards and adhering to the air quality guidelines disseminated in 2000 (EPA Ghana, 2018). Since 2001, Burkina Faso has implemented active emissions standards for automobiles and mopeds to regulate air pollutants. There exist multiple ongoing initiatives to enhance urban transportation and, consequently, mitigate urban emissions and the overall air quality within the Ouagadougou metropolis (Schwela, 2012 and, Ministre de l'Environnement et du Cadre de Vie, Politique Nationale en Matière de l'Environnement, 2005).

While Abidjan, located in the Ivory Coast, is implementing a comparable endeavour in collaboration with the World Bank (Groupe de la Banque Mondiale, 2019). The CCAC has collaborated with the Ivory Coast and Ghana to mitigate short-lived climate pollutants, as evidenced by the publication of their respective action plans (CCAC. Ghana, 2018 and CCAC. Côte d'Ivoire, 2019). The absence of national standards in the Ivory Coast has led to the adopting of the World Health Organization's guidelines for PM pollutants as a benchmark for safeguarding public health. According to Schwela (2012), Guinea currently lacks official regulations and standards for managing air quality and emissions from mobile sources. There has been a dearth of urban air pollution regulatory initiatives in Liberia, although the government acknowledges the pressing necessity of establishing and advancing air quality monitoring measures (Schwela, 2012). Ivory Coast, Niger, and the Gambia nations have implemented measures to diminish the age of their vehicular inventory.

Moreover, this involves imposing limitations on importing five or older automobiles (Amegah and Agyei-Mensah, 2017). The nation of Benin currently possesses air quality standards established in 2001, but they have not yet been officially enacted. The West African country of Mali has implemented two decrees in the years 2000 and 2001, which aim to regulate pollution control and management of air pollutants.

Additionally, fuel standards have been established in the country. However, apart from the disclosure that the National Agency for Sanitation and Pollution Control intends to initiate an action plan to regulate air quality in Bamako (Schwela, 2012), no further updated or specific details have been unearthed. Insufficient data about regulations, legislation, benchmarks, or governmental interventions concerning urban air pollution was discovered for Cabo Verde, Guinea-Bissau, and Sierra Leone countries.

2.5 African cities that monitor exposure to pollutants of concern

The inclusion of air quality monitoring is an essential component within an Air Quality Management Plan (AQMP), as it furnishes decision-makers with the requisite data to facilitate informed decision-making. The monitoring process is of utmost importance in addressing concerns about the magnitude of emissions that require reduction, identifying areas that necessitate control measures, and evaluating the effectiveness of previous management interventions (Pant and Harrison 2012, Pant et al. 2015, and Khare and Khanna 2016). The practical implementation of an Air Quality Management Plan (AQMP) requires monitoring data from a comprehensive, integrated network for tracking data derived from an extensive, integrated network for air quality monitoring (AQMN). An integrated network for monitoring air quality, known as an air quality monitoring network (AQMN), encompasses a range of monitoring techniques.

These techniques include conventional manual methods and stations that provide continuous real-time monitoring and employ sensors (Kumar et al., 2015; Kumar et al., 2015; Moltchanov et al., 2015). Implementing an Air Quality Monitoring Network (AQMN) in Low- and Middle-Income Countries (LMICs) may involve integrating multiple monitoring strategies, considering the financial limitations typically encountered in these regions. This approach aims to maintain the required quality standards throughout the monitoring process. Hence, adopting inexpensive sensors may be better suited for countries with lower economic status, as multiple research studies indicate (Kumar et al., 2015; Kumar et al., 2015; Moltchanov et al., 2015).

Air quality surveillance holds great importance in detecting health risks, formulating economically feasible pollution mitigation strategies, establishing and enforcing appropriate air quality policies, and advancing urban planning that prioritizes the public's well-being (Madonsela et al., 2022). Unfortunately, Schwela (2006) has indicated that only a few African cities have successfully implemented air monitoring systems, with the majority lacking any capacity for monitoring air quality.

The limited accessibility and distribution of data frequently restricts the public's ability to obtain information, consequently impeding the formulation of effective policies. Hence, the challenge is intricate and encompasses various facets requiring careful examination. The lack of air monitoring data hinders the implementation of air quality regulations in different African nations (Schwela, 2006). As per Schwela's (2006) report published by the World Bank, a mere 5 out of the 27 sub-Saharan African nations examined, namely Ethiopia, Ghana, Madagascar, Tanzania, and Zimbabwe, were found to be engaged in the monitoring of PM_{10} or TSP as of 2006. Monitoring activities may have been terminated in certain countries after that time. The World Health Organization (WHO) has published a global database on outdoor air pollution in various cities. In 2013, the WHO studied particulate matter in nine sub-Saharan African countries: Algeria, Botswana, Ghana, Madagascar, Mauritius, Nigeria, Senegal, South Africa, and Tanzania. The countries of Ethiopia and Zimbabwe, as referenced in the report published by the World Bank, were not incorporated into the present database.

Furthermore, surveillance activities in no fewer than four sub-Saharan African nations identified by the World Health Organization were conducted for less than 12 months per annum. Air monitoring is regularly performed in both Egypt and Tunisia. PM monitoring data reports have been published by the governments of seven countries, namely Algeria, Botswana, Egypt, Madagascar, Mauritius, Senegal, South Africa, and Tunisia, as documented by the World Health Organization in 2013. Specific programs and initiatives to improve air quality have recently been discontinued in sub-Saharan Africa. The Regional Air Pollution in Developing Countries and Air Pollution Information Network for Africa, financially supported by the Swedish International

Development Cooperation Agency, were terminated in 2009, as communicated by Schwela D. on May 24, 2011.

2.6 Conclusion

Numerous nations currently document pollutant concentration levels within African regions, primarily focusing on urban areas. The literature review has identified countries facing elevated levels of pollutants, including NO_2, SO_2, and PM_{10}, surpassing the standards set by the World Health Organization (WHO). In addition, the cost of air quality monitoring tools is prohibitively high, rendering it unfeasible for economically disadvantaged African nations to establish their monitoring stations. The extant body of research on air quality is constrained in scope. Yet, the available data suggests that pollution levels exhibit a discernible elevation in areas characterized by industrial, traffic, and commercial activities compared to reference locations.

Moreover, this implies that vehicular traffic and industrial emissions largely influence air pollution, especially in urban regions. Furthermore, it was found that a proportion of towns, precisely none and 12%, exhibited annual and 24-hour mean PM_{10} concentrations that were lower than the corresponding World Health Organization (WHO) Air Quality Guidelines (AQG). A study revealed that a minority, precisely one-third, of the towns examined exhibited increased nitrogen dioxide (NO2) concentrations exceeding 40 μg/m^3 and sulphur dioxide (SO_2) levels below 20 μg/m^3. These elevated levels were observed in towns impacted by traffic and industrial activities. The concentrations of air pollutants display seasonal fluctuations due to changes in meteorological patterns and human activities influenced by the seasons. The levels of ambient pollutants are lower during the wet season compared to the dry season due to the frequent precipitation and increased wind patterns. During periods of intense rain, there is a decrease in the amount of rainfall, accompanied by higher levels of irradiation and temperature.

Additionally, there is an upsurge in biomass burning caused by wildfires and agricultural activities. Insufficient vertical mixing due to inversions led to increased levels of pollutants in the atmosphere during the winter, as opposed to the higher temperatures experienced in the summer months. It is essential to highlight that the exceedance of the relevant Air Quality Guidelines set by the World Health

Organization was not confined to any particular season or period. However, the degree of the excess was more prominent during the dry and winter seasons. The diurnal variation of pollutants demonstrates a bimodal pattern during increased human activity, specifically in the morning and evening.

Several African countries, including South Africa, actively monitor air quality and have established air quality standards to ensure adherence. In contrast, certain countries either lack such standards or fail to enforce compliance effectively. While air quality legislation has been established in other African countries, their implementation is still pending. Addressing the issue of air pollution poses a significant challenge due to the inherent difficulty in its reduction.

CHAPTER 3: RESEARCH DESIGN AND METHODOLOGY

3.1 Preamble

The main aim of this chapter is to discuss the research methods used in the current study to assess air quality compliance in the City of Tshwane Metropolitan Municipality. The adopted methodologies in the present study were instrumental in achieving the objectives of this research. Moreover, this section further details the description of research design, data collection, and data analysis.

A research methodology is a systematic strategy used to explore a research problem. This technique offers a direction to the data involved in a research problem and a realistic approach to gathering, analysing, and interpreting that data (Leedy & Ormorod, 2005; 2009; Wodak & Meyers, 2009).

