UNIVERSITY of RWANDA

COLLEGE OF SCIENCE AND TECHNOLOGY

SPATIAL-TEMPORAL VARIABILITY OF PARTICULATE MATTER LESS THAN 2.5 MICRONS ($PM_{2.5}$) CONCENTRATION IN BYIMANA, RUBAVU AND GICUMBI

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By

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Registration Number: 221027537

A dissertation submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN ATMOSPHERIC AND CLIMATE SCIENCE at University of Rwanda College of Science and Technology

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Kigali,May 2024

DECLARATION

I declare that this Dissertation composed my own work except where specifically acknowledged.

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Signature…………… Date……………

Declaration by Supervisor

This work has been submitted with our approval as supervisor

Dr. Jimmy GASORE

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ABSTRACT

For this research, data on $PM_{2.5}$ concentrations were gathered from three distinct locations in chosen areas of Rwanda. The data collection spanned from 2019 to 2021. These collected data were utilized to examine the diurnal, seasonal, and day-of-the-week patterns of $PM_{2.5}$ concentrations in chosen areas. The study also analyzed the influence of meteorological parameters on the variations in $PM_{2.5}$ levels. Furthermore, the contribution of each area to the overall $PM_{2.5}$ concentrations was also investigated. In both chosen areas, the diurnal patterns of $PM_{2.5}$ showed higher concentrations during the nighttime compared to the daytime. This increase in nighttime concentration is primarily attributed to the accumulation of particles under inversion conditions and atmospheric stability. The lowest $PM_{2.5}$ values were observed in the late afternoon in all three areas. Furthermore, the reduction in human activities during weekends resulted in notably lower $PM_{2.5}$ concentrations on Saturday and Sunday, while higher concentrations were observed on the remaining weekdays, irrespective of the month or weather conditions. The seasonal variation analysis indicates that during the wet season, there is decrease in $PM_{2.5}$ concentrations due to the combined effect of total rainfall and relative humidity. This reduction is a result of washout and wet deposition, leading to lower fine particle concentrations compared to the dry season.

KEY WORDS

Air pollution.

Particulate matter (PM).

PM2.5.

