



UNIVERSITY of
RWANDA

COLLEGE OF SCIENCE AND TECHNOLOGY

SCHOOL OF SCIENCES

DEPARTMENT OF BIOLOGY

ACADEMIC YEAR: 2023-2024

***MASTER'S PROGRAM IN BIODIVERSITY CONSERVATION AND NATURAL
RESOURCES MANAGEMENT***

**EFFECTS OF SEASONAL VARIATIONS ON AIR POLLUTION IN NYAGATARE AND
BUGESERA DISTRICT IN RWANDA**



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A thesis submitted in partial fulfillment of the requirements
for the degree of Masters in Biodiversity Conservation and
Natural Resources Management

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Kigali, October 2024

DECLARATION

This research proposal is declared to be my original research thesis and it has not been presented to any other institution.

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SUPERVISOR DECLARATION

I, **Dr. Fabien RIZINJIRABAKE**, approve that the work appeared in this, will be done by the mentioned candidate under our supervision at the University of Rwanda - College of Science and Technology (CST).

Signature:

Date:

DEDICATION

This research work is dedicated Almighty God

ACKNOWLEDGEMENT

I am very grateful to many individuals for supporting me all along this work and for their contributions towards completing this thesis. Firstly, I am grateful to the Almighty God for the immeasurable divine favor. Second, I am very thankful to our supervisors **Dr. Fabien Rizinjirabake** for their sincere collaboration, tireless supervision, and guidance throughout this research thesis. Without Him, this work could not be realized.

Special thanks to the University of Rwanda-College of Science and Technology, specifically the lecturers who provided skills, guidance, and advice, which made possible my academic journey.

I want to express my heartfelt gratitude to my husband , MUBIRIGI Jean Bernard , for his unwavering support , encouragement, and understanding throughout his journey. His belief in my abilities and his constant reassurance gave me the strength to persevere, even during the most challenging . Without his patience and love, this thesis would not have been possible. His confidence in my skills and his encouragement gave me the willpower to push through the worst times. This thesis would not have been possible without his love and patience.

I wish to acknowledge my lovely mummy, MUSABYEMUNGU Vianney, for her role in bringing me into this world and for the foundation she provided, our journey together has shaped the person I have become and for that, I am thankful.

I want to acknowledge this thesis in memory of my father, HAKIZAMUNGU Bonaventure, Whose guidance, love, and support have shaped the person I am today. Although he is no longer with us his unwavering belief in me and his encouragement throughout my journey have been a constant source of strength. I know he would have been proud of his accomplishment and for and for that, I am forever grateful

ABSTRACT

Air pollution is increasingly recognized as a critical environmental and public health issue, particularly in rapidly urbanizing and industrializing regions like Rwanda. This study investigates the impact of meteorological factors on air pollution in Rwanda's Eastern Province, focusing on quantifying the relationship between these variables and the concentration levels of pollutants such as PM_{2.5}, O₃, and NO₂. The relationship between air quality and meteorological factors were analyzed using variables such as temperature, humidity, wind speed, and rainfall significantly influencing the concentration and dispersion of pollutants in the atmosphere. Data on meteorological variables such as temperature, humidity, wind speed, and rainfall and air pollutants data were obtained from Rwanda Meteorological Agency and from the air quality monitoring stations in Nyagatare and Bugesera. The key findings showed that NO₂ levels peaked at 24.22 µg/m³ in March and dropped to 21.85 µg/m³ in July, while PM_{2.5} concentrations were highest in August (25.12 µg/m³) and lowest in April (15.62 µg/m³). O₃ concentrations followed a similar pattern, reaching 34.10 µg/m³ in July and declining to 20.02 µg/m³ in April. These findings suggest that reduced precipitation and increased sunlight during dry seasons contribute to higher pollutant levels, whereas wet conditions lower them. The results on meteorological factors, indicated that high relative humidity in April (83.97%) correlated with lower O₃ and PM_{2.5} levels, while rainfall was associated with decreased pollutant concentrations. Wind speed influenced pollutant levels, with higher speeds in July linked to moderate pollutant levels and lower speeds in January associated with higher concentrations of NO₂ and PM_{2.5}. The predictions based on meteorological conditions revealed strong correlations between pollutant levels and weather factors. PM_{2.5} concentrations decreased with increased rainfall, while ozone levels were negatively correlated with relative humidity and rainfall. Temperature positively influenced ozone levels, highlighting the role of higher temperatures in enhancing photochemical reactions. NO₂ levels showed a complex relationship with relative humidity, with both pollutant removal and accumulation observed under different conditions. The study suggests that strategies to mitigate air pollution in Rwanda should be tailored to seasonal variations, focusing on reducing emissions during the dry season and controlling O₃ precursors throughout the year. Future research should explore the complex interactions between meteorological factors and secondary pollutants, particularly in different climatic regions of Rwanda, to enhance the effectiveness of air quality interventions

Keywords: Particulate Matter (PM_{2.5}), Ozone (O₃), Nitrogen Dioxide (NO₂), Climatic Factors

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LIST OF ACRONYMS & ABBREVIATIONS

BC:	Black Carbon
CST:	College of Science and Technology
PM:	Particulate Matter
UR:	University of Rwanda
VOCs:	Volatile Organic Compounds
WHO:	World Health Organization
REMA:	Rwanda Environmental Management Authority
O₃	: Ozone
NO₂	: Nitrogen dioxide
T^{°c}	: Temperature
WS	: Windspeed
RF:	Rain fall
HO	: Hydroxyl radical
CO	: Carbon Monoxide

CHAPTER ONE

GENERAL INTRODUCTION

1.1 Background of the study

Air pollution is a critical global environmental issue with profound implications for human health, ecosystems, and climate. The complex relationship between weather conditions and air quality is well-documented, as meteorological factors significantly influence the dispersion, transformation, and concentration of pollutants in the atmosphere (Jacob & Winner, 2009b). Understanding these interactions is essential for developing effective strategies to mitigate air pollution and protect public health (Li *et al.*, 2020). This study aims to quantify the impact of meteorological factors on air pollution on a global scale. By analyzing extensive datasets of meteorological variables such as temperature, humidity, wind speed, precipitation, and atmospheric pressure alongside air quality measurements, the research seeks to elucidate the complex dynamics governing the distribution and intensity of air pollution across different regions and climatic zones (Zhang *et al.*, 2019b). Meteorological factors' influence on air pollution varies across geographical contexts, driven by factors like local topography, land use, and human activities. This study will identify spatial and temporal patterns in the relationship between weather conditions and pollutant concentrations, providing insights into the mechanisms driving air pollution dynamics worldwide (Zhou *et al.*, 2023, Wei *et al.*, 2023). By quantifying meteorological contributions to air pollution levels, this research aims to inform the development of targeted policies to improve air quality and mitigate adverse impacts on health and the environment (Feng *et al.*, 2022).

Africa faces significant air pollution challenges, affecting public health, ecosystems, and socioeconomic development. The continent's diverse climatic conditions, rapid urbanization, industrialization, and biomass burning contribute to varying pollution levels across regions (Kumar *et al.*, 2020). Meteorological factors play a crucial role in modulating the dispersion, transport, and transformation of pollutants in Africa (Shukla *et al.*, 2024). This study focuses on quantifying the impact of meteorological factors on air pollution in Africa, enhancing understanding of the interactions between weather conditions and pollutant concentrations. By analyzing comprehensive datasets of meteorological parameters and air quality measurements, this research aims to identify key drivers of air pollution variability (Li *et al.*, 2023).

Uganda and Kenya, two East African countries, face increasing air pollution challenges due to rapid urbanization, industrialization, and biomass burning. The impact of air pollution on health, ecosystems, and development underscores the need to understand the factors influencing air quality dynamics (Ndetto & Matzarakis, 2015). Meteorological factors significantly modulate pollutant dispersion and transformation in Uganda and Kenya. This study aims to quantify these influences, providing insights into the interactions between weather conditions and pollutant concentrations. By analyzing meteorological data and air quality measurements from both countries, the research seeks to identify key drivers of air pollution variability (Kinney *et al.*, 2011).

1.1.1 Production of Ozone (O₃)

Ozone (O₃) production is influenced by various factors such as temperature, solar radiation, and the presence of precursors like NO_x and VOCs. Studies have shown that O₃ production is sensitive to changes in these parameters (Lin *et al.*, 2023, Yu *et al.*, 2023, Mifsud *et al.*, 2022). For instance, in urban areas like Ji'nan, where O₃ pollution is a concern, observations have revealed high O₃ levels linked to VOC-limited conditions and key VOC precursors like alkenes (Sun *et al.*, 2022). Meteorological factors also influence air pollution levels in Rwanda, particularly in the Eastern province. Temperature, relative humidity, wind speed, and tropospheric stability significantly impact pollutants like black carbon (BC) and ozone (O₃) (Porter *et al.*, 2015). BC concentrations in Rwanda are higher during dry seasons, influenced by regional biomass burning and emissions from northern and southern African biomass burning seasons (Gahungu & Kubwimana, 2022).

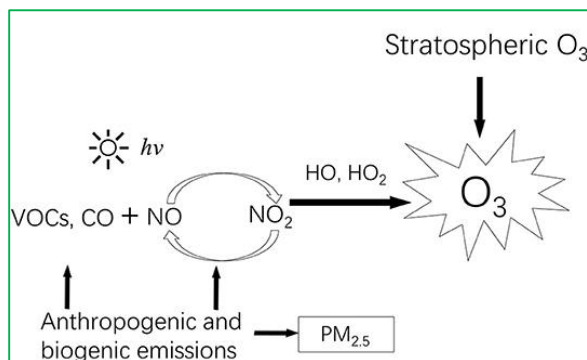


Figure 1: Formation of Ozone (O₃) and its interaction with PM_{2.5}, VOCs, CO and NO

Source: (Zhang *et al.*, 2019a).

Ozone in the stratosphere can move downward to the troposphere, contributing to the “background” level of ground-level ozone. However, high levels of ozone in the troposphere are due to photochemical reactions involving volatile organic compounds (VOCs) and oxides of nitrogen (NO_x: NO, and NO₂). Anthropogenic emissions (e.g., fossil fuel combustion) are responsible for NO_x and mainly responsible for VOCs and CO. Trees also emit certain VOCs (e.g., isoprene). PM_{2.5} from primary emission sources can react with (consume) free radicals (e.g., HO₂) responsible for ozone formation, which partly explains the observations in certain areas where ozone level increased while PM_{2.5} level decreased. hv, photon; VOCs, volatile organic compounds; CO, carbon monoxide; NO, nitric oxide; NO₂, nitrogen dioxide; NO_x, NO and NO₂; HO, the hydroxyl radical; HO₂, The hydroperoxy radical; PM_{2.5}, Particulate matter with a diameter of 2.5µm or less (Zhang et al., 2019a). The meteorological conditions and pollutant levels is crucial for effective policy-making and mitigation strategies in the region. Low-cost sensor technology and machine learning methods are emerging solutions for monitoring and forecasting air pollution trends in Rwanda. Understanding the relationship between

1.2 Problem statement

Air pollution poses a significant threat to public health, ecosystems, and sustainable development across Africa (Imane *et al.*, 2022). Despite increasing awareness of the detrimental impacts of air pollution, there remains a critical gap in understanding the quantifiable influence of meteorological factors on air quality dynamics in the continent (Carlton *et al.*, 2020). The complex interactions between weather conditions and pollutant concentrations present challenges for policymakers, urban planners, and environmental agencies in developing effective strategies to mitigate air pollution and safeguard public health (Ault, 2020). Despite the critical importance of understanding the relationship between meteorological factors like temperature, rainfall, and Relative humidity, coupled with air pollution, there exists a lack of comprehensive research specifically focused on the quantification of these factors in the context of the Eastern province of Rwanda. The absence of detailed analyses hampers the ability of policymakers, environmental agencies, and local communities to develop targeted strategies for mitigating air pollution and protecting public health in these regions. Therefore, there is an urgent need for research aimed at

quantifying the specific influence of meteorological factors on air pollution levels in the Eastern province of Rwanda, to inform evidence-based interventions and policies to close the knowledge gap.

1.3 Objectives of the study

1.3.1 Main objective of the study

The main objective of this study is to investigate how the magnitude of air pollutant concentrations respond to local-scale meteorology in Nyagatare and Bugesera. The study intends to understand the relationship between meteorological factors and air pollution levels in order to contribute to the development of air quality management and to inform public health initiatives focused on reducing the health issues associated with exposure to air pollution.