3.2 Research Design

The research design is the conceptual framework within which the research is carried out. This research involves a quantitative research method consisting of data collection and analysis. This study aims to assess the concentrations of the air quality parameters (NO_2, PM_{10}, and SO_2) in the City of Tshwane Metropolitan Municipality. The Municipality needs to know the levels of air quality parameters within its jurisdiction so that:

1) When the levels are too high compared to the national ambient air quality standards, air quality management can be improved.
2) The management strategy can be maintained when the levels are within the required limit values compared to the national ambient air quality standards.

The nature of the research that was carried out was quantitative, because the goal of the study was to analyse the combined levels of three pollutants (SO_2, NO_2, and PM_{10}) in relation to the long-term annual limit values specified by the National Air Quality Standards, and observe the seasonal and spatial variations of pollutants.

Secondary data on air quality for Nitrogen dioxide, Particulate matter and Sulphur dioxide from SAAQS for a period between 2016 to 2020 are used during the present study.

3.3 **Location of the study area**

Located in the Gauteng Province, the City of Tshwane (CoT) is the administrative capital of South Africa and serves as the country's financial and commercial hub. It is the biggest of the three metropolitan regions in the province, with a land area of 6 345 km^2, making it the third-largest city in the world in terms of land mass. It is the largest of the three metropolitan regions in the province (CoT IDP, 2014). Tshwane has an average yearly rainfall of around 670 mm. Summer (December to February – DJF) has the most rain, whereas winters (July to August – JJA) are pretty dry. The rainy season typically begins in October and ends in April. Summers are hot, with an average temperature of around 22 degrees Celsius, while winters are pleasant, with an average temperature of approximately 12 degrees Celsius. Washington and Todd (1999) say that the days are sunny, the skies are clear, and the nights are cool, though the lowest temperatures may sometimes drop below freezing.

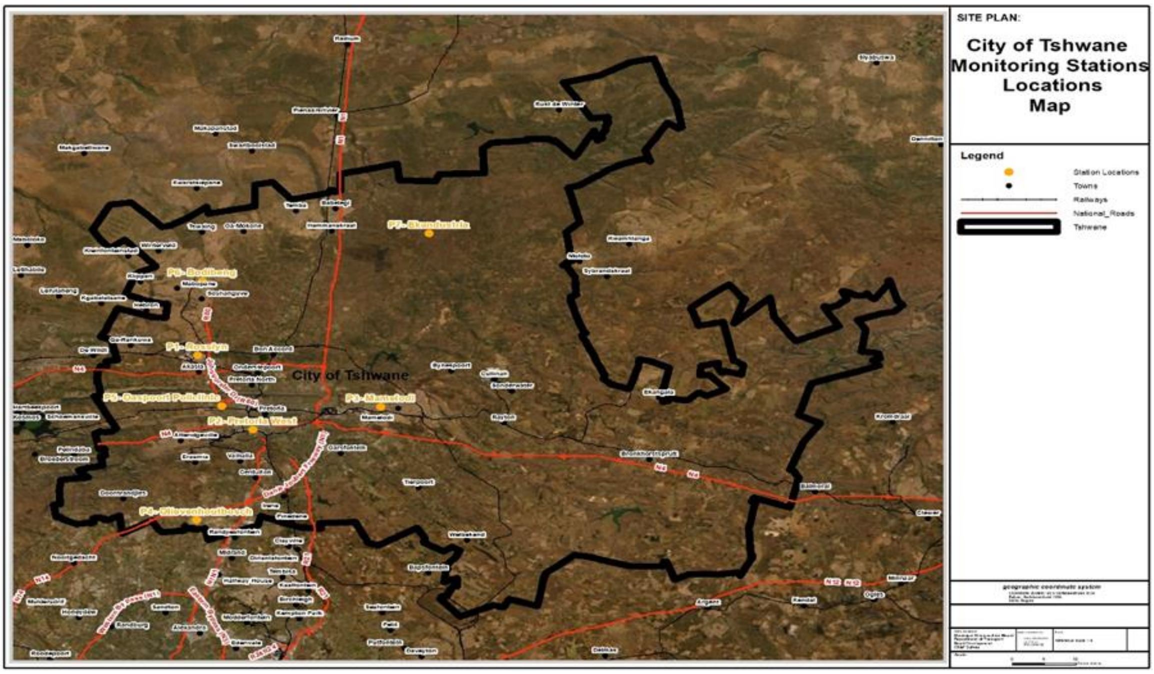

Figure 1: Location of the study area

The City of Tshwane Metropolitan Municipality established an ambient air monitoring network comprising seven (7) permanent stations and one (1) mobile station. These stations are at Rosslyn, Pretoria West, Mamelodi, Booysens, Olievenhoutbosch, Bodibeng, Tshwane Mobile and Ekandustria. The air quality monitoring stations are strategically located to detect changes in ambient air quality caused by industrial, transportation, and residential activity. They help determine if ambient air quality standards are being met in certain places and if the air quality has changed.

3.4 Sampling Methodology

The present study assessed the NO_2, SO_2 and PM_{10} parameters in the City of Tshwane Metropolitan Municipality from 2016 to 2020. The study aims to assess the seven existing monitoring stations which are found in the City of Tshwane, therefore data for all monitoring stations will be used. All existing air quality monitoring stations in the City of Tshwane were selected for this study.

The assessment of NO_2, PM_{10}, and SO_2 concentrations, as well as the variability of pollutants, was carried out with the assistance of secondary air quality data from all the monitoring stations in the City of Tshwane. These data (NO2, PM10, and SO2 concentrations) were obtained from the South African Air Quality Information Systems and covered the period from 2016 to 2020. In order to determine the average concentrations, the data was computed using Microsoft Excel. On the basis of graphs and tables, a comparison was made between the average concentrations of NO_2, PM_{10}, and SO_2 that were measured at each station in the research area.

Therefore, to ascertain the seasonal variation in concentrations of NO_2, PM_{10}, and SO_2, a whisker box plot was created using Microsoft Excel for both the summer and winter seasons.

The bar graphs and tables that were developed were utilised to compare the NO_2, PM_{10}, and SO_2 concentrations present in the City of Tshwane Metropolitan Municipality.

3.5 **Data sources**

In this study, the researcher looked at data on an annual rate and averaged it (for 2016 - 2020) because SO_2, NO_2, and PM_{10} are the most common pollutants and the parameters of concern. Secondary data were requested from the South African Air Quality Information System (SAAQIS) for all the accessible ambient air monitoring network stations. These requests were made because SO_2, NO_2, and PM_{10} are the most prevalent pollutants.

The ambient air monitoring network built by the City of Tshwane now consists of seven (7) fixed stations and one (1) mobile station. The monitoring stations may be Rosslyn, Pretoria West, Mamelodi, Booysens, Olievenhoutbosch, and Bodibeng. Ekandustria is also one of the locations of the stations. (Figure 1). These monitoring stations are located strategically to monitor the impacts of industrial, traffic, and residential activities on the ambient air quality. In addition, this is done to assess compliance with the national standards for ambient air quality and to determine if there are any changes in the state of the air at those sites. Although each monitoring station can track and record all criterion pollutants, this study's scope is limited to sulphur dioxide, nitrogen dioxide, and particulate matter with an aerodynamic diameter of more than 10 millimetres (PM_{10}). The selected stations have sufficiently recovered data (more than one year's worth of data has been retrieved), allowing them to offer annual readings of SO_2, NO_2, and PM_{10}.

South Africa's Air Quality Information System presently receives data managed by the city's Enviman/Opsis and Envidas systems (SAAQIS). The data's original collectors used a NOX Analyzer (Model T200; S/N: 1624), and a Fluorescence SO_2 Analyzer (Model 100E; S/N: 2891), to measure the levels of these gases in the air. The operational methods for the samplers are described in their respective operational manuals (Ecotech – Environmental Monitoring Solutions, 2001; T300, n.d., 2017; T100, n.d., 2017; and T200, n.d., 2017). Furthermore, the data collected by these sensors is invaluable for assessing the quality of the air throughout the Republic.

3.6 **Data collection**

The secondary data on air quality for the study were obtained in South African Air Qualty Information System which conducts exposure assement in line with or in accordance with the rules provided by the Department of Environmental Affairs. The study utilized air quality data collected from seven distinct monitoring locations within the City of Tshwane Metropolitan Municipality. The data collection encompassed the time period from 2016 to 2020. The dataset comprises annual mean concentrations of particulate matter, nitrogen dioxide, and sulphur dioxide. The raw datasets were obtained in the format of an Excel file. The data underwent conversion into graphical and tabular formats, followed by statistical analysis.

3.7 **Statistical analysis**

The data was summed up in a meaningful form using descriptive statistics such as the mean, the standard deviation, and percentages. Furthermore, this allowed for the annual trends of the pollutants in the study area to become apparent.The data were analysed using Microsoft Excel and SPSS 27.0 statistical software. The research utilised descriptive statistics and t-tests to evaluate the changes in air quality measurements. Ultimately, the pollutant concentrations from the monitoring stations were compared with South Africa's National Ambient Air Quality Standards to ascertain whether they were per the city's and the NAAQS's overall air quality limitations.