LIST OF ACRONYMS AND SYMBOLS

AT: Averagetemperature

PBL: Planetary Boundary Layer

CO: Carbon monoxide

CO_2: Carbon dioxide

COMEAP: Committee on the medical effects of air pollutant

DFJ: December, February, January

DRC: Democratic Republic of Congo

EPA: Environmental Protection Agency

GBD: Global Burden Disease

ITCZ: Inter-Tropical Convergence Zone

JJA: June, July and August

MAM: March, April and May

NO: Nitrous Oxide

NO_2: Nitrogen dioxide

O_3: Ozone

OND: October, November and December

PM: Particulate matter

PM_{10}: Particulate matter with aerodynamic diameter of less than 10 micron

$PM_{2.5}$: Particulate matter with aerodynamic diameter of less than 2.5 micron

RAMP: Real-time Affordable, Multi-pollutant

REMA: Rwanda, Environment Management Authority

RH: Relative Humidity

SDGs: Sustainable Development Goals

SO_2: Sulfur dioxide

SON: September, October, November

SSA: Sub-Saharan Africa

TSP: Total Suspended Particulates

UN: United National

WHO: World Health Organization

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CHAPTER ONE: INTRODUCTION

1.1. Background

Rwanda, a country located in equatorial Africa and often referred to as the land of a thousand hills, is a landlocked nation situated within the equatorial region. It is located precisely in central east Africa between latitudes $1^0$4' and $2^0$51' South and between longitudes $28^0$45' and $31^0$15' East. It borders Burundi for 290 km, the DRC for 217 km, Tanzania for, and Uganda for 169 km. it has a surface area of26,338sqr km where 97% is land and 3% is water[1]. Rwanda undergoes two peak and two low points in temperature variations during the year. The warmest maximum temperatures are observed in August, while the coldest maximum temperatures are recorded in February. On the other hand, the two minimum points in temperature occur in June and November, respectively. [2]. The yearly average temperature remains relatively stable, fluctuating between 16^0C and 20^0C without significant deviations. Despite occasional irregularities, rainfall is generally plentiful. Typically, winds blow at approximately 1 to 3 meters per second. In the elevated areas of the Congo-Nile ridge, temperatures fall within the 15^0C to 17^0C, and there is a plentiful amount of rainfall. The volcanic region areas experiences significantly colder temperatures, with some areas even dropping below the freezing point, reaching temperatures below 0^0C. in regions at intermediate altitudes, the mean temperatures fluctuate between 19^0C and 21^0C and the annual mean rainfall is approximately 1000 mm. The rainfall is relatively more consistent, although it can still lead to occasional droughts. In the lowlands (East and Southeast), temperatures are higher and during February and July-August, they can reach extremes exceeding 30^0C. [3].

Due to the Inter-Tropical Convergence Zone (ITCZ) of trade winds' North-South alternating motion, the nation has two rainy seasons every year. When the ITCZ goes to the North, the months of March, April, and May (MAM) correlate to the long rainy season, and the months of October, November, and December (OND), to the short rainy season, when the ITCZ comes back to the South. From January to February, there is short dry period, and from June to September, there is an extended dry season. [2].

Rainfall patterns in Rwanda play a major role in determining the weather. As a result, there are four distinct seasons that alternate between the country's two wet and two dry ones [3]. The population density in Rwanda, which has 12 million residents, is 525 per Km^2 (1,360 people per m^2)[4].

A number of factors contribute to the ongoing deterioration of the air quality in urban area as well as in rural areas of Rwanda, including the country's growing population, significant growth in various economic activities, and an increase in various pollutants produced by, among other things, the country's extensive use of minibike, burning wood for cooking, burning of crops, kerosene lighting, unpaved roads, industries, etc. [5].

1.2. Problem statement

Air pollution is a significant environmental and public health concern, particularly in rapidly urbanization areas such as Rwanda [4]. Air pollution primarily caused by fine particulate matter, which has a diameter of 2.5 Micrometers or less ($PM_{2.5}$), is a significant contributor to various health problems. These include respiratory and cardiovascular diseases, as well as premature mortality. Air pollution has severe health implications, responsible for approximately one-third of all stroke-related deaths, as well as cases of lung cancer and heart disease [6]. Earlier research has examined the spatial and temporal fluctuations of $PM_{2.5}$ in various urban locations globally. In Chine, [7]. observed significant various in $PM_{2.5}$ concentrations, with higher levels found in urban areas during the winter months. Similarly, a study conducted by[8] In South Korea also revealed differences in $PM_{2.5}$ concentrations based on location and season, with urban areas experiencing higher levels during the winter season.

At this moment Rwanda is facing air quality challenges primarily due to the rapid urbanization, changes in land use, socioeconomic transformation, and a substantial increase in population. The issue is exacerbated by a significant portion of the country's vehicle fleet consisting of older vehicles, which contribute significantly to the emission of pollutants. [9].in 2012, Rwanda experienced 2,227 fatalities linked to ambient air pollution, leading to a cumulative loss of 108,622 years of life.[10]. However, there is insufficient research conducted on the spatial and temporal fluctuations of $PM_{2.5}$ in chosen urban regions of Rwanda. These urban areas are witnessing a surge in population, industrial operations, and transportation, all of which can potentially lead to heightened levels of $PM_{2.5}$ pollutions. Therefore, there is a need to understand the spatio-temporal variability of $PM_{2.5}$ in these areas to inform effective air pollution control measures and protect public health.