1.3.2. Specific Objectives

This study was guided by the following specific objectives:

1. To determine the seasonal variation of air pollutants in the study area
2. To quantify the meteorological factors and air pollutants in the study area
3. To predict the change of air pollution pollutants using meteorological conditions in the study area

1.4. Research questions

1. What is the seasonal variation in the concentration of pollutant based on meteorological conditions in the study area?
2. How much quantity of meteorological factors and air pollutants like PM_{2.5}, O₃, and NO₂ in the study area?
3. Does the linear model between air pollutants and local meteorological factors predict the change of air quality in the study area?

1.5 Research Hypotheses

This study is guided by the following research hypothesis:

1. The highest level of air pollutants in the study area is due to increased temperatures and reduced humidity. This hypothesis suggests that higher temperatures and low humidity

leads to higher air pollutant concentrations due to anthropogenic activities and atmospheric conditions.

2. The quantity of meteorological and air pollutants factors is statistically significant. This hypothesis suggests that meteorological factors such as temperature, wind, humidity, and precipitation drive air quality, and the lack of significant variability in pollutant levels could be due to the competing effects, threshold effects, and homogeneous conditions across stations.
3. The meteorological conditions such as temperature, humidity, wind speed, and rainfall significantly influence the change in concentration of air pollution pollutants in the study area, with specific conditions leading to either an increase or decrease in pollutant levels.

1.6. Scope and significance of the Study

For contextual scope, the study aims to investigate the relationship between meteorological factors and air pollution levels in both the Eastern Province of Rwanda. It seeks to quantify how meteorological variables such as temperature, humidity, wind speed, and precipitation influence air quality parameters such as PM_{2.5} and O₃ concentrations. Geographically, the study focused on the Nyagatare and Bugesera District in the Eastern Province of Rwanda from 01/01/2022 to 31/12/2023.

The study holds significant importance in the domains of environmental pollution, air pollution, and academia for several reasons. The study is intended to help in understanding the relationship between meteorological factors, and air pollution levels. The study's findings can contribute to the development of air quality management plans aimed at reducing the exposure of populations in the study area to harmful pollutants. The insights gained from the study can inform public health initiatives focused on reducing the incidence of respiratory diseases, cardiovascular problems, and other health issues associated with exposure to air pollution. After that, by quantifying the impact of meteorological factors on air pollution, policymakers can implement adaptive measures to mitigate the health risks posed by air pollution during specific weather conditions. The study's findings can help policymakers and environmental agencies to develop effective strategies for mitigating air pollution and to identify the meteorological conditions that exacerbate air pollution episodes. Targeted interventions such as emission controls, urban

planning measures, and public health advisories can be then implemented to reduce pollution levels and protect human health. Finally, yet importantly, the results from this study will be used as reference documents in the field of academic research. The study contributes to the body of scientific knowledge by providing empirical evidence on the relationship between meteorology and air quality in a specific geographical context.

1.6. Limitations

In addition to the limited geographical focus on Nyagatare and Bugesera stations, one significant limitation of this research is the restricted temporal coverage of pollutant data. The data accessed from the Rwanda Environment Management Authority (REMA) only spanned two years, from 2022 to 2023, which may not be sufficient to capture long-term trends and variations in air pollution levels.

Another limitation is the potential inaccuracy or gaps in the data collected from the REMA monitoring stations. The reliability of the data depends heavily on the calibration and maintenance of the monitoring equipment. Any inconsistencies in data collection methods or equipment malfunctions could have introduced biases or errors in the pollutant concentration levels reported. Additionally, the spatial distribution of monitoring stations is sparse, particularly in rural and less developed areas, which means that the data may not fully represent the air quality across the entire regions of Nyagatare and Bugesera.

CHAPTER TWO

LITERATURE REVIEW

This chapter deals with the reviewed literature related to the topic of Quantification of Meteorological factors on Air Pollution. It indicates the impact of temperatures, rainfall, wind speed, and relative humidity variations on air pollution.

2.1. Impact of temperatures, rainfall, wind speed, and relative humidity Variations on Air Pollution

A comprehensive literature review synthesized findings from various studies on the impact of meteorological factors on air pollution. Studies highlighted the significant role of meteorological parameters like temperature, humidity, wind speed, and rainfall in influencing the concentration of air pollutants (Faruk *et al.*, 2022, Tiwari & Shukla, 2021, Zhu *et al.*, 2021). The relationship between meteorological factors and air pollutants was explored in various regions and seasons, showing correlations between parameters such as PM_{2.5}, O₃, CO₂, and NO₂ with different meteorological conditions (Ansar *et al.*, 2021).

Many studies have examined how meteorological conditions affect air quality. For example, some research has found that local surface ozone (O₃) levels are influenced by temperature and duration of sunlight, with relative humidity and precipitation playing minor roles. Furthermore, the impact of wind speed on air pollution levels varied significantly among various cities in the Shanxi Province, China (Chen *et al.*, 2022). In instances where there was a notable association between local surface ozone levels and meteorological factors impacting photochemical reactions, like temperature and sunlight duration, the pollution was mainly attributed to local photochemical processes. Alternatively, in regions across China, regional wind direction and speed were identified as the primary factors. It is therefore important to mention that all monitoring stations used in this study were located in urban areas, which means the interactions between urban and rural areas affecting photochemical processes governing ozone production were not considered in the findings.

Research examining the relationship between PM concentration levels and meteorological factors is prevalent due to the significant impact of PM (Hernandez *et al.*, 2017, Ejohwomu *et*

al., 2022). A study examining the impact of temperature and humidity on PM concentrations in Auckland, New Zealand, found that there was an inverse relationship between temperature and PM_{2.5} levels across the day. Conversely, relative humidity was generally positively associated with PM_{2.5}, although this correlation stopped beyond 75% relative humidity (Hernandez et al., 2017). The researchers proposed that as humidity rises, moisture particles expand until they reach a critical point, causing dry deposition and lowering PM_{2.5} levels (Hernandez et al., 2017). Moreover, the natural deposition of PM is affected by relative humidity, as atmospheric PM concentration rises when moisture particles bind to PM. In another study in urban and rural areas in Birim *et al.* (2023), the most influential factor on PM_{2.5} concentration levels was found to be relative humidity, while temperature did not exhibit a statistically significant effect. The researchers suggested that in Birim et al. (2023) enhancing the regression models presented in the study could be achieved by including extra meteorological factors like atmospheric pressure and precipitation (Birim et al., 2023).

While there have been previous investigations into air pollution in West Africa, there is a scarcity of studies focusing on the connections between meteorological factors and air quality. This was highlighted in a study referenced in the literature (Abulude & Abulude, 2021), The relationship between temperature, humidity, and different sizes of particulate matter (PM_{2.5}) was explored using data collected from five monitoring stations located across five states in Nigeria, West Africa (Osun, Kebbi, FCT, Delta, Lagos). Notably, one station was positioned further north in the country, experiencing shorter rainy seasons (four months) compared to a station in the central region (seven months of rainy season), and three stations in the southwest (eight months of rainy season). The results showed strong correlations between all PM sizes like PM_{2.5} and relative humidity in Delta. However, weak correlations were observed in the other states. Furthermore, the studies indicated weak associations between PM sizes like M_{2.5} and ambient temperature across all five sites in the states. It's important to highlight that these investigations were conducted over different durations at the five sites, ranging from 2 months (Kebbi) to 7 months (Abuja) (Abulude & Abulude, 2021).

A study conducted at an urban site in Port Harcourt, West Africa Onuorah *et al.* (2019), investigated the impact of wind direction and speed, rainfall, ambient temperature, and relative

humidity on the concentrations of PM_{2.5}. The results indicated that wind speed, rainfall, and ambient temperature significantly affected PM_{2.5} concentrations, albeit with weak correlations. Relative humidity values showed a weak yet statistically significant correlation with PM_{2.5} concentrations, whereas the correlation with PM_{2.5} concentrations was weak and not statistically significant. This study was conducted over 8 months. A similar examination carried out in Akure, West Africa, by (Akinwumiju *et al.*, 2021), found weak correlations between wind speed, humidity, temperature, and concentrations of PM_{2.5}. In an earlier study in Ile-Ife, West Africa, conducted by (Owoade *et al.*, 2012), similar results were obtained, although only 162 samples of PM_{2.5} were collected over 10 months.

2.2. Impact of temperatures, rainfall, wind speed, and relative humidity Variations on Ozone

Variations in temperatures, rainfall, wind speed, and relative humidity have significant impacts on ozone pollution levels. Studies in Suzhou, Hong Kong, Southeast China, and Siberia highlight these effects (Gao *et al.*, 2020). Higher temperatures are associated with increased ozone pollution, while relative humidity shows a negative correlation with ozone concentration in most cases (Xu *et al.*, 2020). Additionally, weather conditions with little rain and low wind speeds contribute to ozone pollution events. In contrast, intense solar radiation after rain can decrease ozone concentrations. Furthermore, in Siberia, the relationship between ozone concentration and absolute humidity varies with temperature, affecting ozone formation differently. Currently, research on PM_{2.5} particulate matter predominantly centers on various aspects including identifying its sources, understanding pollution characteristics and health impacts, and investigating contributing factors. Concerning source analysis, previous studies by Li *et al.* (2019) have mainly relied on methodologies like the inventory-based chemical mass balance (I-CMB) model (Fan *et al.*, 2020a), chemical mass balance (CMB) method (Guo *et al.*, 2019), and atmospheric diffusion model method to establish emission inventories (Wang *et al.*, 2021). Studies in Turkey mainly focused on the factors causing the changes in PM_{2.5} concentration levels, such as long-range transport (Baltaci *et al.*, 2020, Baltaci, 2021, Baltaci & Ezber, 2022), local meteorological factors (Baltaci *et al.*, 2019), and their impact on health problems (Baltaci *et al.*, 2022, Arslan *et al.*, 2022). For Ozone, İm *et al.* (2006) analyzed hourly ozone, NOX, and VOC concentrations during summer and found that a decrease in inversion heights in the early

hours of the day leads to an increase in ozone concentrations (İm et al., 2006). Can (2017) found that the highest ozone value is observed in the summer season (Can, 2017). Unal et al., (2021) analyzed the relationship between air pollution and asthma, bronchitis and pneumonia and found that pneumonia, asthma and bronchitis cases were associated with increases in ozone concentrations (Ünal *et al.*, 2022).

Ozone levels are affected by both natural meteorological conditions and human-caused emissions. Meteorological factors such as intense solar radiation, cloud cover, high temperatures, low relative humidity, atmospheric stability, and the location of pollutant sources all play a role in determining ozone concentrations. Otero *et al.* (2016) researched the connection between local and synoptic meteorological conditions and surface ozone levels across Europe during the spring and summer seasons. Li *et al.* (2017b) demonstrated that elevated temperatures, low relative humidity, easterly winds, and low wind speeds influence urban ozone episodes in China. Chen *et al.* (2020) highlighted temperature as the primary factor influencing ground-level ozone concentrations in China.

2.3. Impact of temperatures, rainfall, wind speed, and relative humidity Variations on particulate Matter PM_{2.5}

The fluctuations in temperatures, rainfall, wind speed, and relative humidity can significantly influence the levels of particulate matter PM_{2.5}. Temperature variations can impact the atmospheric stability and dispersion of PM_{2.5}, affecting its concentration in the air (Sfică *et al.*, 2018, Almeida *et al.*, 2020). Rainfall can lead to the removal of PM_{2.5} from the atmosphere through wet deposition, thereby reducing its concentration (Zhou *et al.*, 2020). Wind speed plays a crucial role in dispersing PM_{2.5} particles, potentially transporting them over long distances or increasing local concentrations depending on the source and direction of the wind. Relative humidity affects the size and behavior of PM_{2.5} particles, with higher humidity levels potentially causing hygroscopic growth and altering their atmospheric lifetime. Overall, these meteorological factors interact complexly to influence the distribution and concentration of PM_{2.5} in the environment. Precipitation hours of the same level differed for the different national air quality monitoring stations in the same city. Since heavy rainfall tended to occur more in specific localities, the average deviation of occurrence in LR, MR, and HR steadily rose,

reaching 14.75%, 26.42%, and 35.01%, respectively. With increasing rainfall intensity, the divergence in precipitation occurrence at national air quality monitoring stations within the same area also grew larger. This illustrates the validity of studying the individual occurrences of precipitation across different national air quality monitoring stations (Zhou et al., 2020) and (Wang & He, 2020).