3.8 **Conclusion**

This chapter discussed the research methods used in a study on air quality compliance in the City of Tshwane Metropolitan Municipality. The adopted methodologies were effective in achieving the research objectives. The chapter also provides a detailed description of the research design, data collection, and data analysis.

Furthermore, the research design for this study is quantitative, and it aims to assess the concentrations of air quality parameters in the City of Tshwane Metropolitan

Municipality. The study used secondary data from 2016 to 2020 to analyze the levels of pollutants and their compliance with national ambient air quality standards. The findings of this research will inform air quality management strategies and actions within the municipality.

Moreover, the study aimed to assess the levels of NO_2, SO_2, and PM_{10} in the City of Tshwane Metropolitan Municipality from 2016 to 2020. Data from all seven existing monitoring stations in the city were used for the study.

In addition, the researcher conducted a study using data from the South African Air Quality Information System to analyze the levels of SO_2, NO_2, and PM_{10} pollutants in the ambient air. The study focused on the monitoring stations in the City of Tshwane, which consist of seven fixed stations and one mobile station strategically located to assess the impact of industrial, traffic, and residential activities on air quality. The study's scope was limited to the three pollutants mentioned, and the selected stations provided sufficient data for annual readings.

Furthermore, the study utilized secondary data on air quality collected from seven monitoring locations in the City of Tshwane Metropolitan Municipality in South Africa. The data, obtained included annual mean concentrations of particulate matter, nitrogen dioxide, and sulphur dioxide. The data was converted into graphical and tabular formats and underwent statistical analysis.

Finally, the data analysis using descriptive statistics and statistical software revealed annual trends in pollutant concentrations in the study area. The comparison with the National Ambient Air Quality Standards helped determine if the air quality met the city's and national standards.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the comprehensive results and discussion of the findings on the assessment of air quality compliance in the City of Tshwane. The results are displayed for each criterion pollutant in the form of a whisker box plot and bar graphs to demonstrate the behaviour of the pollutants in the City of Tshwane. In addition, this is necessary as the investigation primarily examined the spatiotemporal exposure levels of all contaminants included in the current study. Furthermore, a comprehensive analysis was undertaken to investigate the seasonal variations and ascertain the specific timeframe of heightened pollution levels. Lastly, the study aimed to assess the degree of adherence to the National Ambient Air Quality Standards (NAAQS). All this was undertaken to achieve the objectives of the current research study.

4.2 The spatiotemporal exposure levels

4.2.1 Spatiotemporal exposure levels of NO_2

The diagram depicted in Figure 2 provides a visual representation of the various levels of NO_2 concentration observed at the designated air quality monitoring stations located within the City of Tshwane Metropolitan Municipality. The data presented in the figure spans the period from 2016 to 2020. In 2016, the monitoring station located in Booysens observed increased amounts of NO_2, reaching approximately 60.03 $\mu g/m^3$. Similar heightened concentrations in Rosslyn were recorded in the same year, reaching 43.35 $\mu g/m^3$. In addition, elevated levels of NO_2 were documented in Mamelodi at a concentration of 39.17 $\mu g/m^3$ and finally in Pretoria West at a value of 54.05 $\mu g/m^3$ during the year 2018. Furthermore, it was noted that there were heightened levels of NO_2 concentrations in the areas of Mamelodi, measuring 50.9 $\mu g/m^3$, and Pretoria West, measuring 80.75 $\mu g/m^3$, during the year 2019. In 2020, heightened amounts of pollutants were detected in Booysens, measuring 51.37 $\mu g/m^3$, and in Ekandustria, measuring 39.79 $\mu g/m^3$. Elevated levels of NO_2 have been documented in regions characterized by industrial zones, namely Rosslyn, Pretoria West, Mamelodi, and Booysens. Hence, industrial emissions play a significant role in the elevation of NO_2 exposure concentrations. This study resembles the research conducted in Abidjan, Côte d'Ivoire, where elevated levels of NO_2 were quantified across three industrial locations (Bahino et al., 2018).

Consistent data loss was documented at the following stations: Olievenhoutbosch in 2017, 2018, 2019, and 2020; Mamelodi in 2016 and 2017; Rosslyn in 2018 and 2020; and Pretoria West in 2016. This phenomenon is associated with the absence of data as a result of dysfunctional monitoring stations, as highlighted by Madonsela (2019), Madonsela et al. (2023), and Ndletyana et al. (2023).

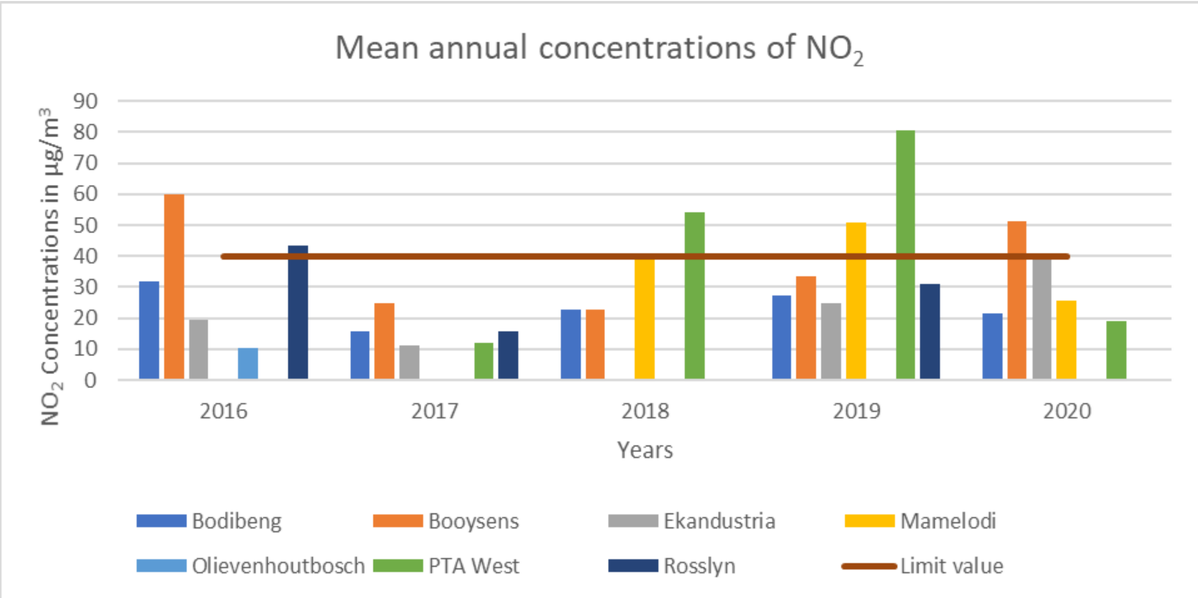

Figure 2: Mean annual concentrations of NO_2 in the City of Tshwane study areas from 2016 and 2020.

4.2.2 **Spatiotemporal exposure levels of SO_2**

The present study examined the average yearly concentration of SO_2 across all monitoring sites within the City of Tshwane Metropolitan Municipality. Based on the information depicted in Figure 3, it can be observed that the monitoring stations exhibit fluctuations in the levels of SO_2 concentrations, both in terms of spatial and temporal distribution. In 2018, the monitoring station located in Pretoria West observed elevated exposure concentrations of SO_2, reaching 22.33 μg/m^3. Furthermore, in the year 2019, there were observed excessive levels of SO_2 of 46.06 μg/m^3 at Booysens. In a similar trend during 2020, an increased level of SO_2 concentration was found, specifically at 163.76 μg/m^3, as documented at the Booysens monitoring station.

The yearly mean readings exhibit a progressive upward trend at the Booysens monitoring station, commencing with 7.34 μg/m^3 in 2016 and escalating to 163.76 μg/m^3 in 2020. The Booysens monitoring station is situated inside a mixed-use area encompassing industrial and residential zones, including an informal settlement. The implementation of lockdown measures significantly impacted the operating capacity of industries in South Africa in 2020. However, this did not affect the elevated concentration levels of SO_2 at the Booysens monitoring station. Nevertheless, it is worth noting that biomass burning originating from residential areas may have emerged as a prominent source of exposure to SO_2 concentration.

Consequently, emissions may have originated from the informal settlement. Due to the absence of power connections in their households, most individuals depend on the combustion of coal, wood, and tires for cooking and heating purposes. Notably, this practice commonly occurs in open areas, particularly during winter. Given the information mentioned above, it is worth noting that residential fuel sources, namely coal, wood, and paraffin, are used for cooking and heating in lower-class households and informal settlements in South Africa (Koppman et al., 2011; madonsela , 2023). This reliance on such fuel sources can be attributed to the absence of more affordable or alternative options.