This study holds crucial insights that can assist policymakers and stakeholders in formulating and executing specific measures to mitigate $PM_{2.5}$ pollutions in urban regions and their background. Furthermore, it can contribute to the advancement of sustainable urban planning and management strategies aimed at enhancing residents' quality of life

1.3 Objectives

1.3.1 General Objectives

The main aim of this study is to investigate the spatial and temporal fluctuations in the concentration of particulate matter less than 2.5 microns ($PM_{2.5}$) in chosen areas of Rwanda.

1.3.2 Specific objectives

- To assess the diurnal and weekly variation of $PM_{2.5}$ concentrations in chosen areas of Rwanda.
- To analyze the seasonal variation of $PM_{2.5}$ over the chosen areas.
- To assess the impact of local geographic features and meteorological conditions on $PM_{2.5}$ levels over the selected areas.

1.4 Hypothesis of the study

In this study, we anticipate that particulate matter concentrations less than 2.5 microns in chosen areas of Rwanda will exhibit significant variations during contrasting times: day and night, weekdays and weekends, and between the dry and wet seasons.

This expectation is grounded on Rwanda's geographical location, meteorological conditions, level of development, and human activities, taking into account previous studies and reports.

1.5 Scope of the study

Our study is primarily focused on the spatio-temporal variability and the measurement particulate matter concentrations less than 2.5 microns ($PM_{2.5}$) in the chosen areas of Rwanda. Air pollution control is the primary issue that we are interested in. the main information will be provided by a number of air quality sensors located throughout the nation and at the Rwanda Meteorology agency.

CHAPTER TWO: LITERATURE REVIEW

2.1 Air pollution and pollutants

$PM_{2.5}$ denotes particles with an aerodynamic diameter smaller than 2.5 micrometers. Because of their small size, these fine particulate matter particles can remain suspended in the atmosphere for extended periods, enabling them to travel long distances [11]. Air pollution, particularly in the form of atmospheric $PM_{2.5}$ is recognized as a global environmental issue with significant adverse impacts on ecosystems and the environment.[12].

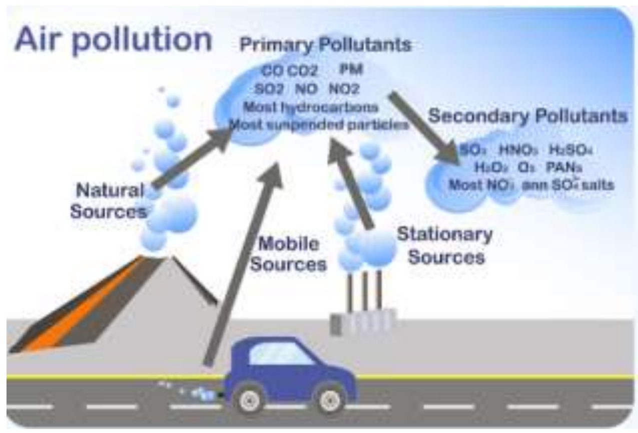


Figure 2.1 Different types of air pollutant

https://www.clarity.io/blog/how-measuring-different-types-of-air-pollutants-creates-a-more-holistic-picture-of-air-pollution

Particulate matter (PM) or atmospheric aerosol particles are categorized as air pollutants that are either directly released into the atmosphere (primary PM) or produced in the atmosphere from precursor gases through reactions (secondary PM). They may be of anthropogenic (fuel combustion for the production of electricity, home heating and transportation, industry, and waste incineration, etc.) or natural origin (marine aerosol, mineral dust, biological aerosol, volcanic ash, etc.) [13]. Air pollutants can exist as either solid substance or as particles in the form of gas. These solid particles, which create what is known as particulate matter (PM), come in range of sizes, spanning from very small to larger particles. The compositions of PM also differ, underscoring the significance of assessing the proportion of highly harmful PM types like black carbon, various gaseous forms of air pollutants are also detected, encompassing substances such as ground-level ozone, nitrogen dioxide, and volatile organic compounds (VOCs).