2.4. Impact of temperatures, rainfall, wind speed, and relative humidity Variations on Nitrogen Dioxide (NO₂)

Variations in climatic factors like temperatures, rainfall, wind speed, and relative humidity can all have significant impacts on the levels of nitrogen dioxide (NO₂) in the atmosphere. Temperature fluctuations influence the rate of NO₂ formation through chemical reactions, with higher temperatures generally leading to increased NO₂ production. Rainfall can help remove NO₂ from the atmosphere through wet deposition, reducing its concentration. Wind speed plays a crucial role in dispersing NO₂ emissions from their sources, affecting the distribution of NO₂ across different areas. Relative humidity can also influence NO₂ levels by affecting atmospheric chemistry and the formation of secondary pollutants.

Research indicates that human exposure to nitric oxide (NO), Nitrogen dioxide (NO₂), and NO_x (the combination of NO and NO₂) tends to be higher in close proximity to roads compared to areas further away from them (Janssen *et al.*, 2001). Several studies have investigated concentration gradients near roads to understand how pollutant levels change with distance from the road, as summarized by Karner et al. (2010): $C = f(x)$. In the context of assessing near-road exposures, the near-road zone is defined as the area near the road where traffic-related air pollution concentrations are higher compared to areas further downwind or upwind of the road (Jung *et al.*, 2024). Background levels are typically considered to be on an urban scale, ranging from 4 to 50 kilometers, based on U.S. Environmental Protection Agency regulations for siting ambient air quality monitors outlined in 40 CFR Part 58 App. D. The concentration gradient with distance from the road, represented as dC/dx , serves as an indicator of the size of the near-road zone where NO₂ and NO_x concentrations from vehicles are elevated. A steep gradient (i.e., a large magnitude of dC/dx) suggests a narrow near-road zone, where concentrations return to background levels over a short distance from the road's edge. Conversely, a gentle gradient (i.e.,

a small magnitude of dC/dx) indicates a wider near-road zone, where concentrations return to background levels over a greater distance. While existing studies have primarily focused on the extent of concentration changes, none have explicitly identified the factors influencing dC/dx (Jung et al., 2024). Such analysis is crucial as it would enable exposure and risk assessors to consider variability in traffic-related pollution near roads and improve predictions of exposures in these areas with diverse meteorological, geological, or built characteristics (Jung et al., 2024).

2.5. Air pollution in the Eastern Province of Rwanda

Maintaining good air quality is crucial for human health and overall well-being, as people rely on a healthy environment with clean air (Korukire *et al.*, 2023). The issue of air pollution has gained global attention, given that exposure to contaminated air is linked to various serious health conditions, leading to adverse outcomes such as hospitalizations and fatalities (Ghorani-Azam *et al.*, 2016). Air pollution in both the Eastern Province of Rwanda presents significant environmental and public health concerns. Various factors contribute to air pollution in these regions, including industrial activities, vehicular emissions, biomass burning for cooking and heating, and natural sources such as dust and pollen. In the Eastern Province, urban centers like Rwamagana and Kayonza may experience elevated levels of air pollutants due to increased industrialization and transportation activities. Additionally, agricultural practices in rural areas, such as burning crop residues, can contribute to air pollution. The use of biomass for cooking and heating in rural areas can release particulate matter and other pollutants into the air, while transportation and industrial activities in urban centers contribute to emissions of nitrogen oxides and other pollutants. Efforts to address air pollution in both provinces may include implementing cleaner technologies, promoting renewable energy sources, improving public transportation infrastructure, and enforcing regulations to reduce emissions from industrial and agricultural activities. Additionally, public awareness campaigns and community engagement initiatives can play a vital role in fostering sustainable practices and reducing air pollution levels in Rwanda's Eastern Province.

CHAPTER THREE

METHODOLOGY

Chapter three deals with the description of the area, data collection techniques, statistical analysis, and quality of data.

3.1. Description of the study area

The study area encompasses the Eastern province of Rwanda, situated in the Eastern parts of the country, respectively. Both provinces exhibit unique characteristics and face distinct environmental challenges, influencing the dynamics of air pollution within each region. In the Eastern Province, characterized by rolling hills and fertile valleys, meteorological factors such as wind patterns, temperature variations, and humidity levels play significant roles in influencing air pollution levels. Strong winds may contribute to the dispersion of pollutants emitted from industrial activities and vehicular traffic, affecting air quality in urban centers. Additionally, temperature inversions and low relative humidity can exacerbate pollution episodes by trapping pollutants close to the ground, leading to adverse health effects for residents. Two (2) Meteorological stations now are selected during this study, mainly Nyagatare, and Bugesera, from the Eastern Province; and from these sites, the researcher tries to collect NO₂, O₃, and PM_{2.5}. The map indicating the study area is given in Figure 3.2.

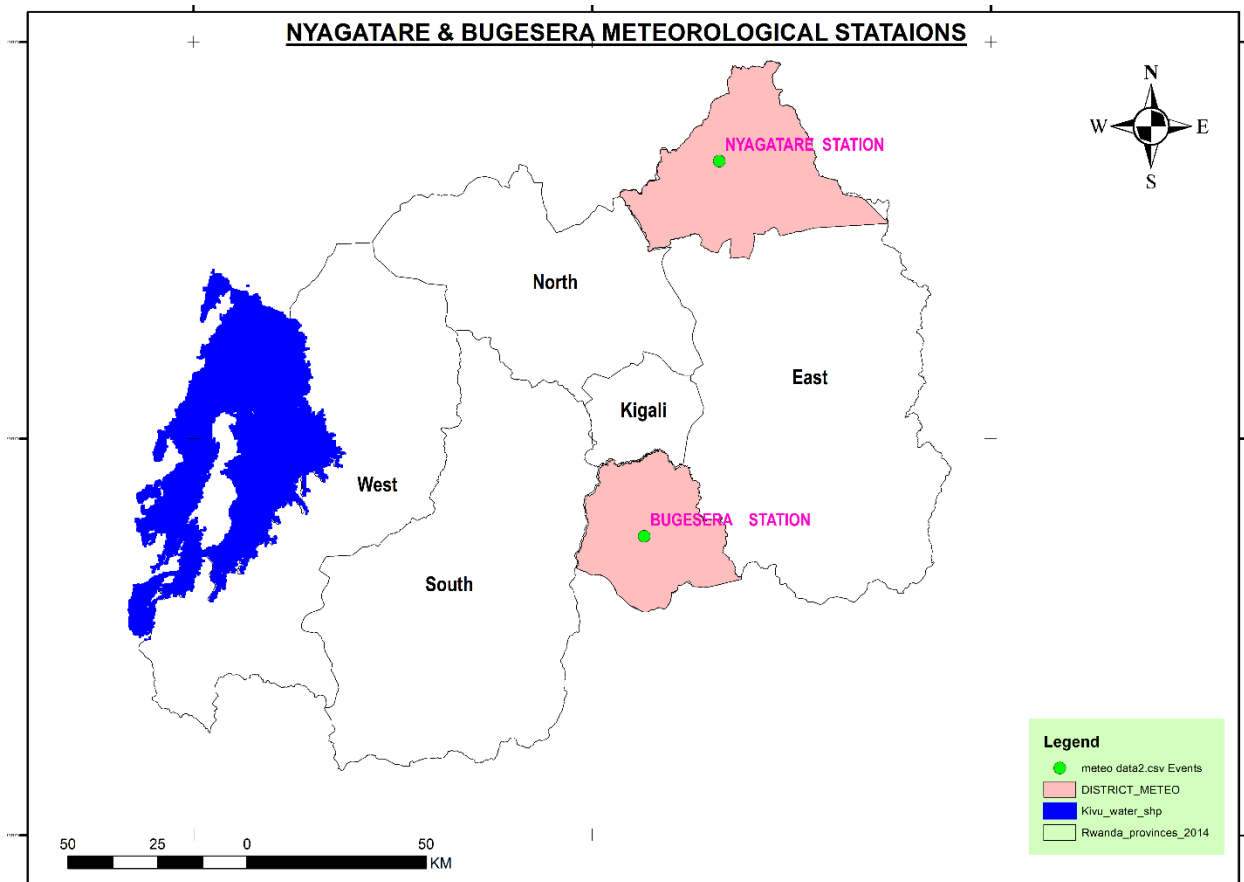


Figure 3: Location of the study area

3.2. Data collection and analysis

The meteorological parameters include Relative Humidity (RH), Rainfall, Wind Speed at 2 meters (WS2M), Temperature ($T^{\circ}\text{C}$), and air pollutants such as Particulate ($\text{PM}_{2.5}$), Nitrogen Dioxide (NO_2), and Ozone (O_3). The data for these parameters were collected and analyzed for the years 2022 and 2023.

Meteorological data like rainfall, temperature variations (Min and Max) and Relative humidity were collected from <https://power.larc.nasa.gov/data-access-viewer/>, and the daily data recorded from January to December 2022 to 2023 were taken into account for time series analysis. Data related to air pollution like air pollution like $\text{PM}_{2.5}$, NO_2 , and O_3 were collected accordingly from <https://aq.rema.gov.rw/> from the period of 2022 to 2023.

3.3. Data analysis

Collected data were analyzed by the MATLAB 16.0 version and Ms Excel. The t-test was used to compare means of PM_{2.5}, NO₂, and O₃, for two years of 2022 and 2023, for wet and dry seasons, and for the study sites. Descriptive analysis was performed to indicate the means and standard deviation. In addition, the Spearman correlation analysis between individual air pollutant and meteorological factor was performed to predict the air quality in the study area. The Spearman correlation coefficient, also known as Spearman's rank coefficient of correlation, is a statistical method used to assess the degree of correlation between two variables based on their ranks rather than their raw values. It is particularly useful when the data does not meet the assumptions of parametric methods or when the relationship between variables is monotonic but not necessarily linear. The Spearman Coefficient can take a value between +1 to -1 where, a value of +1 means a perfect association of rank, a value of 0 means no association of ranks while a value of -1 means a perfect negative association between ranks. It has been noticed that also closer the value to 0, the weaker the association between the two ranks. By identifying significant correlations between meteorological factors like temperature, humidity, and wind speed, and pollutants such as PM_{2.5}, O₃ and NO₂, the Spearman correlation can predict the air quality or air pollution in the study area.

3.3.1 Regression Analysis

Regression analysis is a statistical method used to model and predict the relationship between air pollution levels (dependent variable) and meteorological conditions (independent variables). In this context, meteorological factors such as temperature, wind speed, humidity, and rainfall are critical predictors of pollutant concentrations in the atmosphere. The analysis begins with identifying relevant weather variables and their potential impact on pollutants like PM_{2.5}, NO₂, or O₃. By fitting a regression model, we can quantify how changes in these meteorological conditions influence air pollution, providing insights into the dynamics between weather patterns and pollutant levels.

In this line; multivariate analysis, particularly simple linear regression, is a valuable tool for predicting air pollution changes using meteorological conditions, as it allows the simultaneous examination of one independent variable to see the prediction change of the dependent variable.

In this context, it can assess the combined effects of various meteorological factors like temperature, humidity, wind speed, and rainfall on pollutant concentrations. A general equation for multivariate regression analysis can be expressed as:

$$Y = \beta_0 + \beta_n X_n + \epsilon$$

Where: Y is the dependent variable (e.g., concentration of air pollution pollutants), β_0 is the intercept (the value of Y when all independent variables are zero), β_n is the coefficient that represent the contribution of each independent variable to Y; X_n is the independent variables (e.g., temperature, humidity, wind speed, rainfall) while ϵ is the error term that accounts for the variability in Y not explained by the independent variable.

CHAPTER FOUR:

RESULTS PRESENTATION

4.1. Seasonal variation of air pollution in the study area

The figures in the provided document show the seasonal variation of three key air pollutants—NO₂, PM_{2.5}, and O₃ during the years 2022 and 2023. The patterns observed across different seasons provide insights into how weather and environmental conditions impact pollutant concentrations.

4.1.1 Seasonal variation of NO₂ during years 2022 and 2023

The seasonal variation of NO₂ (nitrogen dioxide) levels is a critical aspect of understanding air quality dynamics, as NO₂ is a significant pollutant with various health and environmental impacts. NO₂ concentrations can fluctuate throughout the year, influenced by changes in weather patterns, human activities, and natural processes. During the wet and dry seasons, factors such as precipitation, temperature, and wind speed play crucial roles in determining NO₂ levels in the atmosphere. Analyzing the seasonal variation of NO₂ over the years 2022 and 2023 provides valuable insights into how these factors interact and affect pollutant concentrations, helping to inform strategies for improving air quality and reducing exposure to harmful emissions.