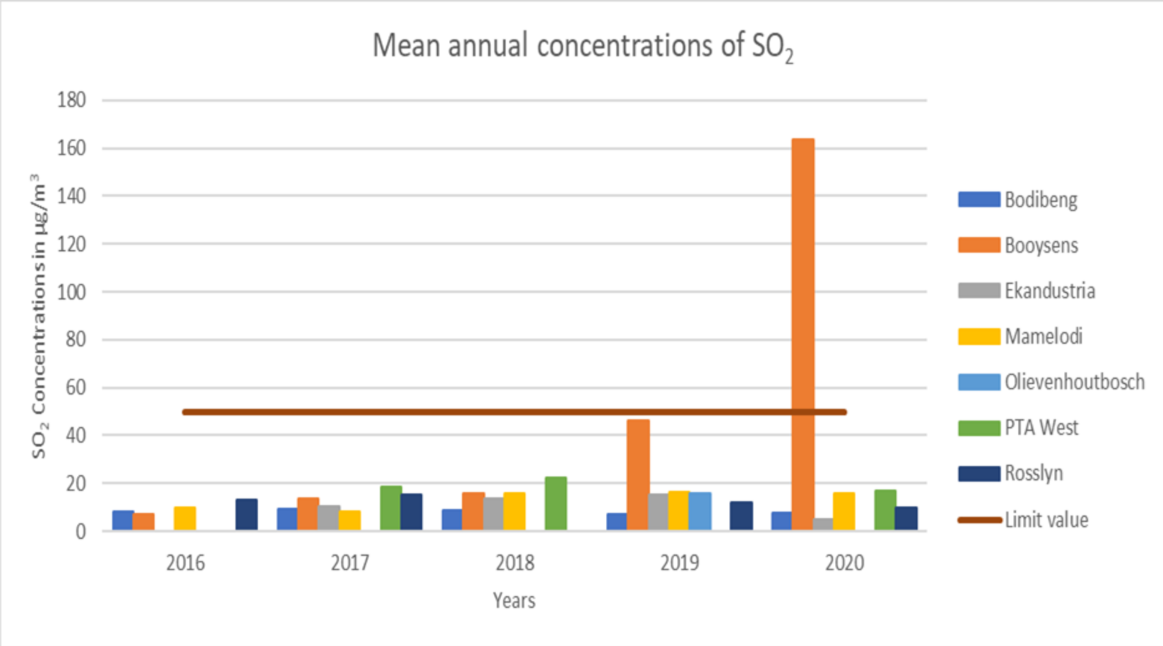

Figure 3: Mean annual concentrations of SO_2 in the study area from 2016 to 2020.

4.2.3 **Spatiotemporal exposure levels of PM_{10}**

When we consider the spatial characteristics of air pollution in cities, we may better understand how air pollution affects the city as a whole. Additionally, assistance should be provided in locating the origins of urban air pollution and formulating policies that can effectively mitigate the effects of air pollution. Based on the findings presented in Figure 4, it was noted that Bodibeng had notably higher concentrations of PM_{10}, with levels reaching as high as 49.21 µg/m^3 during the year 2016. Moreover, heightened concentrations were documented in the Bodibeng region, with a recorded value of 62.55 µg/m^3 in 2017. Similarly, in 2017, it was reported that Booysens had elevated PM_{10} levels of 61.99 µg/m^3. Furthermore, in 2017, Rosslyn exhibited notably high levels of PM_{10}, with concentrations reaching 500.58 µg/m^3. Additionally, it is worth noting that Bodibeng had a notable increase in PM_{10} concentrations, reaching a 78.18 µg/m3 level in 2018. Similarly, Booysens exhibited elevated levels of PM_{10}, with concentrations reaching 36.54 µg/m^3 in the year 2018. Moreover, it is worth stating that in 2018, Mamelodi saw increased levels of PM_{10}, with concentrations reaching as high as 67.37 µg/m^3. In 2019, Booysens exhibited elevated levels of PM_{10}, with concentrations reaching 60.31 µg/m^3. In contrast to Booysens, Olievenhoutbosch showed higher levels of PM_{10} concentration, reaching 124.2 μg/m^3 over the season of 2019. Furthermore, Rosslyn had a notable increase in PM_{10} concentration levels, reaching 54.61 μg/m^3 in the year 2019. Additionally, an examination conducted on the levels of PM_{10} concentration in Mamelodi, revealed concentration of 206.63 μg/m^3 in 2020. In conclusion, it is fundamental to indicate that the measured concentrations of PM_{10} in Rosslyn were 39.76 μg/m^3.

According to WHO (2022) the sources of air pollution in African cities include industrial sources, emissions from dwellings, and vehicles, amongst other things. Similarly, the City of Tshwane is one of the capital cities of South Africa; therefore, it is regarded as the economic hub where there is a lot of traffic to and from the city. As a result, a high concentration of PM_{10} might be emanating from the increased traffic volume of cars. This observation is similar to the discoveries recorded by Ndletyana et al. (2023), where it was discovered that elevated concentrations of PM_{10} were found close to national highways and traffic intersections in the Central Business District in Cape Town.

Among other factors, one of the primary contributors to air pollution is the rise in car ownership and individual utilization for transportation purposes within African cities and metropolitan regions. This method conveniently facilitates the production of intricate combinations of air contaminants that adversely affect human health. More precisely, they affect the emission of harmful particulate matter (PM) and nitrogen dioxide (NO_2) levels. Regrettably, it has been established in previous studies that both pollutants are linked to an escalation in the prevalence of illness and the worsening of pre-existing health disorders (Bowe et al., 2017; Strak et al., 2021). Therefore, given the greater risk of the burden of disease associated with these pollutants, their epidemiological effects monitoring is of paramount importance for the vulnerable population of Sub-Saharan Africa. These would provide the relevant data that is fundamentally needed to inform air quality management policy and, in the process, minimize the extrapolation of epidemiological effects data that disregards the social vulnerability.

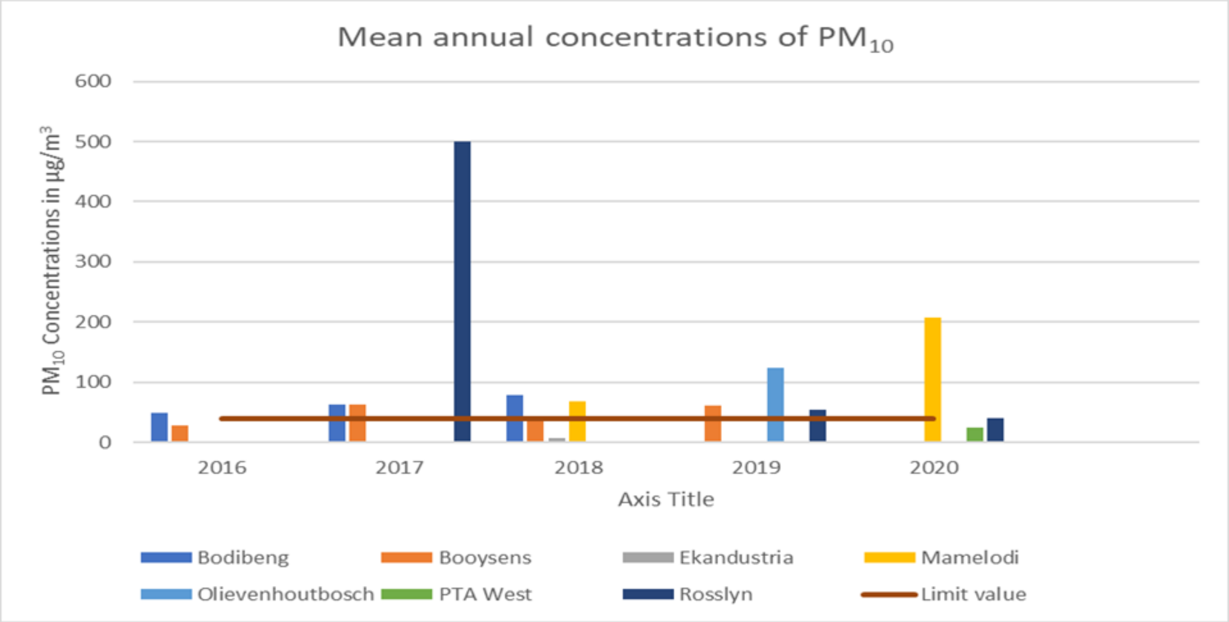

Figure 4: Mean annual concentration of PM_{10} from 2016 to 2020.