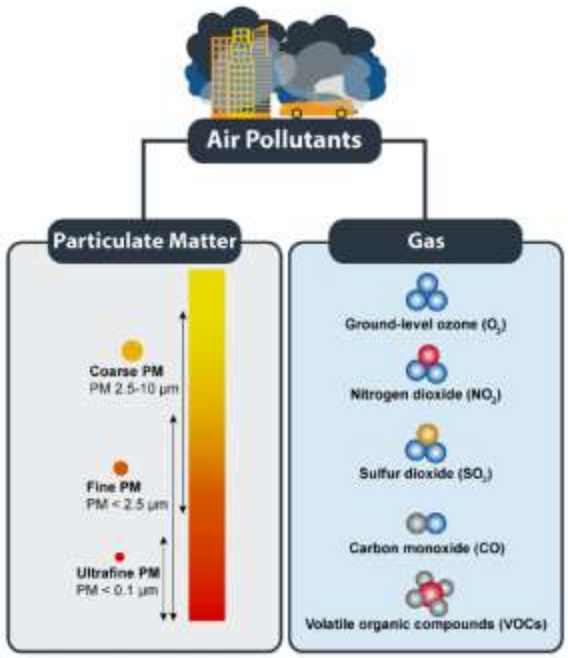


Figure 2.2 Air pollutant classification

[14].$PM_{2.5}$ has had a significant negative impact on people's health as the primary source of air pollution in cities. In accordance with a World Health Organization (WHO) report, 4.2 million individuals worldwide pass away each year as a result of exposure to ambient air pollution. Research focused on the spatial and temporal patterns of $PM_{2.5}$ concentrations the urban agglomeration level and an investigation into the influencing factors will offer crucial insights for enhancing urban air quality, reducing health risks for residents and supporting the sustainable development of urban areas. Currently, the majority of studies on $PM_{2.5}$ rely on data collection and evaluation of the characteristics of the spatiotemporal distribution and the underlying causes. Environmental monitoring sites are the primary sources of data [15]. Most studies on the $PM_{2.5}$ concentration distribution have been done from a spatial and temporal perspective. [16][17].

Air contamination is assessed to cause the unexpected losses of 310,000 Europeans every year. More than three million citizens of Europe have lost their lives as a result of this. On average, Europeans live longer lives by nearly nine months. In addition to affecting human health, air pollution has other effects. Ecosystems like lakes, forests, and others are becoming increasingly acidic as a result. Moreover, an abundance of nitrogen is brought to the soils, lakes and seas to cause eutrophication. Ozone and air pollution at ground level cause damage to buildings. These impacts will moreover be watched out for in the Effective Framework on Air Pollution [18]. Around three billion people worldwide use cook stoves that burn solid fuels today. This pollutes the indoor air and causes millions of premature deaths each year in developing countries[19].

2.2. Introduction to air pollutants

An air pollutant is a substance present in the air that has the potential to cause harm to both human being and environment. Particles that are solid, droplets that are liquid, or gases are all examples of pollutants. Additionally, they may be man-made or natural [20]. Air toxin is seen as the presence in the air of substances or energy in such amounts and of such span that is at risk to hurt life, harm to man-made materials and designs, or changes in the climate and environment[21].

Particulate matter (PM) is the term used to portray dense stage (strong or fluid) particles suspended in the climate. It includes pollen and soil particles, in addition to substances known as smoke, soot, and dust. Particulate matter can either be produced by the reaction of atmospheric gases (secondary particles) or directly emitted into the atmosphere (referred to as primary particles). Particles in the air can be anywhere from a few nanometers to several hundred micrometers in size.