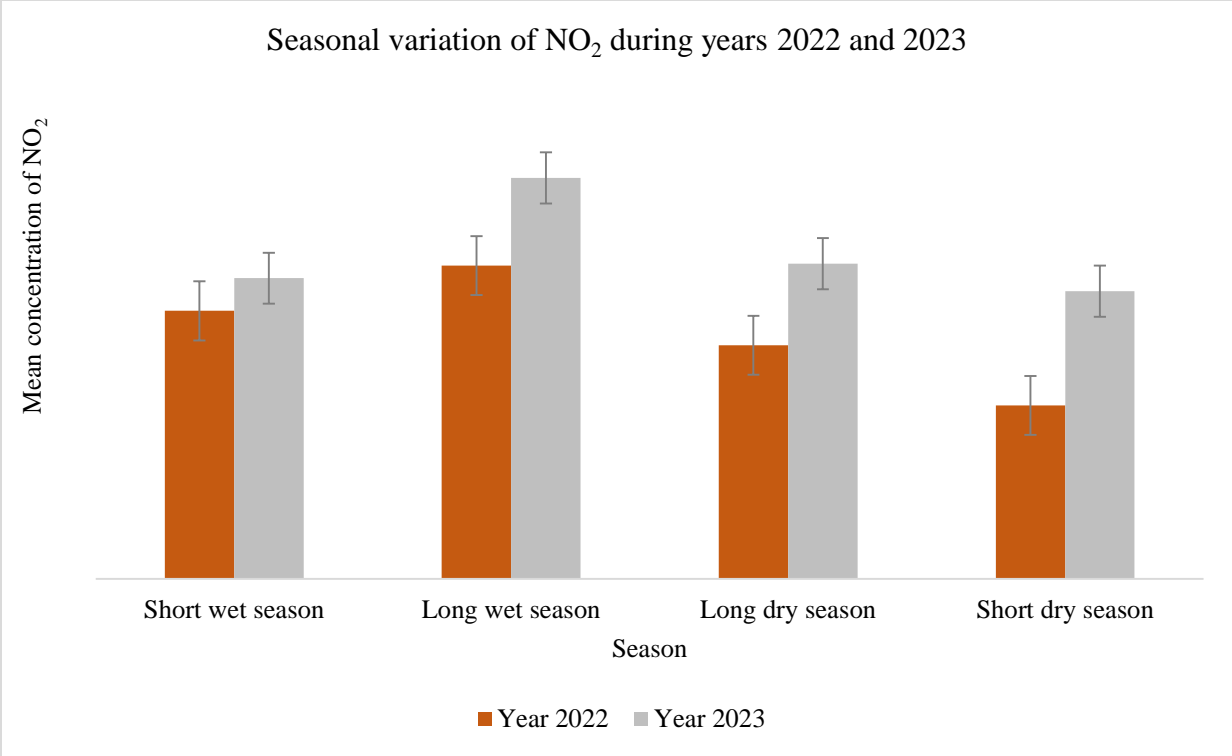


Figure 2: Seasonal variation of NO₂ during years 2022 and 2023

Figure 2 illustrates the seasonal variation of NO₂ (nitrogen dioxide) levels. NO₂ concentrations generally fluctuate across the short wet season, long wet season, long dry season, and short dry season. In both years, NO₂ levels appear to be higher during the dry seasons compared to the wet seasons. This trend can be attributed to reduced precipitation during dry periods, which limits the natural cleansing of pollutants from the atmosphere, leading to higher NO₂ accumulation. Additionally, increased vehicular and industrial emissions during dry seasons, coupled with stable atmospheric conditions, may prevent the dispersion of NO₂, further contributing to elevated concentrations. These findings align with studies by Zhang et al. (2016), who also observed higher NO₂ levels during dry seasons in urban areas due to similar factors.

4.1.2 Seasonal variation of PM_{2.5} during years 2022 and 2023

The seasonal variation of PM_{2.5} (particulate matter with a diameter of 2.5 micrometers or less) is a crucial factor in understanding air pollution patterns and their potential impacts on human health and the environment. PM_{2.5} levels can vary significantly across different seasons due to changes in weather conditions, emissions sources, and atmospheric processes. During the wet

and dry seasons, factors such as rainfall, humidity, and temperature can influence the concentration and distribution of $PM_{2.5}$ in the air. Analyzing the seasonal variation of $PM_{2.5}$ during the years 2022 and 2023 allows for a deeper understanding of how these environmental factors affect air quality, providing insights that can guide efforts to mitigate pollution and protect public health.

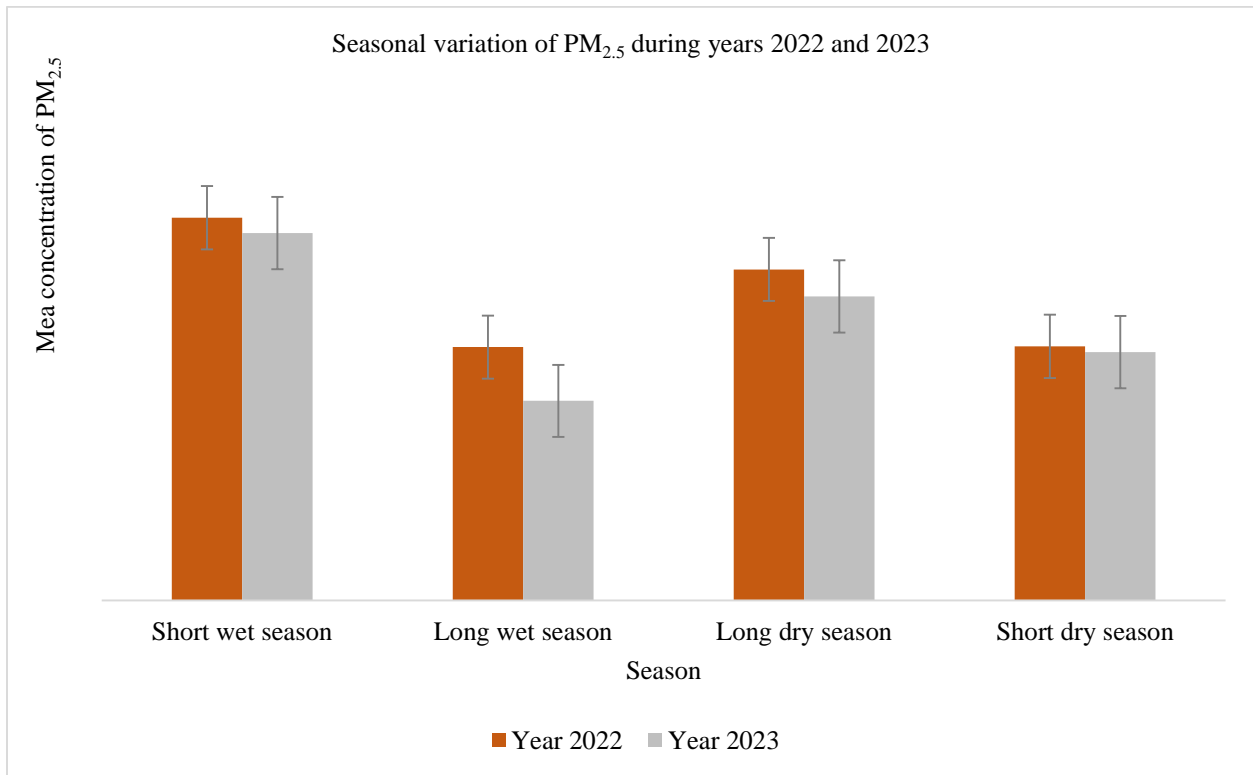


Figure 3: Seasonal variation of $PM_{2.5}$ during years 2022 and 2023

Figure 3 shows the seasonal variation of $PM_{2.5}$ (particulate matter) levels. The data reveals a pattern where $PM_{2.5}$ concentrations are higher during the dry seasons and lower during the wet seasons for both 2022 and 2023. The reduction in $PM_{2.5}$ levels during wet seasons can be explained by the cleansing effect of rainfall, which removes particulate matter from the atmosphere through wet deposition. Conversely, the dry seasons, characterized by low humidity and increased dust generation, result in higher $PM_{2.5}$ levels. This pattern is consistent with the findings of Tai et al. (2010), who demonstrated that rainfall significantly reduces $PM_{2.5}$ concentrations by washing out airborne particles, whereas dry conditions exacerbate particulate matter levels.

4.1.3 Seasonal variation of O₃ during years 2022 and 2023

The seasonal variation of O₃ (ozone) is a key aspect of atmospheric chemistry and air quality, as ozone levels can fluctuate throughout the year due to changes in environmental conditions and human activities. Ozone is a secondary pollutant formed through complex photochemical reactions involving sunlight, volatile organic compounds (VOCs), and nitrogen oxides (NO_x). The concentration of ozone is highly sensitive to seasonal factors such as temperature, sunlight, and weather patterns, which can lead to significant variations across different seasons. Examining the seasonal variation of ozone during the years 2022 and 2023 provides valuable insights into how these factors influence ozone levels, helping to understand the broader implications for air quality, human health, and climate change.

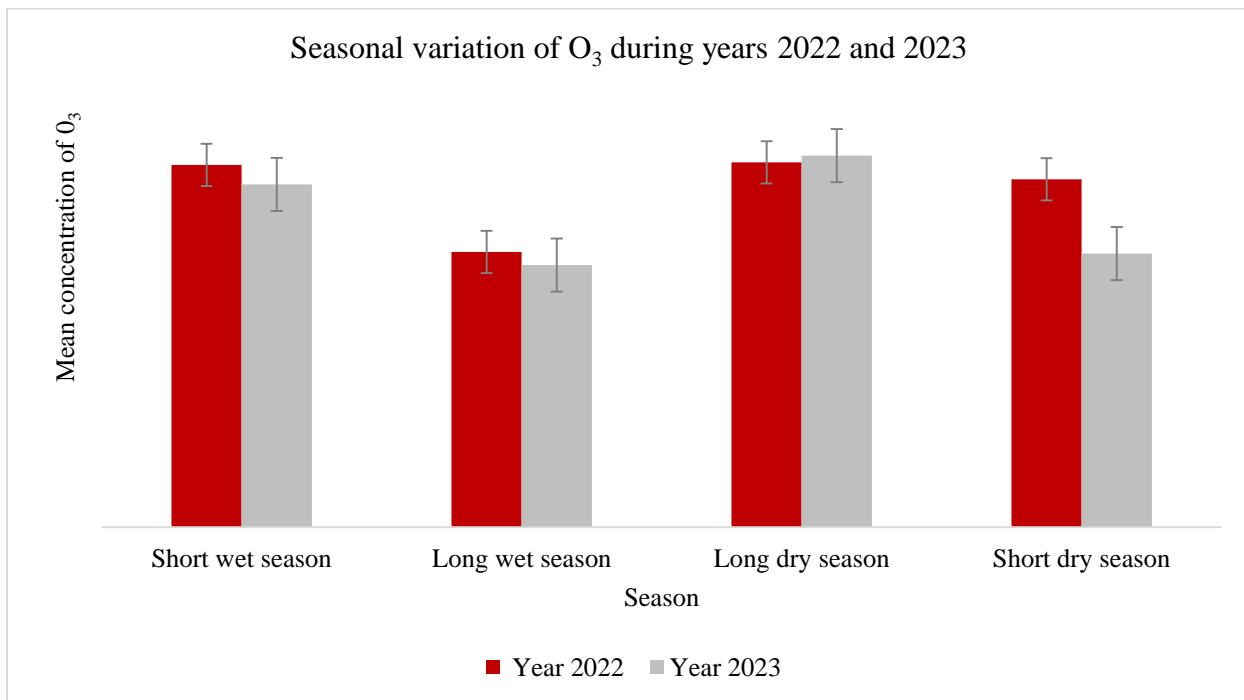


Figure 4: Seasonal variation of O₃ during years 2022 and 2023

Figure 4 presents the seasonal variation of O₃ (ozone) levels. The data indicates that O₃ concentrations peak during the long dry season and are lowest during the wet seasons in both years. This seasonal pattern is largely driven by the increased sunlight and higher temperatures

during dry periods, which enhance the photochemical reactions responsible for ozone formation. During wet seasons, cloud cover and rainfall reduce sunlight intensity and limit ozone production. These observations are in line with the work of Jacob and Winner (2009), who found that ozone levels typically rise during dry, sunny conditions due to increased photochemical activity and decrease during wet seasons when such conditions are less favorable.