4.3 **Seasonal exposure variation in the study areas of Tshwane**

The concentration of pollution in the lower atmosphere has historically been influenced by seasonality (WHO, 2000). Safeguarding the well-being of community members, particularly children, from the adverse health consequences of air pollution constitutes a paramount objective within environmental health research and initiatives. Hence, it is imperative to underscore the correlation between air quality and seasonality to effectively monitor pollution patterns and proactively address health concerns associated with seasonal variations in pollutant levels. The study examined two seasons, specifically Summer and Winter. All the stations included in this study were analysed from 2016 to 2020.

4.3.1 **Seasonal exposure variation of NO_2 in all the stations**

Figure 5 below illustrates distinct seasonal variation patterns, wherein the highest pollution levels are recorded during the winter months, while the lowest levels are observed during the summer months at all the monitoring stations in the study. The box and whisker plots depict the fluctuations in pollutant exposure levels among several stations, emphasizing the discrepancies observed throughout different seasons as emphasised by Madonsela et al. (2024). The findings suggest a seasonal change in the levels of NO_2 across all the monitoring stations from 2016 to 2020. According to the data presented in Figure 5, the concentrations of Ekandustria varied between 12.85 and 40.85 μg/m^3 throughout the summer. In contrast, during the winter season, the concentrations ranged between 37.42 and 87.22 μg/m^3 throughout the years.

Moreover, in contrast to Ekandustria, the Mamelodi monitoring station observed NO_2 values ranged between 21.44 and 31.91 μg/m^3 during non-winter months; however, during winter, the concentration levels ranged between 52.31 and 75.41 μg/m^3. In addition, Bodibeng observed nitrogen dioxide concentrations that varied from 19.71 to 21.96 μg/m^3 during the summer season, while on the other hand, during the winter season, a sharp curve of pollutant concentrations increased by twofold, ranging from 44.7 to 55.78 μg/m^3. Furthermore, the concentrations of NO_2 observed in Pretoria West exhibited a range of 38.35 to 52.92 μg/m^3 during the summer season; however, during the winter season, the range increased and was recorded to be between 57.85 and 195.02 μg/m^3. In conclusion, the NO_2 concentrations exposure levels in Booysens varied between 18.25 and 24.35 μg/m^3 during the summer, whereas during winter, the concentrations ranged from 34.93 to 59.77 μg/m^3. The concentrations of NO_2 demonstrate a gradual rise from the summer to the winter within the designated study region. During the winter, there was a noticeable increase in pollution levels for NO_2. This study's results resemble prior research carried out in the core business centre of Cape Town. The study conducted by Ndletyana et al. (2023) found a significant rise in NO_2 levels in the winter, whereas conversely, lower concentrations were detected during the summer months. This observation demonstrates that the transition between seasons significantly impacts the rise in air pollution levels. The heightened levels of exposure that have been recorded are likely to be affected by the land-use practices that are now prevalent. Multiple factors contribute to the occurrence of air pollution, including the burning of wood and biomass as well as the release of pollutants from motor operations, particularly in the monitoring stations of Booysens and PTA West. These regions are notable for their industrial presence and informal settlements, further exacerbating the problem. The studies by Bouchlaghem and Nsom (2012), Laakso et al. (2012), Mentz et al. (2018), and Muttoo et al. (2018) found that elevated

NO_2 concentrations during the winter season can be attributed to higher heating demands, decreased photochemical activities, and reduced atmospheric mixing. Furthermore, the levels of NO_2 throughout both the summer and winter seasons are subject to substantial effects from an intensified oxidation process. This process involves decreased photochemical interactions between NO_2 and hydroxyl (OH) radicals, forming nitric acid (HNO_3). Several ambient air quality monitoring studies have also observed this pattern (Nguyen et al., 2006; Al Katheeri et al., 2012).

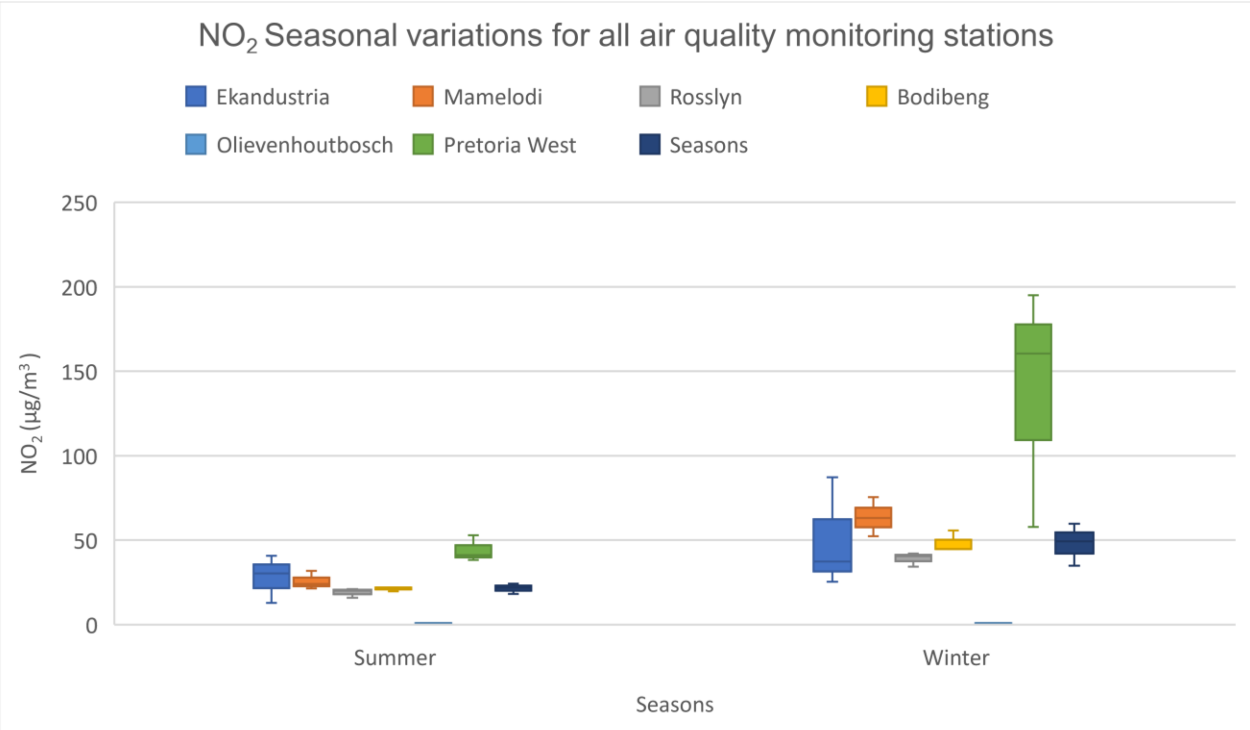

Figure 5: Mean annual concentration of NO_2 during summer and winter months in the study areas of Tshwane.

4.3.2 **Seasonal exposure variation of SO_2 in all the stations**

The seasonal variation of SO_2 concentrations in the City of Tshwane's seven monitoring sites throughout 2016 to 2020 is depicted in Figure 6. The Box and Whisker plots illustrate the variations in pollutant exposure levels across different stations, highlighting the seasonal disparities. Based on the data provided, it can be observed that the summer SO_2 concentrations recorded at the Ekandustria monitoring station exhibited a range of values between 8.69 and 9.01 µg/m^3. Conversely, throughout the winter season, the SO_2 concentrations varied within a broader range, specifically between 12.99 and 23.35 μg/m^3. Additionally, Mamelodi observed SO_2 levels that varied between 10.43 and 19.34 μg/m^3 during the summer season and between 17.8 and 23.43 μg/m^3 in winter. This observation implies a fluctuation in concentrations, which was impacted by seasonal changes in the places. Similarly, Rosslyn observed SO_2 concentrations within the range of 11.46 to 15.7 μg/m^3 throughout the summer. Conversely, a slight variation was noted during winter, with SO_2 concentrations ranging from 14.88 to 21.35 μg/m^3. Furthermore, Bodibeng documented the concentration values that exhibited a range of 8.94 to 11.7 μg/m^3 during the summer season. However, in the winter season, the concentrations of SO_2 ranged from 10.44 to 22.33 μg/m^3. Similarly, the Pretoria West station documented SO_2 concentrations ranging from 32.16 to 41.29 μg/m^3 during summer. In contrast, the quantities observed during winter varied between 42.11 and 70.15 μg/m^3.