By show, those more modest than (<) 2.5 µm measurement are alluded to as fine particles and those more prominent than (>) 2.5 µm width as coarse. Particulate matter primarily defined based on the measurement method rather than being a clearly defined compound or physical component of the air. It constitutes a complex mixture comprising various components from diverse sources. The composition of PM varies due to emissions, weather conditions, local and regional contributions, and changes over time. From tiny amounts of pollution caused by cigarettes and natural processes like eruptions, to large quantities of pollution caused by automobile engines and industrial processes[22]**,** The majority of those who pass away due to ambient air pollution and 4.3 million from household air pollution do so in Asia[23]. Humans come into contact with a variety of air pollutants primarily through inhalation and ingestion, so higher levels of PM2.5 were found to be significantly associated with significantly higher [24]**.**

Air contamination remains a significant challenge in Africa, with approximately $6x10^5$ deaths attributed to this invisible killer every year across the continent. [5]**.** The rapid growth of population and industrial activities is Sub-Sahara Africa (SSA) cities, such as Kigali, has led to decline in air quality, in Africa, the primary sources of air pollution include biomass burning, natural emissions from vegetation and soil, lightning NOx emission, and various human-made sources like the combustion of fossil fuels for energy, transportation, and domestic purposes. [25].

The air quality in SSA cities is a major concern; for instance, from[26]. the absolute most noteworthy fine molecule's levels on the planet have been kept in urban areas of SSA and other creating districts. PM2.5 focuses in SSA urban communities has been assessed at around 100 µg/m3compared to <20 µg/m3in most European and North American urban areas [25]; [27]**.** Sadly, there is a foundational absence of persistent observing of air contamination in most SSA urban communities and consequently it is yet to be checked whether SSA will meet the set air quality focuses of the sustainable development goals (SDGs) by the year 2030 [28].

2.3. Particulate air pollutants

2.3.1. Classification, formation, and sources of particulate matter

Particulate matter (PM) suggested besides as climatic particles or smoke sprayers are depicted as a suspension of fine strong or fluid particles in a vaporous medium. PM Things include a wide range of substances, including metallic, normal, and crustal mixtures, essential carbon, and inorganic particles [29]**.** PM is a broad air contamination, comprising of a combination of strong and fluid particles suspended in the air**.** PM can be categorized into different groups, including TSP with PM_{30} (coarse particles), $PM_{2,5}$ (fine particles) and ultrafine particles. PM consists of particles with a diameter smaller than 0.1 microns. Particles with diameter s ranging from 0.1 to 1 microns can persist in the atmosphere for days or even weeks, making them susceptible to long-distance transport through the air.[30]**.**

In addition, PM can be divided into primary particles, which are those that are released into the atmosphere as a result of industrial activities, traffic on roads, road dust, sea spray, and soil blown by the wind; They also contain metals, metal oxides, and ions, carbon, and an organic compound. Gaseous substances undergo chemical transformation to produce secondary particles [31]. PM, sulfur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), carbon monoxide (CO), and carbon dioxide (CO_2) are the air pollutants that we encounter most frequently in our daily lives. However, a number of air pollutants (PM, nitrogen dioxides, sulfur dioxide, carbon monoxide, ozone, lead, etc.) [18].

Most significant air pollutant is $PM_{2.5}$, which exhibits typical characteristics of compound and regional pollution. rapid urbanization and industrialization have coincided with a sharp rise in energy consumption and automobile ownership. Total suspended particles (TSP) in the air have skyrocketed as a result of airborne dust caused by urbanization, atmospheric pollution caused by coal burning, and automobile exhaust fume emissions becoming more severe [32].