For broader discussion, the seasonal variations observed in NO₂, PM_{2.5}, and O₃ concentrations in the current study align with findings from other scholars who have examined similar patterns in different regions. The increased NO₂ and PM_{2.5} levels during dry seasons, as well as the peak in O₃ concentrations during periods of high sunlight, are consistent with broader trends identified in urban air quality studies. For example, Zhang et al. (2016) studied seasonal air pollution trends in Beijing and found that NO₂ levels were significantly higher during the winter dry season due to increased emissions and limited atmospheric dispersion. Similarly, the study by Tai et al. (2010) on particulate matter highlighted the role of precipitation in reducing PM_{2.5} levels, a finding that is echoed in the current study's observation of lower PM_{2.5} concentrations during wet seasons. Regarding ozone, the seasonal trend observed in the current study higher concentrations during dry seasons parallels the findings of Jacob and Winner (2009), who emphasized the influence of sunlight and temperature on ozone formation. These studies collectively reinforce the idea that seasonal variations in meteorological conditions play a critical role in shaping air pollutant levels, and similar patterns are observed across different geographic regions. Thus, the seasonal variation in NO₂, PM_{2.5}, and O₃ concentrations observed in this study is consistent with the broader literature on air quality. The findings underscore the importance of considering seasonal meteorological factors when assessing air pollution levels and implementing mitigation strategies.

4.2 Quantification of meteorological factors and air pollutants in the study area

Quantification of meteorological factors and air pollutants is a fundamental process in assessing air quality and understanding the complex interactions between atmospheric conditions and pollution levels in a study area. Meteorological factors such as temperature, relative humidity, wind speed, and atmospheric pressure directly influence the concentration, distribution, and transformation of air pollutants like nitrogen dioxide (NO₂), ozone (O₃), particulate matter

(PM_{2.5}), and other harmful substances. By systematically measuring and analyzing these factors, researchers can identify patterns and correlations that provide insights into the sources and behavior of pollutants under different weather conditions.

4.2.1 Average quantity of meteorological factors in 2022 and 2023 of the study area

Analyzing the average quantity of relative humidity in 2022 and 2023 within the study area is essential for understanding the atmospheric moisture patterns that influence both weather conditions and air quality. Relative humidity, which represents the percentage of moisture in the air relative to the maximum amount the air can hold at a given temperature, plays a significant role in various environmental processes. It affects cloud formation, precipitation patterns, and the dispersion of air pollutants. By examining the average relative humidity over these two years, researchers can identify trends, seasonal variations, and potential anomalies that may have influenced both local climate conditions and pollution levels. This analysis is crucial for gaining insights into the interplay between humidity and other meteorological factors, as well as for developing strategies to address the impacts of changing humidity levels on agriculture, health, and the overall environment in the study area.

Table 1: Average quantity of meteorological factors in 2022 and 2023 in the study area

Months	Average Monthly Climatic Factors				Average Monthly air Pollutants		
	RH	RF	WS	T° C	NO ₂	O ₃	PM _{2.5}
January	75.686	282.5	1.335	20.094	21.739	31.056	28.548
February	75.194	559.6	1.260	20.515	23.346	29.203	27.831
March	79.119	434.4	1.227	20.265	24.222	24.691	19.844
April	83.971	673.2	1.354	19.688	24.138	20.024	15.622
May	83.035	260.5	1.461	19.852	21.989	24.164	15.604
June	77.107	102.0	1.654	19.339	22.425	30.187	22.436
July	68.083	17.2	1.906	19.309	21.885	34.103	25.115
August	66.819	30.1	1.873	20.840	22.489	32.235	25.421
September	72.844	432.1	1.615	21.019	22.875	29.317	22.486
October	73.759	295.0	1.510	20.952	21.788	28.403	18.536
November	82.518	554.3	1.282	19.836	22.028	24.733	17.223
December	80.823	1934.5	1.319	20.042	21.846	28.009	21.328
Monthly Average	76.563	464.6	1.485	20.145	22.555	28.022	21.640

The results presented in Table 1 provide a comprehensive overview of the interactions between average monthly climatic factors and air pollutant levels in the study area for the years 2022 and

2023. The relationship between these variables is crucial for understanding the dynamics of air quality in response to changing meteorological conditions.

Relative humidity (RH) demonstrates significant seasonal variations, with the highest levels observed during the wet months of April, May, and November, where RH exceeds 80%. During these months, the concentrations of ozone (O_3) and particulate matter ($PM_{2.5}$) are at their lowest. This inverse relationship suggests that increased moisture content in the air can suppress the formation of O_3 and facilitate the removal of particulate matter from the atmosphere through processes like wet deposition. For instance, in April, when RH is at its peak (83.97%), O_3 and $PM_{2.5}$ levels drop to their lowest points, $20.02 \mu\text{g}/\text{m}^3$ and $15.62 \mu\text{g}/\text{m}^3$ respectively. Conversely, in drier months such as July and August, when RH dips to around 68%, O_3 and $PM_{2.5}$ concentrations rise, indicating that drier conditions may enhance the formation and persistence of these pollutants. When looking at the impact of Relative Humidity and Rainfall on Air Pollutants, several studies have demonstrated that increased relative humidity and rainfall contribute to the reduction of air pollutants, particularly ozone (O_3) and particulate matter ($PM_{2.5}$). For example, Wang *et al.* (2019) found that high humidity suppresses ozone formation due to reduced photochemical activity, while rainfall promotes wet deposition, effectively removing pollutants from the atmosphere (Wang et al., 2019)

Rainfall (RF) follows a similar pattern, with higher rainfall generally corresponding to lower levels of O_3 and $PM_{2.5}$. During the months of April and November, where rainfall averages 6.73 mm and 5.54 mm respectively, there is a marked decrease in the concentrations of these pollutants. Rainfall contributes to the reduction of air pollutants through wet deposition, where pollutants are removed from the atmosphere by precipitation. This effect is particularly evident in months with significant rainfall, such as December, where the average rainfall reaches 19.35 mm, leading to relatively low levels of $PM_{2.5}$ ($21.33 \mu\text{g}/\text{m}^3$). However, in months with minimal rainfall, such as July (0.17 mm), $PM_{2.5}$ concentrations are notably higher, reinforcing the role of precipitation in mitigating air pollution. When looking the effect of Rainfall and Its Impact on Air Pollution; scholars like Haapea and Tuhkanen (2006) in their studies, showed the effects of rainfall on particulate matter concentrations and found that wet deposition significantly reduces levels of pollutants like $PM_{2.5}$ and PM_{10} in the atmosphere. Their research highlights that rainfall

can wash out airborne particles, thereby improving air quality during and after precipitation events (Haapea & Tuhkanen, 2006).

Wind speed (WS) exhibits variability throughout the year, with higher speeds recorded during the months of June, July, and August. Wind plays a critical role in the dispersion of pollutants, and the data indicates that increased wind speed is associated with moderate levels of NO₂, O₃, and PM_{2.5}. For example, in July, when wind speed is highest at 1.91 m/s, the concentration of NO₂ is relatively low (21.88 µg/m³), reflecting the dispersive effect of wind on pollutants. This pattern supports the understanding that wind enhances the dilution of air pollutants, reducing their concentrations near emission sources. Similarly, the months with lower wind speeds, such as January and November, tend to show higher pollutant concentrations, indicating that stagnant air conditions contribute to the accumulation of pollutants. The relationship between wind speed and air pollutant dispersion is well-documented. According to Lv *et al.* (2021), higher wind speeds facilitate the dilution and transport of pollutants such as nitrogen dioxide (NO₂) and PM_{2.5}, reducing their concentrations near emission (Lv et al., 2021).

Temperature (T°C) remains relatively stable throughout the year, with minor fluctuations. However, slight increases in temperature during the warmer months are correlated with higher levels of O₃. This correlation is expected, as temperature influences the rate of photochemical reactions that produce O₃. For instance, in August, where the temperature peaks at 20.84°C, O₃ concentration reaches 32.23 µg/m³, among the highest recorded in the year. This relationship between temperature and O₃ is well documented, as higher temperatures enhance the reaction rates of ozone precursors like nitrogen oxides (NO_x) and volatile organic compounds (VOCs). On the other hand, NO₂ levels show less pronounced seasonal variation but tend to be slightly higher during cooler months with lower temperatures, such as February (23.34 µg/m³), suggesting that lower temperatures may slow the dispersal of NO₂ and lead to its accumulation. The influence of temperature on ozone levels has been extensively studied. Research by Li *et al.* (2017a) shows that higher temperatures accelerate photochemical reactions involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs), leading to increased ozone production, particularly during summer months (Li et al., 2017a).

Comparing these findings with the results of other scholars, similar patterns are observed. Numerous studies have shown that higher humidity and rainfall reduce concentrations of pollutants like O₃ and PM_{2.5} due to increased removal processes, such as wet deposition and reduced photochemical activity. For instance, research conducted in urban areas has consistently demonstrated that wet and humid conditions lead to lower O₃ levels, as increased moisture in the atmosphere inhibits the photochemical formation of O₃. Furthermore, studies have indicated that temperature is a key driver of O₃ production, with warmer temperatures leading to higher concentrations of this pollutant, particularly during the summer months. The role of wind speed in pollutant dispersion is also widely acknowledged, with higher wind speeds facilitating the dilution and transport of pollutants away from their sources, leading to improved air quality. For a broader discussion, the results from the study area highlight the significant influence of monthly climatic factors on air pollutant levels. Higher humidity and rainfall generally lead to reductions in pollutants like O₃ and PM_{2.5}, while temperature and wind speed modulate the formation and dispersion of pollutants such as O₃ and NO₂. These findings are consistent with broader scientific literature, underscoring the importance of meteorological conditions in shaping air quality outcomes. Understanding these relationships is crucial for developing effective strategies to manage air pollution and mitigate its impacts on public health and the environment.

4.3 Prediction of air pollutants change using meteorological conditions in the study area

The prediction of air pollutant changes using meteorological conditions is a crucial approach to understanding and managing air quality. Meteorological factors such as temperature, humidity, wind speed, and rainfall play significant roles in influencing the concentration and dispersion of pollutants in the atmosphere.

4.3.1 Mean concentration of PM_{2.5} against mean Rainfall

The relationship between the mean concentration of PM_{2.5} (particulate matter with a diameter of 2.5 micrometers or less) and mean rainfall is essential for understanding how meteorological conditions influence air quality. PM_{2.5} is a major air pollutant that poses significant health risks, and its concentration in the atmosphere can be affected by various weather factors, particularly rainfall. Rainfall can act as a natural cleansing agent by removing particulate matter from the air through wet deposition. Analyzing the mean concentration of PM_{2.5} against mean rainfall helps

to assess the extent to which precipitation influences the dispersion and reduction of airborne particles, offering valuable insights into the interaction between atmospheric conditions and pollution levels.