In conclusion, the concentrations of SO_2 exhibited a range of (17.35 to 89.89 μg/m^3) during the summer, but the corresponding values were (22.57 and 43.16 μg/m^3) in the winter season. The findings suggest a discernible variation in the concentration of SO_2 within the study area due to seasonal fluctuations. The results are similar to that of Laakso et al. (2012) study that revealed seasonal fluctuations in the concentration of SO_2. Furthermore, this finding aligns with the research conducted by Zou et al. (2011), which observed that the average yearly concentrations of SO_2 during winter were more significant compared to the lower levels of SO_2 concentrations observed during summer. In line with Elminir's (2007) research findings, it can be noticed that the mean concentration of SO_2 in Egypt displays a seasonal fluctuation, with elevated levels recorded during the winter season in contrast to the summer season. Furthermore, this is similar to the current study. Specifically, high levels of SO_2 are often recorded during seasons characterized by reduced rainfall and limited air circulation induced by inversion (Laakso et al., 2012).

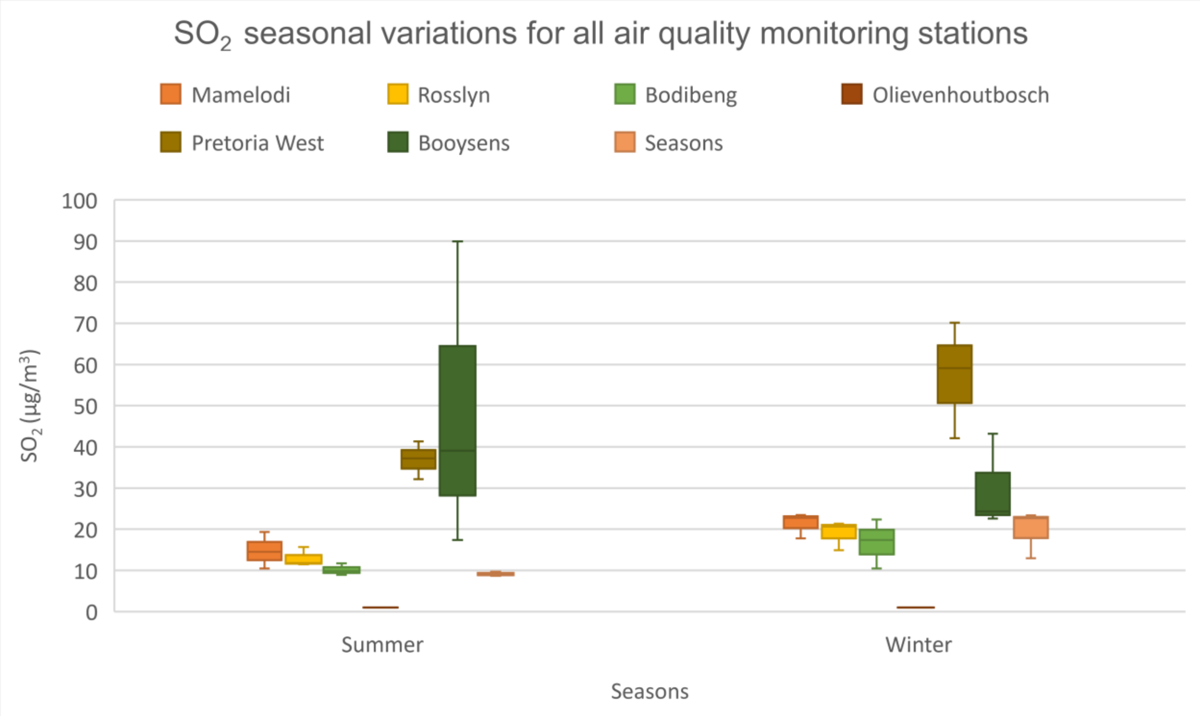

Figure 6: Mean seasonal concentrations of SO_2 for all the monitoring stations in the study.

4.3.3 **Seasonal exposure variation of PM_{10} in all the stations**

Figure 7 depicts the mean seasonal levels of PM particulate matter ascertained during the summer and winter seasons. Box and Whisker plots visually represent the range and distribution of pollutant exposure data across different seasons. These differences were shown to exist across several other locations. According to the results depicted in Figure, Booysens exhibited PM_{10} concentration levels ranging from 39.53 to 49.91 µg/m^3 during the summer season. Conversely, these levels increased to 80.27 to 85.53 µg/m3 during the winter season. In a similar trend, the Mamelodi monitoring station documented a range of 1 to 90.74 µg/m^3 for PM_{10} concentrations throughout the summer season. However, during winter, the recorded PM_{10} concentrations varied between 63.30 and 68.49 µg/m^3. Furthermore, Rosslyn observed levels of PM_{10} concentrations ranging between 25.49 to 28.38 µg/m^3 during the summer season, and during the winter season, the range increased to 59.02 and 66.14 µg/m^3. Additionally, it was observed that the concentration level at Bodibeng was within the range of 44.22 to 51.06 µg/m^3 during the summer season, whereas in winter, the PM_{10} concentrations varied from 93.70 to 101.67 µg/m^3. Similarly, Olievenhoutbosch recorded PM_{10}

concentration levels ranging between 1 and 31.96 μg/m^3 during summer and 94.13 and 111.65 μg/m^3 during winter. Consistently, PM_{10} concentration levels in summer ranged between 1 and 21.11 μg/m^3, while it was found to be between 54.75 and 64.81 μg/m^3 during winter. The findings of this investigation are consistent with a previous study conducted in Rome, where it was observed that the PM_{10} concentrations were significantly greater during the cold season compared to the warmer season (Bodor et al., 2020). In contrast, the findings of Bodor et al. (2020) substantiated the pronounced seasonal patterns of PM_{10}, with peak concentrations occurring during the winter months and the lowest levels observed during the summer. Moreover, the results align with the assertions made by Laid et al. (2006) that the mean PM_{10} levels in Algiers exhibited a higher value during the winter period (74 ± 35 μg/m^3) in comparison to the summer period (48 ± 21 μg/m^3). Furthermore, this finding aligns with the research conducted by Moja (2019) in the City of Tshwane, which observed elevated levels of PM_{10} during the winter season and decreased levels during the summer season.

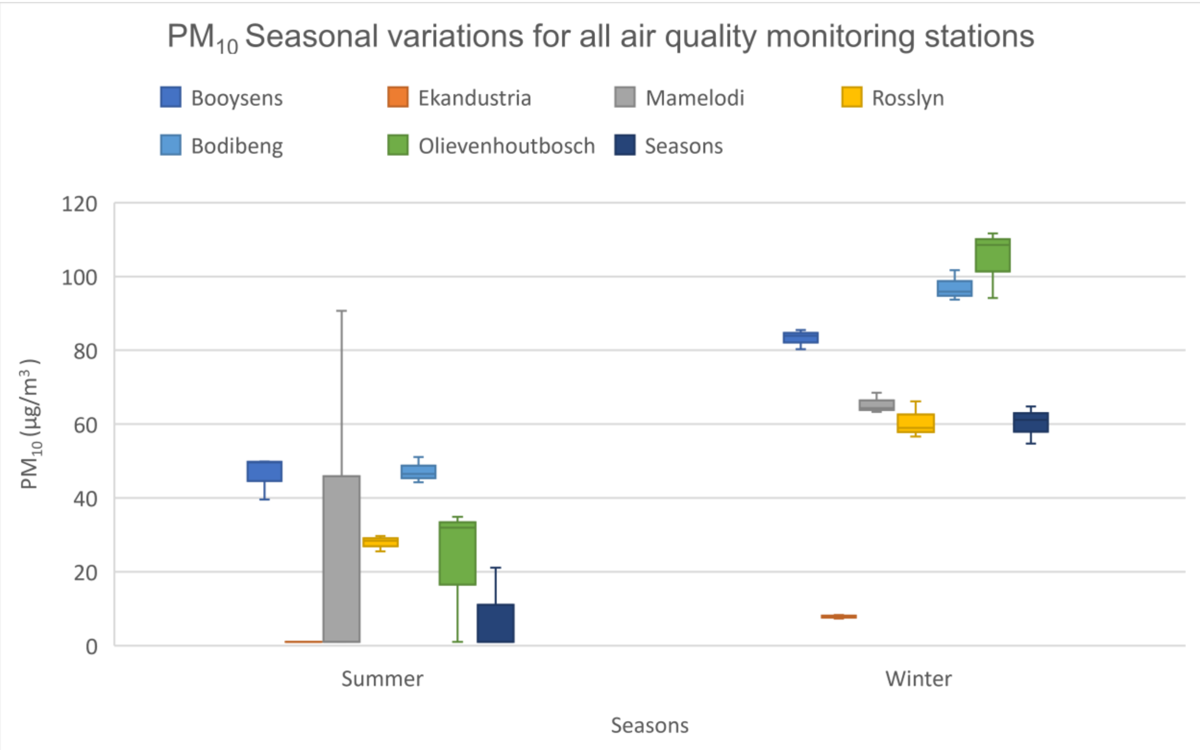

Figure 7: Mean seasonal concentrations of PM_{10} for all stations.