The speed increase of industrialization and urbanization in the beyond couple of many years has prompted expanding levels of contaminations being discharged close by significant energy utilization, and these cycles have truly impacted the nature of air. Particulate matter can come from either natural or man-made sources. Numerous natural sources inject millions of tons of particulate matter annually. Volcanic eruptions, dust and wind storms, forest fires, salt spray, rock debris, the reaction of gaseous emissions, and soil erosion are some examples. Millions of tons of particulate matter are released annually by man-made activities like the combustion of fuel, industrial processes, such as steel production, petroleum refineries, cement manufacturing, and glass production, as well as smelting and mining activities. Other contributors are fly-ash emissions from power plants, coal combustion, and the burning of agricultural waste.[33]**.**

2.3.2 properties of particulate matter

Particulate matter encompasses a complicated combination of solid and liquid particles that remain suspended in the air. These particles come in various sizes, shapes, and chemical compositions, and they can be derived from both natural sources (like dust, pollen, and volcanic eruptions) and human activities or human activities (such as industrial processes, vehicle emissions, and burning of fossil fuels). Particulate matter can range in size from nanometers to micrometers and even larger. The size distribution is often categorized into different fractions based on their aerodynamic diameter, such as PM_{10} (particles with a diameter of 10 micrometers or smaller) and $PM_{2.5}$ (particles with a diameter of 2.5 micrometers or smaller). Ultrafine particles, with diameter less than0.1 micrometer, are also of concern due to their ability to penetrate deeply into the respiratory system [30]. Particles in the air can be composed of various substances like organic and elemental carbon, sulfate, nitrate, metal, dust, pollen, and biological components. The chemical composition of particulate matter can vary depending on the emission sources and atmospheric processes it undergoes [18][34]. aerosol particles present in the atmosphere consist of sulfate, ammonium, organic substances, crustal elements, sea salt, metal oxides, hydrogen ions, and water. Among these species, fine particles are notably abundant in sulfate, ammonium, organic and elemental carbon, as well as certain transition metals [4]. the larger fraction of coarse aerosol particles is known to consist of crystalline substances like silicon, calcium, magnesium, aluminum, and iron, alongside biogenic organic particles such as pollen, spore, and plant fragments [21].

The number of particles in a given volume or mass of air is referred to as the particle matter concentration. Parts per million (ppm) or micrograms per cubic meter ($\mu g/m^3$) are frequently used as unit of measurement. Urban locations, places close to industrial sites, times of wildfires, and areas with significant dust storms can all experience high quantities of particulate matter [35].

2.3.3 Effects of particulate matter on the environment and health

As stated in the reports by COMEAP (Committee on the Medical Effects of Air Pollutants) titled" Effects of long-term air pollution exposure on mortality" (2009) and the "mortality effects of long-term exposure to particulate air pollution in the United Kingdom" (2010), the impacts of long-term air pollution exposure on mortality were studied and analyzed. As of 2021, the deterioration of air quality was identified as the most significant environmental health risk on a global scale, in 2021, more than three million premature deaths were attribute to poor ambient air quality worldwide (WHO,2018). The majority of these fatalities, around 87 percent, were recorded in low and middle-income countries [36][37][5].

Over the past few decades, anthropogenic emissions, particularly in developing nations, have rapidly increased, producing more atmospheric aerosols and having a considerable negative impact on both health and the environment [38]. The UN environmental program estimates that PM caused the deaths of nearly 1.1 billion people. Because inhaled PM can produce major harmful effects, their ability to penetrate deeply into the lungs was of special concern [39]. Various scientific researchers have established links between exposure to particle pollution and several health problems, including nonfatal heart attacks, premature death in individuals with heart or lung diseases, irregular heartbeat, worsened asthma, reduced lung capacity, and increased respiratory symptoms such as airway irritation, coughing, or breathing difficulties.[21]. The quality of the air we breathe is reaching hazardous levels, with 90 percent of the global population exposed to polluted air, resulting in the loss of seven million lives annually [28]. Air pollution has severe health implications, accounting for 30% of stroke-related deaths and contributing to the incidence of lung cancer and heart disease[40].