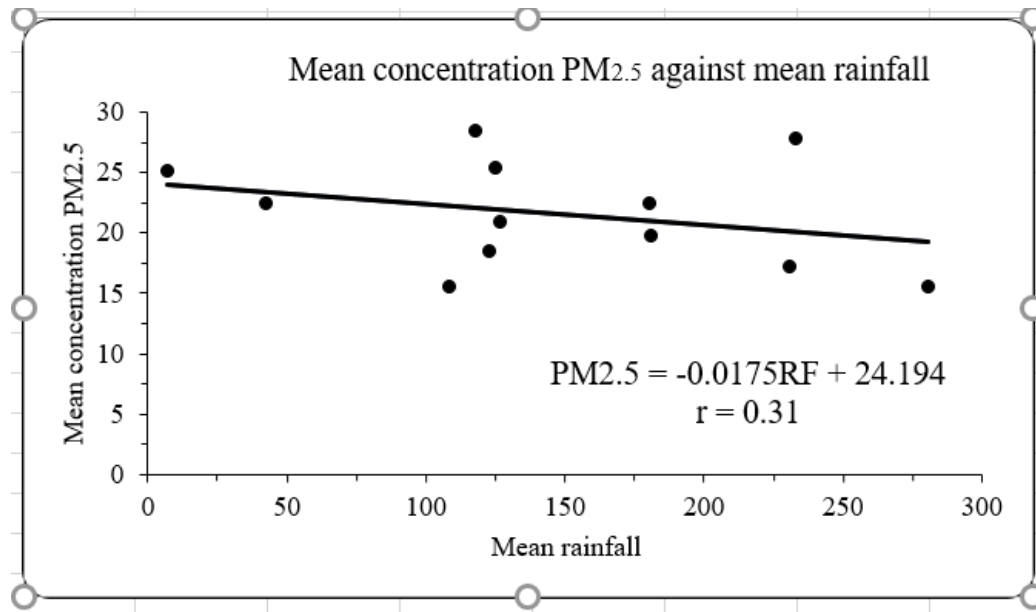


Figure 5: Mean concentration of PM_{2.5} against mean Rainfall

In **Figure 5**, the plot of PM_{2.5} concentrations against mean rainfall typically shows a negative correlation. This suggests that as rainfall increases, PM_{2.5} levels tend to decrease. The r^2 value in this case would indicate the extent to which rainfall can predict PM_{2.5} concentrations. A high r^2 value suggests a strong relationship, while a low r^2 value implies that rainfall alone does not explain much of the variance in PM_{2.5} levels. The negative trend can be attributed to rainfall's ability to cleanse the atmosphere through a process known as wet deposition. Raindrops capture airborne particulate matter, removing it from the atmosphere and lowering PM_{2.5} levels. This phenomenon is supported by various studies, including those by Fan et al. (2020a), which demonstrate how rainfall reduces particulate matter concentrations by washing them out of the air.

4.3.2 Mean concentration of PM_{2.5} against mean Relative humidity

The relationship between the mean concentration of PM_{2.5} (particulate matter with a diameter of 2.5 micrometers or less) and mean relative humidity is a critical factor in understanding how atmospheric moisture influences air quality. Relative humidity, which measures the amount of

moisture in the air, can affect the behavior and concentration of PM_{2.5} in several ways. High humidity levels can lead to the agglomeration of particles, causing them to settle out of the atmosphere, while also promoting the formation of secondary particles through chemical reactions. By analyzing the mean concentration of PM_{2.5} against mean relative humidity, we gain valuable insights into the complex interactions between moisture levels and particulate matter, which can help in developing strategies to manage and improve air quality.

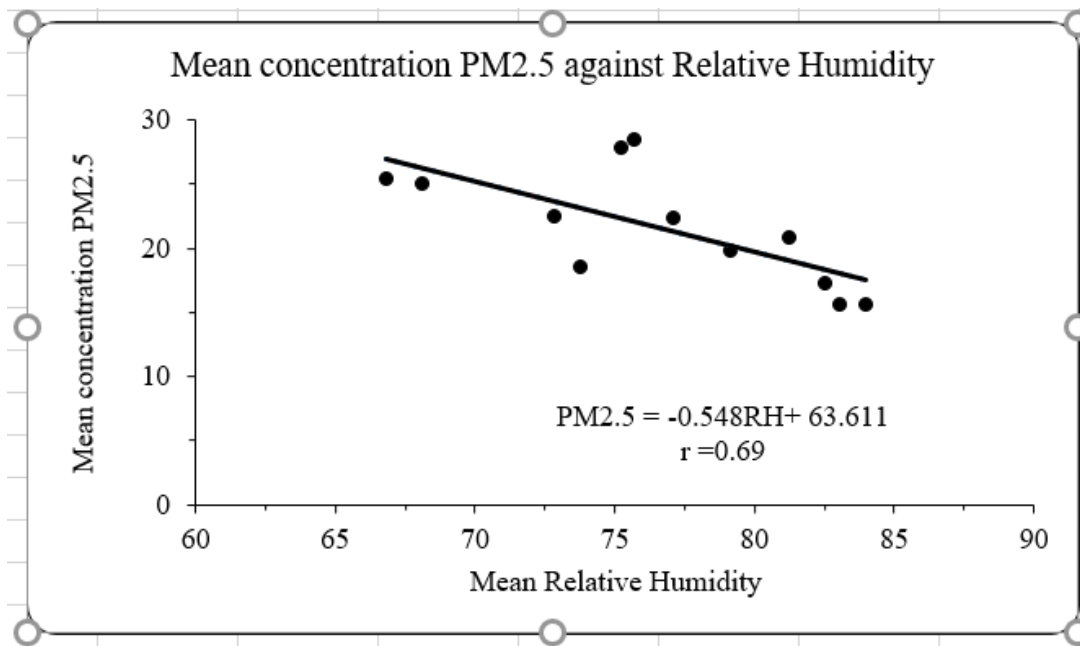


Figure 6: Mean concentration of PM_{2.5} against mean Relative humidity

Figure 6 examines the relationship between PM_{2.5} concentrations and relative humidity. The trend here can vary, showing either a positive or negative correlation, depending on the region and prevailing atmospheric conditions. A high r^2 value would suggest that relative humidity significantly influences PM_{2.5} levels, whereas a low r^2 value implies a weaker relationship. Relative humidity affects particulate matter through two primary mechanisms. First, higher humidity can lead to the agglomeration of particles, causing them to settle more quickly and reducing PM_{2.5} concentrations. On the other hand, high humidity can also promote the formation of secondary particulate matter via chemical reactions in the atmosphere, potentially increasing PM_{2.5} levels. The work of Seinfeld and Pandis (2016) elaborates on the complex interplay

between humidity and particulate matter, highlighting how the effects can vary depending on the broader environmental context.

4.3.3 Mean concentration of Ozone (O₃) against mean Relative humidity

The relationship between the mean concentration of ozone (O₃) and mean relative humidity is important for understanding how moisture levels in the atmosphere influence ozone formation and persistence. Ozone is a secondary pollutant that forms through complex photochemical reactions involving sunlight, volatile organic compounds (VOCs), and nitrogen oxides (NO_x). Relative humidity, which reflects the amount of moisture in the air, can significantly impact these reactions and thus the concentration of ozone. High humidity levels can inhibit ozone formation by increasing cloud cover and reducing sunlight penetration, while also promoting chemical processes that break down ozone.

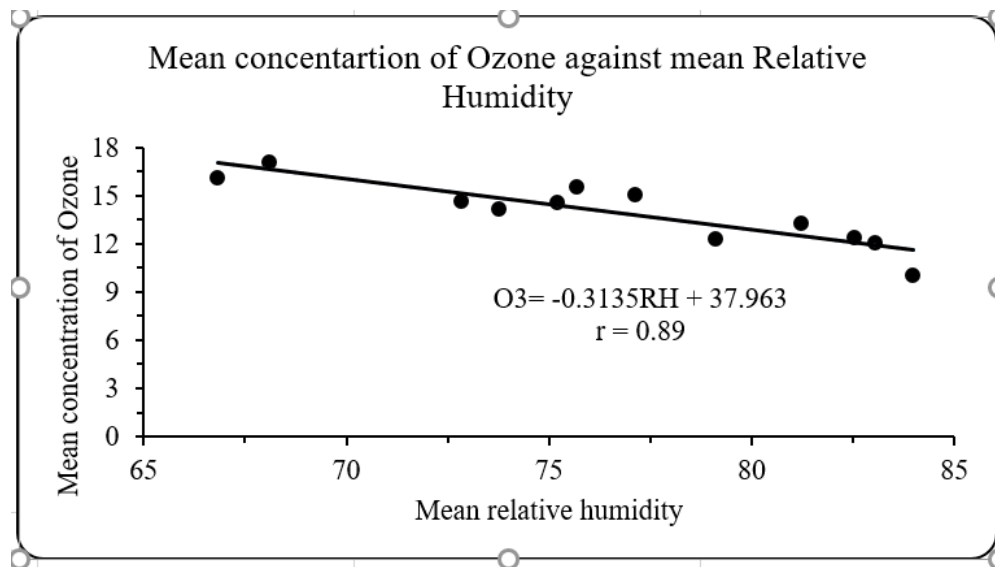


Figure 7: Mean concentration of Ozone (O₃) against mean Relative humidity

In Figure 7, the relationship between ozone (O₃) concentrations and relative humidity is presented. Typically, ozone concentrations decrease as relative humidity increases, leading to a negative correlation. A high r^2 value in this case would indicate that relative humidity is a strong predictor of ozone levels. The negative trend can be explained by the role of humidity in facilitating the destruction of ozone through increased cloud cover and water vapor, which

absorbs ultraviolet radiation necessary for ozone formation. This effect is discussed in studies such as those by Jacob and Winner (2009a), who emphasize the importance of relative humidity in modulating ozone levels through its impact on sunlight penetration and chemical reactions in the atmosphere.

4.3.4 Mean concentration of Ozone (O₃) against mean Rainfall

The relationship between the mean concentration of ozone (O₃) and mean rainfall is a key area of study in understanding how precipitation influences atmospheric ozone levels. Ozone, a secondary pollutant formed through photochemical reactions involving sunlight, nitrogen oxides (NO_x), and volatile organic compounds (VOCs), can be affected by rainfall in several ways. Rainfall can reduce ozone concentrations by washing out its precursors from the atmosphere and cooling the environment, which slows down the photochemical reactions that produce ozone

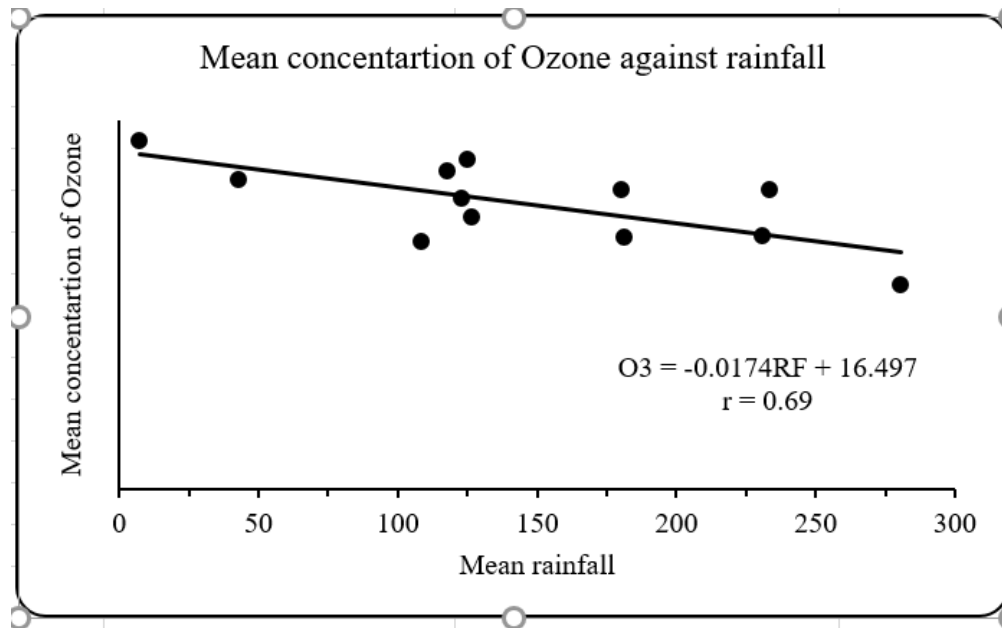


Figure 8: Mean concentration of Ozone (O₃) against mean Rainfall

Figure 8 shows the relationship between ozone concentrations and rainfall. Generally, this relationship is negative, as increased rainfall tends to lower ozone levels. A strong r^2 value would suggest that rainfall significantly impacts ozone concentrations. The reduction in ozone during rainfall can be attributed to the scavenging effect of rain, which removes ozone precursors like

nitrogen oxides (NO_x) from the atmosphere, thus reducing ozone formation. Additionally, rain-induced cooling of the atmosphere can slow down the photochemical reactions responsible for ozone production. Studies by He *et al.* (2019a) support these findings, showing that rainfall events are often associated with decreased ozone levels due to the removal of precursor gases.

4.3.5 Mean concentration of Ozone (O₃) against mean Temperature

The relationship between mean concentration of Ozone (O₃) and mean temperature is a critical subject in atmospheric science, particularly in understanding air quality and its broader environmental impacts. Ozone, a key component of smog, forms through complex photochemical reactions involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight. Temperature plays a significant role in these reactions by accelerating the chemical processes that lead to the formation of O₃. As temperature increases, the rate of O₃ production typically rises, often leading to higher concentrations in urban areas during warm periods.