4.3.4 Independent-sample t-test comparing seasons

The independent-sample t-test is a tool used to test whether there are significant differences in the mean scores on the dependent variable (continuous variables) for two seasons (Summer and winter). The independent-sample t-test, comparing seasons for created continuous variables, is summarized in Table 4.1.

Table 4.1: independent-samples t-test comparing seasons

	N	Mean	Std. Deviation	Std. Error Mean
SO_2				
Summer	42393	6.3749	17.38964	0.08446
Winter	38881	7.9366	12.72367	0.06453
NO_2				
Summer	33344	10.6709	12.65260	0.06929
Winter	32354	25.8248	36.20045	0.20126
PM_{10}				
Summer	17124	43.8076	77.48116	0.59210
Winter	24466	77.7849	95.52787	0.61073

Table 4.1 shows each group's mean and standard deviation (summer/winter). It also shows the number of air quality data in each group (N).

Table 4.2: Independent-samples t-test seasonal variations

	Levene's Test for Equality of Variances		t-test for Equality of Means			
Independent t-test	F	Sig.	T	Df	p-value	Mean Difference
SO_2						
Equal variances assumed	49.916	<,001	-14.503	81272	<,001	-1.56174
Equal variances are not assumed.			-14.694	77525.036	<,001	-1.56174
NO_2						
Equal variances assumed	5144.598	0.000	-72.039	65696	0.000	-15.15389
Equal variances are not assumed.			-71.195	39933.000	0.000	-15.15389
PM_{10}						
Equal variances assumed	827.096	<,001	-38.514	41588	0.000	-33.97735
Equal variances are not assumed.			-39.944	40697.848	0.000	-33.97735

Table 4.2 above shows a significant difference between the means of SO_2, NO_2 and SO_2 for the two independent groups (season).

Levene's test for homogeneity of variances was employed to examine whether there is an equal amount of variation in scores between the two independent groups, namely summer and winter. The determination of the t-value to employ is based on the outcome of Levene's test. If the p-values obtained from Levene's test are greater than 0.05, it can be concluded that the homogeneity of variance assumptions were not violated. Therefore, the premise of equal variances should be understood. Nevertheless, when the significance threshold is equal to or less than p=0.05, it indicates that the variances of the two groups (summer and winter) are statistically different. Hence, the assumption of unequal variances should be employed to account for the presence of non-identical variances.

Table 4.4 shows that Levene's test significance level types of SO_2, NO_2 and PM_{10} are <0.001,0.000 and 0.000, respectively.

The results of the independent-samples t-test indicate that there is a statistically significant difference between the groups in terms of SO_2 levels. The mean score for the summer season (M = 6.3749, SD = 17.38964) was found to be considerably lower than the mean score for the winter season (M = 7.9366, SD = 12.72367), t (77525.036) = -14.694, p < 0.001. In relation to NO_2, the average score during the summer (M = 10.6709, SD = 12.65260) exhibited a statistically significant decrease compared to the average score during the winter (M = 25.8248, SD = 36.20045), t (39933.000) = -71.195, p=0.000. Additionally, the analysis of PM_{10} data reveals that the average score during the summer season (M = 43.8076, SD = 77.48116) was considerably lower compared to the average score during the winter season (M = 95.52787, SD = 95.52787), t (40697.848) = -39.944, p=0.000. Therefore, this means that the variances of the two groups (summer and winter) are statistically different.

4.4 Compliance of Tshwane's exposure concentrations with NAAQS exposure levels for PM_{10}, NO_2 and SO_2

The monitoring data from the seven monitoring sites was assessed to facilitate a comparison with the national ambient air quality standard, as shown in Table 4.3 below. The establishment of ambient air quality standards plays a crucial role in managing air quality from a policy perspective. Implementing the National Ambient Air Quality Standards (NAAQS) in South Africa marked a significant change in the approach to air quality management, shifting the emphasis from source-oriented to receptor-oriented strategies. This transition was initially set in motion with the passage of the National Environmental Management: Air Quality Act (NEM: AQA). The development of the National Ambient Air Quality Standards (NAAQS) took several factors into account, including the potential health implications, prevailing ambient levels, and the economic growth of South Africa. The study findings are reported for the three primary pollutants that are of significant importance in South Africa, specifically Nitrogen dioxide, sulphur dioxide, and particulate matter (Thompson et al., 2011; Lourens et al., 2011; Venter et al., 2012).

Table 4.3 South African Air Quality Standards

Air quality standards for Sulphur Dioxide		
1 year	50 µg/m^3	DEA (2009)
Air quality standards for Nitrogen Dioxide		
1 year	40 µg/m^3	DEA (2009)
Air quality standards for particulate matter		
1 year	40 µg/m^3	DEA (2009)

Sulphur Dioxide

Based on the National Ambient Air Quality Standard in South Africa, the prescribed threshold for SO_2 concentration is 50 µg/m^3 annually, as indicated in Table 4.3. The concentrations of SO_2 exhibited consistently low levels across all monitoring stations except the Booysens monitoring station. The levels of SO_2 concentrations showed fluctuations from 2016 to 2020.

The analysis reveals that a solitary instance exceeding the prescribed limit was seen at the Booysens monitoring station in 2020, with a recorded value of 163.76 µg/m^3. The Booysens monitoring station is in a mixed-use region comprising industrial and residential zones. Furthermore, the residential areas include informal settlements. Hence, the emission of SO_2 may originate from the combustion of biomass as well as vehicular transportation. Regular exposure to SO_2 can lead to various respiratory symptoms, including the production of phlegm, difficulty breathing, and a dry cough, as well as the development of a sore throat (Sandra, 2013; Wahyuddin et al., 2016).

In addition, SO_2 is recognized as a prominent air contaminant in metropolitan areas. The primary contributors to the release of SO_2 into the atmosphere include burning fossil fuels, industrial smelting processes, and producing sulphuric acid. The combustion of coal represents the primary anthropogenic contributor of SO_2, constituting almost half of the total yearly global emissions. Severe air pollution issues can arise, particularly in urban areas, due to meteorological circumstances, topographical features, city planning and design, and human activity (EEA, 2012). SO_2 is the primary indicator of air quality, particularly emphasising metropolitan environments where it is the most extensively monitored pollutant. SO_2 impacts the human respiratory system and the environment due to its role in acidifying ecosystems regarding soil and water quality (EEA, 2012). Acid deposition can potentially adversely affect aquatic ecosystems within rivers and lakes and induce detrimental consequences on forests, crops, and other forms of vegetation. SO_2 emissions also play a secondary particle pollutant in generating particulate matter in the atmosphere, a significant air pollutant with detrimental effects on human health (EEA, 2012).

Nitrogen Dioxide

According to Table 4.3, the findings suggest that the levels of NO_2 concentrations in the monitoring stations of Bodibeng, Ekandustria, and Olievenhoutbosch were all below the established threshold value of 40 μg/m^3. The recorded values ranged from 10.41 μg/m^3 to a maximum of 39.79 μg/m^3. Nevertheless, it was observed that the concentration in Mamelodi was above the designated limit amount, measuring 50.9 μg/m^3 in 2019. Comparably, monitoring stations such as Booysens recorded concentrations of 60 and 51.37 μg/m^3 in the years 2016 and 2020, correspondingly. Rosslyn recorded a concentration of 43.35 μg/m^3 in 2016. Notably, Pretoria West experienced a doubling of the exceedance, reaching a concentration of 80.75 μg/m^3. This finding resembles a previous investigation conducted in Libya, where the concentration of NO_2 surpassed the allowable thresholds, particularly in the vicinity of industrial zones such as electricity generation and cement manufacturing, as documented by Nassar et al. (2017). It is essential to highlight that all these recorded values exceeded the established air quality limits. Due to the proximity of these monitoring sites to roadways, it is possible that emissions from motor vehicles were the cause of the elevated levels of NO_2 concentration. In and around the Tshwane central business area, there is typically heavy automobile traffic early in the morning and late in the evening throughout the weekdays. Biomass burning, the combustion of fossil fuels, transportation, and thermal power plants are some of the most significant human-caused contributors to NO_2 levels in the atmosphere (Georgoulias et al. 2019; He et al. 2019; Qin et al. 2020; Wang and Su 2020; Lerma et al. 2021).