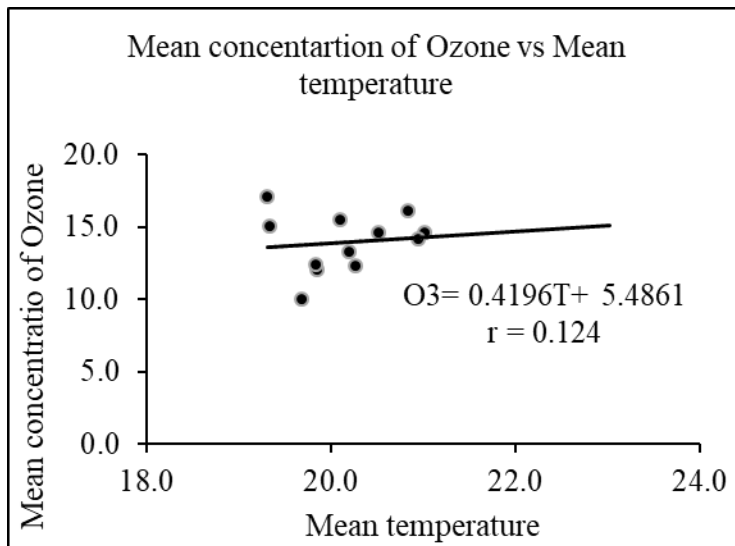


Figure 9: Mean concentration of Ozone (O₃) against mean Temperature

In Figure 9, the focus shifts to the relationship between ozone concentrations and temperature. Here, a positive correlation is typically observed, with ozone levels increasing as temperature rises. A high r^2 value would indicate that temperature is a strong predictor of ozone

concentrations. The positive trend is rooted in the fact that higher temperatures enhance the photochemical reactions that produce ozone. Sunlight and heat are critical in converting volatile organic compounds (VOCs) and nitrogen oxides into ozone, leading to higher concentrations during warmer periods. This relationship is well documented in atmospheric chemistry, with studies like those by Jacob and Winner (2009) emphasizing how temperature influences ozone levels through increased photochemical activity.

4.3.6 Mean concentration of NO₂ against mean Relative Humidity

The relationship between the mean concentration of nitrogen dioxide (NO₂) and mean relative humidity is a significant focus in air quality studies, as it reveals how atmospheric conditions influence pollutant behavior. Nitrogen dioxide, a harmful air pollutant, is primarily produced from the combustion of fossil fuels, such as in-vehicle emissions and industrial processes. Relative humidity, which measures the amount of moisture in the air, can affect the concentration and dispersion of NO₂ in complex ways. High relative humidity can lead to the formation of secondary pollutants through chemical reactions involving NO₂, such as the production of nitric acid or particulate matter, which may reduce NO₂ levels in the atmosphere.

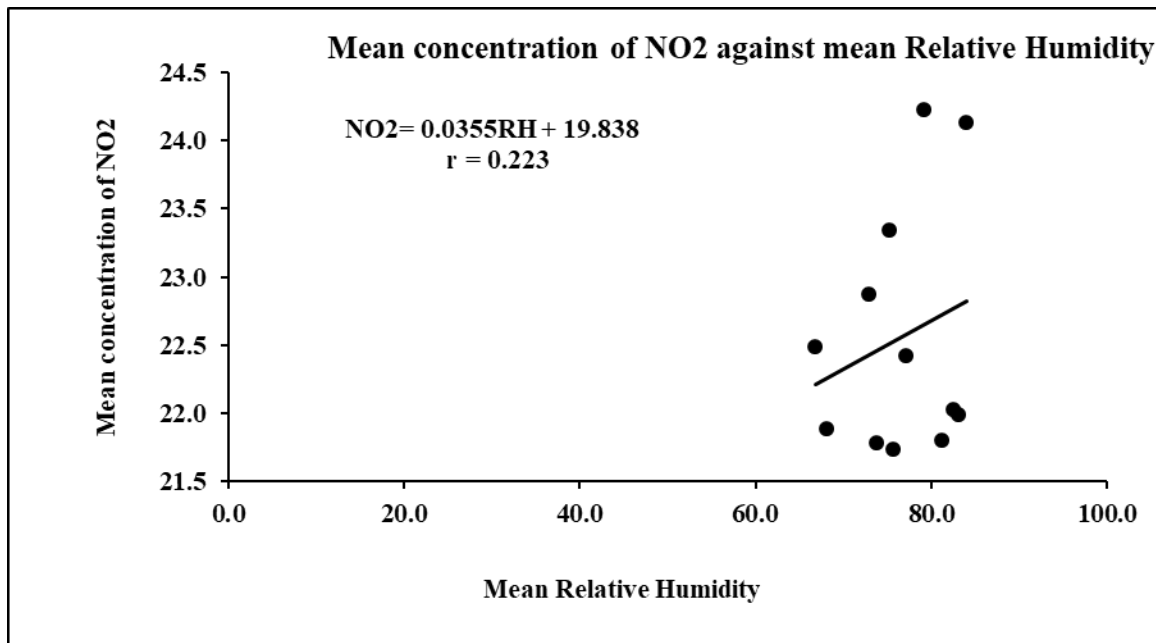


Figure 10: Mean concentration of NO₂ against mean Relative Humidity

Figure 10 explores the connection between NO₂ concentrations and relative humidity. The trend in this case can be either positive or negative, depending on the local conditions. A strong r² value would suggest a significant relationship between relative humidity and NO₂ levels. High relative humidity can reduce NO₂ concentrations by promoting the formation of nitric acid (HNO₃) through reactions with water vapor, which is then removed from the atmosphere. Alternatively, under certain conditions, high humidity can trap pollutants near the ground, leading to higher NO₂ concentrations. The dual role of humidity in affecting NO₂ levels is discussed in various studies, including those by Seinfeld and Pandis (2016), which highlight the complexity of the interactions between humidity and atmospheric chemistry.

4.3.7 Mean concentration of NO₂ against mean Temperature

The relationship between mean concentration of nitrogen dioxide (NO₂) and mean temperature is a crucial area of study in environmental science, particularly for understanding air pollution dynamics. Nitrogen dioxide, a prominent pollutant, is mainly generated from combustion processes, such as vehicle emissions, power plants, and industrial activities. Temperature significantly influences the behavior of NO₂ in the atmosphere, affecting both its formation and dispersion. Higher temperatures can enhance the chemical reactions that produce NO₂, particularly during photochemical processes involving sunlight. Additionally, elevated temperatures can contribute to the stratification of air, which may trap NO₂ closer to the ground, leading to higher concentrations at the surface level. On the other hand, lower temperatures might reduce the rate of these chemical reactions and promote the dispersion of NO₂, resulting in lower concentrations.

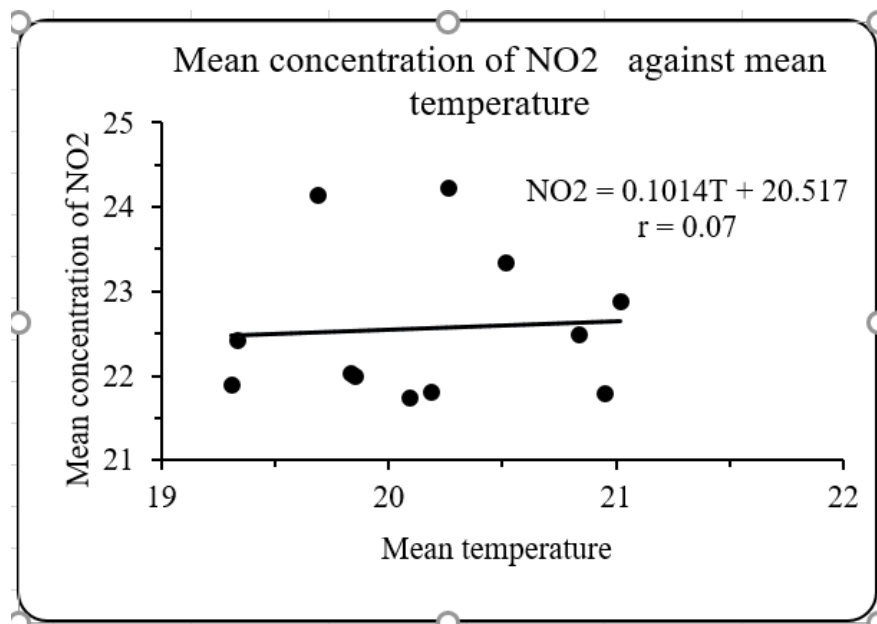


Figure 11: Mean concentration of NO₂ against mean Temperature

In **Figure 11**, the relationship between NO₂ concentrations and temperature is examined. Typically, this relationship is positive, with NO₂ levels increasing as temperature rises. A high r^2 value would suggest that temperature is a significant predictor of NO₂ concentrations. The positive trend can be explained by the fact that higher temperatures enhance the chemical reactions that produce NO₂, particularly from vehicular and industrial emissions. Elevated temperatures also increase the volatility of organic compounds, leading to more NO₂ formation. Studies such as those by Finlayson-Pitts *et al.* (2003) support these findings, showing that NO₂ concentrations tend to be higher during warmer periods due to enhanced chemical reactions.

4.3.8 Mean concentration of NO₂ against mean Wind Speed

The relationship between the mean concentration of nitrogen dioxide (NO₂) and mean wind speed is a critical aspect of atmospheric studies, as wind plays a fundamental role in the dispersion and distribution of air pollutants. Nitrogen dioxide, a key pollutant primarily produced from fossil fuel combustion, is often concentrated in urban areas and near sources of emissions such as vehicles and industrial sites. Wind speed influences the concentration of NO₂ by affecting how quickly and efficiently the pollutant is dispersed in the atmosphere. Higher wind

speeds typically lead to better mixing and dispersion of NO₂, reducing its concentration near the emission sources and improving air quality.

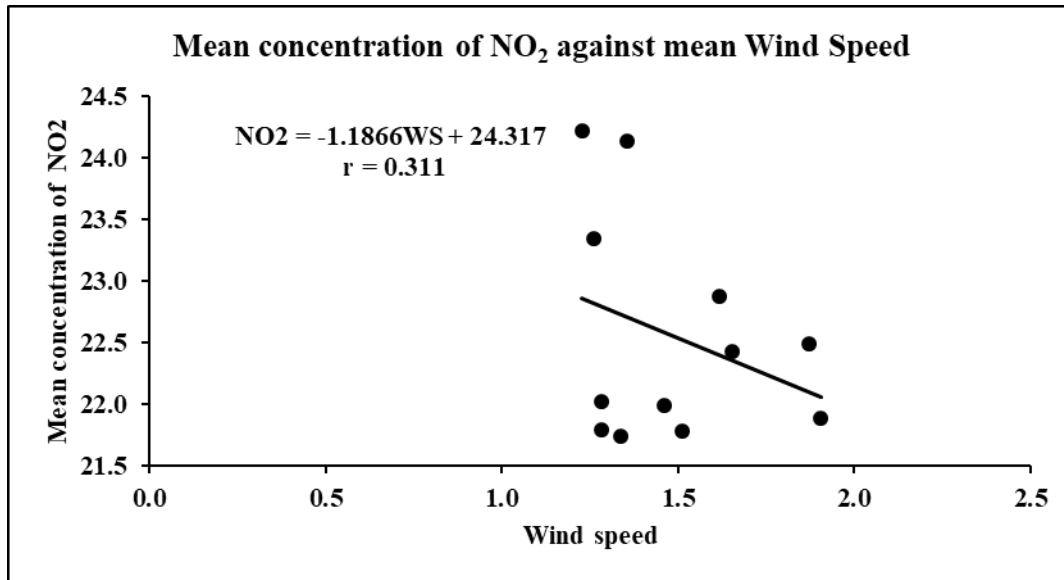


Figure 12: Mean concentration of NO₂ against mean Wind Speed

Finally, **Figure 8** investigates the relationship between NO₂ concentrations and wind speed. Typically, a negative correlation is observed, with NO₂ levels decreasing as wind speed increases. A strong r^2 value would indicate that wind speed is a significant predictor of NO₂ concentrations. The negative trend observed from the above figure can be attributed to the dispersal effect of wind. Higher wind speeds help to dilute and disperse NO₂, reducing its concentration in the atmosphere. This relationship is supported by numerous studies, including those by Rao et al. (2003), which demonstrate how increased wind speed can lead to lower concentrations of air pollutants like NO₂ by enhancing atmospheric mixing and transport. By partial conclusion, the simple linear regression analyses presented in these figures provide valuable insights into the relationships between air pollutant concentrations and meteorological factors. However, the strength of these relationships, as indicated by the r^2 values, varies, suggesting that while meteorological factors play a critical role, other elements such as emissions, chemical transformations, and local topography must be considered.

CHAPTER FIVE: RESULTS DISCUSSION

From the results presented in Table 1, the findings from the analysis of meteorological and air quality parameters in Nyagatare and Bugesera for the years 2022 and 2023 were averagely summed up and reveal significant trends with profound implications for health issues, biodiversity, and environmental pollution.

5.1. Seasonal Variation of air pollutants and their different effects

Understanding the seasonal variation of key air pollutants NO_2 , $\text{PM}_{2.5}$, and O_3 is crucial for comprehending the dynamics of air quality and its impact on health and the environment. Analysis of data from 2022 and 2023 reveals distinct seasonal patterns influenced by various meteorological factors, such as precipitation, temperature, and atmospheric conditions.

Nitrogen Dioxide (NO_2) levels exhibit a pronounced seasonal variation, with higher concentrations observed during the dry seasons compared to the wet seasons. This pattern is driven by reduced precipitation during dry periods, which limits the natural cleansing of pollutants and allows NO_2 to accumulate in the atmosphere. Additionally, dry seasons often see increased vehicular and industrial emissions combined with stable atmospheric conditions that inhibit the dispersion of NO_2 , leading to elevated concentrations. This observation aligns with Zhang et al. (2016), who reported similar trends in urban areas, attributing higher NO_2 levels during dry seasons to increased emissions and limited atmospheric cleansing. The stable, low-wind conditions during these periods further exacerbate NO_2 accumulation, reinforcing the need for targeted pollution control measures during these times.

Particulate Matter ($\text{PM}_{2.5}$) also demonstrates seasonal variation, with higher concentrations during the dry seasons and lower levels during the wet seasons. The increase in $\text{PM}_{2.5}$ during dry periods can be attributed to lower humidity and increased dust generation, which contribute to elevated particulate matter levels. Conversely, the wet seasons experience a reduction in $\text{PM}_{2.5}$ due to the cleansing effect of rainfall, which removes airborne particles through wet deposition. Tai et al. (2010) corroborate these findings, highlighting that rainfall effectively reduces $\text{PM}_{2.5}$ concentrations by washing out particulate matter from the atmosphere. This seasonal pattern

underscores the impact of weather conditions on particulate matter levels and highlights the importance of considering these variations in air quality management strategies.

Ozone (O₃) levels exhibit a clear seasonal trend, peaking during the long dry season and reaching their lowest during the wet seasons. The higher O₃ concentrations during dry periods can be attributed to increased sunlight and higher temperatures, which enhance the photochemical reactions that produce ozone. During the wet seasons, cloud cover and rainfall reduce sunlight intensity, limiting ozone production. This seasonal variation is consistent with the findings of Jacob and Winner (2009), who noted that ozone levels rise during dry, sunny conditions due to increased photochemical activity and decrease during wetter periods when such conditions are less prevalent. This highlights the sensitivity of ozone levels to changes in meteorological conditions, particularly sunlight and temperature.

The seasonal variations in NO₂, PM_{2.5}, and O₃ observed in this study are consistent with broader trends reported in the literature. The results of Li et al. (2019) found that NO₂ levels are higher during dry seasons due to increased emissions and limited dispersion, while Tai *et al.* (2012) demonstrated the role of rainfall in reducing PM_{2.5} levels. Similarly, Jacob and Winner (2009) emphasized the impact of sunlight and temperature on ozone formation. These studies reinforce the importance of considering seasonal meteorological factors when assessing air quality and developing strategies to mitigate pollution. Finally, the observed seasonal variations in NO₂, PM_{2.5}, and O₃ levels reflect the complex interplay between meteorological factors and pollutant dynamics. Higher NO₂ and PM_{2.5} concentrations during dry seasons, coupled with elevated O₃ levels in sunny conditions, underscore the need for targeted pollution control measures and strategies to address the specific challenges posed by seasonal variations. Understanding these patterns is crucial for developing effective air quality management practices and mitigating the adverse impacts of air pollution on public health and the environment.

5.2. Quantification of meteorological and Air pollutants of the study area.

The study of meteorological factors and their impact on air pollutants in the study area for 2022 and 2023 provides valuable insights into the dynamics of air quality. Key variables are relative

humidity (RH), rainfall (RF), wind speed (WS), and temperature (T°C) interact in complex ways with pollutant concentrations, specifically NO₂, O₃, and PM_{2.5}, influencing overall air quality.

Relative humidity shows significant seasonal variation, with higher levels observed during the wet months of April, May, and November, where RH exceeds 80%. This elevated humidity is associated with lower concentrations of ozone (O₃) and particulate matter (PM_{2.5}). For example, in April, when RH peaks at 83.97%, O₃ and PM_{2.5} levels drop to their lowest recorded values, 20.02 µg/m³ and 15.62 µg/m³, respectively. This negative correlation indicates that increased atmospheric moisture suppresses O₃ formation and facilitates the removal of particulate matter through wet deposition. Wang et al. (2019) support this observation, noting that high humidity reduces photochemical activity, which in turn lowers O₃ levels and enhances the removal of pollutants.

Rainfall similarly impacts pollutant levels, with increased precipitation generally corresponding to reduced concentrations of O₃ and PM_{2.5}. During April and November, where rainfall averages 6.73 mm and 5.54 mm respectively, there is a noticeable decrease in these pollutants. The role of rainfall in mitigating air pollution is evident, as wet deposition helps cleanse the atmosphere of airborne pollutants. This finding is consistent with Haapea and Tuhkanen (2006) research, which highlights the effectiveness of rainfall in reducing particulate matter concentrations through atmospheric washing.

Wind speed, which varies throughout the year, affects the dispersion of pollutants. Higher wind speeds, recorded in June, July, and August, are associated with moderate levels of NO₂, O₃, and PM_{2.5}. For instance, in July, when wind speed is highest at 1.91 m/s, NO₂ concentrations are relatively low (21.88 µg/m³). This indicates that increased wind speeds facilitate the dilution and dispersion of pollutants, reducing their concentrations near emission sources. Lv et al. (2021), who found that higher wind speeds enhance the dispersion of pollutants, thereby lowering their concentrations, support this observation.

Temperature remains relatively stable, but slight increases during warmer months correlate with higher O₃ levels. For example, in August, where temperatures peak at 20.84°C, O₃ concentrations reach 32.23 µg/m³, among the highest recorded. This relationship is explained by the accelerated

rate of photochemical reactions that produce O₃ at higher temperatures. Li et al. (2017a) confirm that higher temperatures enhance the production of O₃ through increased reactions involving nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Conversely, NO₂ levels tend to be higher during cooler months, such as February, suggesting that lower temperatures may impede the dispersal of NO₂ and contribute to its accumulation. Furthermore, the results highlight the significant influence of meteorological factors on air pollutant levels. Elevated humidity and rainfall generally lead to reductions in O₃ and PM_{2.5} due to increased removal processes and decreased photochemical activity. In contrast, temperature and wind speed play roles in modulating the formation and dispersion of pollutants, with higher temperatures leading to increased O₃ levels and higher wind speeds contributing to pollutant dilution. These findings align with broader scientific literature, emphasizing the critical role of meteorological conditions in shaping air quality. Understanding these interactions is crucial for developing effective strategies to manage air pollution and mitigate its impacts on public health and the environment.

5.3. Prediction of the variation in levels of air pollutants using meteorological conditions.

The findings from the study reveal significant relationships between various meteorological factors and air pollutants, such as PM_{2.5}, NO₂, and O₃. The study highlights key trends and correlations that are critical for understanding air quality dynamics in the region. For instance, the analysis of PM_{2.5} concentrations against rainfall demonstrates a clear negative correlation, suggesting that higher rainfall generally reduces PM_{2.5} levels. This aligns with the wet deposition theory, where raindrops capture and remove airborne particles, thus lowering pollution levels. Similar conclusions were drawn by Fan *et al.* (2020b), who emphasized rainfall's role in cleansing the atmosphere.

The relationship between PM_{2.5} and relative humidity presents more complexity, as the study identifies both positive and negative correlations depending on the conditions. While higher humidity can lead to particle agglomeration and settling, it can also facilitate the formation of secondary particles. This dual effect is consistent with findings by Seinfeld and Pandis (2016), who explored the multifaceted impacts of humidity on particulate matter.

Regarding ozone (O₃), the study shows that higher relative humidity tends to decrease ozone levels, likely due to increased cloud cover reducing sunlight penetration, which is necessary for

ozone formation. Jacob and Winner (2009), who noted the role of humidity in breaking down ozone, support this finding. Additionally, the study reveals a negative correlation between O₃ and rainfall, indicating that rainfall events tend to reduce ozone concentrations by washing out precursors like NO_x, a conclusion echoed by (He *et al.*, 2019b).

On the other hand, temperature exhibits a positive correlation with ozone concentrations. As temperatures rise, the rate of photochemical reactions that produce ozone increases, leading to higher ozone levels. This relationship has been extensively documented, with studies like those by Jacob and Winner (2009) confirming that warmer temperatures enhance ozone formation due to increased photochemical activity.

For NO₂, the study highlights that higher temperatures can elevate NO₂ concentrations by enhancing the chemical reactions involved in its formation. This is consistent with findings from Finlayson-Pitts *et al.* (2003), who noted that NO₂ levels tend to rise with temperature. Conversely, increased wind speed generally reduces NO₂ concentrations by dispersing pollutants more effectively, a phenomenon supported by Rao *et al.* (2003). For example, more recent research continues to emphasize the significant role of meteorological factors like humidity, rainfall, and temperature in influencing air pollution levels. Studies have increasingly focused on the effects of extreme weather events, such as heatwaves and heavy rainfall, on air quality, with results aligning closely with the patterns observed in this study; and thus, the study provides valuable insights into the intricate relationships between meteorological factors and air pollutants. The findings align well with recent research, reinforcing the importance of considering both weather conditions and pollution sources in air quality management strategies.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The analysis of NO₂, PM_{2.5}, and O₃ levels reveals distinct seasonal patterns influenced by meteorological conditions. Higher concentrations of NO₂ and PM_{2.5} are observed during dry seasons due to reduced precipitation and increased emissions, which inhibit natural pollutant dispersion and removal. Conversely, O₃ levels peak during dry periods due to enhanced photochemical reactions driven by increased sunlight and higher temperatures. These findings align with existing literature, highlighting the significant impact of seasonal variations on air quality (**Seasonal Variability in Air Pollutants**).

Meteorological factors, including relative humidity, rainfall, wind speed, and temperature, play crucial roles in shaping pollutant levels. Increased humidity and rainfall generally lead to reductions in O₃ and PM_{2.5} due to enhanced removal processes and decreased photochemical activity. Higher temperatures contribute to increased O₃ production, while wind speed affects pollutant dispersion. The study's results corroborate previous research, emphasizing the importance of considering these factors in air quality assessments (**Impact of Meteorological Factors**).

The study demonstrates clear relationships between meteorological conditions and air pollutant levels. Higher rainfall and humidity are associated with lower PM_{2.5} and O₃ concentrations due to enhanced atmospheric cleansing and reduced photochemical activity. Conversely, higher temperatures and increased sunlight contribute to higher O₃ levels. These findings are consistent with recent research and underscore the role of weather conditions in predicting and managing air quality (**Predictive Relationships**).

6.2 Recommendations

- Given the pronounced seasonal variations in pollutant levels, it is recommended to enhance air quality monitoring systems to account for seasonal and meteorological variations. Implementing continuous monitoring and incorporating meteorological data can provide a more accurate assessment of air quality and inform targeted interventions during high pollution periods (**Enhanced Pollution Monitoring**).
- To mitigate the effects of elevated pollutant levels during dry seasons, targeted pollution control measures should be developed. These could include stricter regulations on emissions from vehicular and industrial sources, especially during periods of low rainfall and high temperatures. Additionally, promoting practices that reduce dust generation can help lower PM_{2.5} concentrations during dry periods (**Strategic Pollution Control**).
- Increasing public awareness about the impact of seasonal air quality variations on health is crucial. Developing and implementing policies that address the specific challenges posed by seasonal changes, such as heatwaves or heavy rainfall, can enhance public health protection. Policies should also promote strategies for reducing exposure to pollutants during peak periods and consider the broader implications of meteorological conditions on air quality (**Public Awareness and Policy Development**).

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