Nitrogen dioxide (NO_2) is a pollutant with a very short lifespan, as evidenced by studies conducted by Marchenko et al. (2015) and Lamsal et al. (2020). It is particularly prevalent in urban settings, as indicated by the research undertaken by Georgoulias et al. (2019) and Otmani et al. (2020). NO_2 exhibits detrimental effects on the environment and human health, particularly when individuals are exposed to it for extended periods (Manisalidis et al., 2020; Otmani et al., 2020). Several adverse effects on human health have been identified, such as respiratory ailments, coughing, and wheezing, which can be attributed to the ability of NO_2 to infiltrate and erode the inner regions of the lungs (Manisalidis et al., 2020; Wang & Su, 2020). In addition, NO_2 is known to produce nitric acid, nitrate aerosols, and peroxyacetyl nitrate (HNO_3) (Lamsal et al., 2020; Wang and Su, 2020). These compounds adversely affect agricultural yields (Manisalidis et al., 2020) and the environment. NO_2 and nitric oxide (NO), collectively known as nitrogen oxides, play a crucial role in the photochemical reactions involving ozone (O_3) in both the stratosphere and troposphere (Grajales and Baquero-Bernal, 2014; Lamsal et al., 2020; Qin et al., 2020). These reactions occur under the influence of solar radiation (Lerma et al., 2021).

Particulate Matter

The results indicate that the concentrations of PM_{10} in Figure 3 exceeded the prescribed air quality threshold at Ekandustria and Pretoria West, with recorded measurements of 6.77 and 24.28 µg/m^3, respectively, as presented in Table 4.3. However, the prescribed limit was exceeded in several stations. Bodibeng, for instance, recorded PM_{10} concentrations of 49.21, 62.55, and 78.18 µg/m^3 in 2016, 2017, and 2018, respectively. Similarly, Booysens recorded 61.99 and 60.31 µg/m^3 concentrations in 2017 and 2019, respectively. Olievenhoutbosch recorded a concentration of 124.4 µg/m^3 in 2019, while Mamelodi recorded a concentration of 206.63 µg/m^3 in 2020. Lastly, Rosslyn recorded a concentration of 500.58 µg/m^3 in 2017. The above stations are in regions characterized by industrial establishments, formal and informal residential settlements, and high-traffic road networks. Consequently, it is possible that the observed heightened levels of PM_{10} could be attributed to many sources, such as industrial operations, transportation, residential activities involving biomass burning, and the suspension of dust particles. In addition, residential fuel sources such as coal, wood, and paraffin are commonly utilized for cooking and heating purposes in lower-class households and informal settlements in South Africa (Koppman et al., 2011). Therefore, the reliance on such fuel sources can be attributed to the absence of more affordable or readily available alternatives. Moreover, the Tshwane region is characterized by a substantial informal settlement, making it one of the largest in Gauteng. Consequently, the prevalence of pollution stemming from household fuel burning is notably greater in this area (DEA, 2010).

Additionally, the spatial and temporal variations in PM_{10} concentration levels are influenced by various factors, including meteorological conditions and human activities. These activities include emissions from vehicles, households, and industries. This variability has been observed throughout different provinces in South Africa, as shown by Mkoma et al. (2011) and Czernecki (2017).

Furthermore, PM_{10} is considered the best indicator of ambient air pollution health effects (Burnett et al., 2014; WHO, 2014). Many human activities contributing to ambient PM_{10} also contribute to climate change and other health impacts (Karagulian et al., 2014). Understanding the sources and activities contributing to local ambient air pollution levels is vital to reduce exposure to air pollution and the associated health impacts. For this reason, a growing number of regional studies focus on the contribution of sources to air pollution levels, most often at the town level. Such studies consider several pollution sources, such as industrial actions, transport, biomass burning/residential activities, re-suspended dust, sea salt and different unspecified pollution sources of human origin (Karagulian et al., 2014).

The emission of particulate matter can have a variety of detrimental consequences on human wellness, both in the short term and the long term, such as a rise in the number of health problems (Chang, Peng, and Dominici, 2011; Cassee et al., 2013; Beltrando, 2014; Li and et al., 2018; Chen et al., 2019).

4.5 **Conclusion**

The study revealed that the average concentrations of SO_2, NO_2, and PM_{10} concentrations exceeded the prescribed limits established by the National Ambient Air Quality Standards (NAAQS) across several areas over five years. Moreover, this suggests that the air pollution levels in the City of Tshwane Municipality concerning SO_2, NO_2, and PM_{10} are substantial and have potential health and environmental implications.

In general, the analysis of pollutant distribution patterns within the study reveals variations in concentration based on spatial and temporal factors. These variances arise due to the specific activities conducted at a particular site, such as high volumes of traffic, open incineration practices, and emissions from industrial sources.

The study locations exhibited variances in terms of seasons, specifically summer and winter. Based on the findings, it was noted that there were elevated concentrations of SO_2, NO_2, and PM_{10} during the winter season, but lower amounts were seen during the summer. Furthermore, this implies that seasonal variations influence the magnitude of atmospheric emissions within a specific geographical region.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Introduction

This chapter will provide a comprehensive summary of the primary research findings concerning the research aims and questions and their significance and contribution to the field. Additionally, this study will critically evaluate the constraints inherent in the research design and suggest avenues for further investigation.

5.2 Conclusion

The main objective of this study was to evaluate the levels of air quality, explicitly targeting the prominent air pollutants within the City of Tshwane, Gauteng. The research investigation focused on NO_2, PM_{10}, and SO_2 levels at seven distinct air quality monitoring stations in different regions within the City of Tshwane. In addition, secondary data on air quality from SAAQS for the years 2009 to 2020, including nitrogen dioxide, particulate matter and sulphur dioxide nitrogen dioxide, particulate matter, and sulphur dioxide levels was used for this study. Seasonal and spatial variability were determined at this study's selected stations. Based on the results obtained, it was observed that the concentrations of three primary ambient air pollutants, namely NO_2, PM_{10}, and SO_2, in the sampled regions within the City of Tshwane, exhibited a tendency to be relatively elevated during the winter season, characterized by frequent occurrences of atmospheric inversions. Conversely, these pollutant concentrations were observed to be comparatively lower during the summer season.

The study also documented temporal fluctuation when higher levels of particulate matter were reported in industrial locations compared to certain residential areas. This phenomenon may be attributed to the significant release of pollutants which may have originated from industrial operations. However, the study also discovered that particle pollution was significantly greater in residential areas that included (formal and informal settlements). This phenomenon may arise due to the use of firewood and coal for cooking and heating.

Additionally, the research revealed that the City of Tshwane did not adhere to the NAAQS concerning the levels of SO_2 (163.76 μg/m^3) in Booysens monitoring station, NO_2 (60 μg/m^3, 51.37 μg/m^3) in Booysens, (50.9 μg/m^3) in Mamelodi, (43.35 μg/m^3), and (80.75 μg/m^3) in Pretoria West monitoring stations and PM_{10} concentrations, Bodibeng recorded PM_{10} concentrations of 49.21, 62.55, and 78.18 μg/m^3 in the years 2016, 2017, and 2018, respectively. In the same way, Booysens recorded concentrations of 61.99 and 60.31 μg/m^3 in 2017 and 2019, respectively. Olievenhoutbosch recorded a concentration of 124.4 μg/m^3 in 2019, while Mamelodi recorded a concentration of 206.63 μg/m^3 in 2020. Last but not least, Rosslyn recorded a concentration of 500.58 μg/m^3 in 2017. However, the concentration levels of PM_{10} were determined to be the highest of all pollutants.

The lack of primary data has resulted in inconsistent monitoring of the contaminants in this investigation. Consequently, the evaluation of air quality within the City of Tshwane Metropolitan Municipality is impeded due to the incomplete data from all monitoring stations. The cause of this issue can be attributed to the presence of malfunctioning monitoring stations, potentially stemming from inadequate maintenance practices. Hence, determining the overall air quality compliance of the City poses significant challenges.

The findings suggest that human-induced activities within urban areas significantly affect the emission of NO_2, PM_{10}, and SO_2. Moreover, the impact of these activities on pollutant levels is further exacerbated by prevailing weather conditions, particularly in residential zones, for example, in winter when it's cold. The findings indicate that the concentration of poor air quality in specific city regions, particularly in low-cost residential and industrial sectors, can be attributed to biomass burning and coal-powered power plants.

5.3 **Recommendations**

Based on the above conclusions, there is a need for uninterrupted air quality monitoring of pollutants to have real-time measurements. Therefore, maintenance of the existing monitoring stations should be done timeously. It is also recommended to consider supplementing the montirong stations with low-cost air quality sensors in the City, which are easy to use and cost-effective in terms of maintenance.

5.4 Limitations of the study

Data availability from certain monitoring stations is one of the challenges that the researcher has encountered. Without air quality data, it is difficult to determine the impact of air quality pollutants on the environment and human beings.

5.5 Future research

To gain a deeper comprehension of the ramifications of these findings, the forthcoming investigations should prioritize the meticulous monitoring and regular maintenance of the air quality monitoring stations. This will guarantee their optimal functionality at all times, thereby preventing any data gaps and facilitating the identification of primary and secondary PM_{10} components' contributions to the overall PM mass. It is also imperative to explore the influence of different attributes of superfine, fine, and coarse particles responsible for detrimental health and environmental effects.

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