Particulate matter exerts influences on both the environment and human health. A crucial atmospheric component that profoundly affects climate is aerosols, specifically fine particulate matter. As they consist of natural and anthropogenic emissions, their presence alters the optical properties of the air, impacting the way the atmosphere absorbs or scatters solar energy, thereby contributing to global warming.[41]. At present, air pollution poses the most significant environmental health hazard on a global scale, as numerous regions experience alarmingly high levels of pollutants in the air. Recent estimates from the World Health Organization (WHO) indicate that 90% of world's population is exposed to elevated levels of air pollutants. Shockingly, air population is responsible for 1 in every 9 deaths worldwide [42]. the atmospheric temperature is commonly influenced by these fine particles. Moreover, wind can transport these particles over several days before they finally settle on land or water. The various implications of this settling process significantly contribute to global climatic challenges. [43].

2.3.4 Variability in particulate matter throughout time and space

The concentration of atmospheric aerosols shows significant spatial and temporal variations due to factors such as aerosol emissions, precursor emissions, aerosol size and shape, and chemical characteristics[44]. Metropolitan regions are particularly susceptible to elevated levels of contaminants, including particulate matter, compared to rural areas. This disparity is primarily attributed to diverse human activities that are concentrated in urban centers. As a result, particulate matter concentrations fluctuate based on factors like the season, day of the week, and weather conditions. Additionally, the intensity of air mixing plays a crucial role in shaping the daily concentration patterns, especially for species with significant local sources[10].

Due to the lower atmospheric mixing height during nighttime, certain species tend to attain high concentrations early in the morning, reaching a peak at approximately 6:00 AM, coinciding with the start of rush hour traffic. Although the traffic emissions during rush hour are comparable to those in the morning, they disperse over a broader volume of the boundary layer, leading to considerably lower concentrations. To evaluate the impact of local emissions one can utilize these diurnal variations [45][17][46]. Spatio-temporal analysis involves examining data that pertains to both space and time. By investing the spatial distribution of air, soil, or waterborne contaminants through their abiotic factors, researchers can gain insights into their origins and the factors that influence them. This understanding is crucial for assessing environmental and health risks associated with these contaminants. [47].

2.4 Particulate Matter less than 2.5 microns ($PM_{2.5}$)

2.4.1 Formation and sources of $PM_{2.5}$

Like other pollutants, $PM_{2.5}$ is produced by both anthropogenic and natural sources. $PM_{2.5}$ is a heterogeneous combination of particles with an aerodynamic diameter of less than 2.5 micrometers ($PM_{2.5}$)[48]. In terms of contribution to the overall concentration, human-made sources of $PM_{2.5}$ are more significant. As a result, $PM_{2.5}$ levels adjacent to, say, roadsides and industrial zones are frequently substantially greater than those in background locations[49]. Fine particulate matter can enter the atmosphere through direct emissions (referred to as primary particles) or can be produced through the chemical reaction of atmospheric gases (known as secondary particles). These airborne particles vary in size, ranging from a few nm to several 100 micrometers[50].$PM_{2.5}$ is primarily generated by both human activities and natural sources. Various activities such as agricultural operations, industrial processes, burning of activities and fossil fuel, construction, and demolition work contribute to the entrainment of road dust and the release of $PM_{2.5}$ into the air[51]. The total $PM_{2.5}$ issue is additionally exacerbated by sources that are natural (i.e., neither anthropogenic or biogenic). These include flames and dust caused by the wind [52]. Along with these primary emissions of particles, secondary particles like sulphur dioxide (SO_2) and nitrogen oxides (NOx) can also result from the chemical reactions of gases, which is how $PM_{2.5}$ is created [53][38].According to EPA, $PM_{2.5}$ can stay suspended in the atmosphere for a duration ranging from minutes to weeks and has the capacity to travel 1000 km[54]. Other factors that can affect how long it stays suspended in the atmosphere is weather and particle size. According to their chemical characteristics, atmospheric aerosol constituents can be classified as either inorganic or organic[55].

Ambient $PM_{2.5}$ is composed not only of primary particles but also includes natural elements like dust and sea salt[56]. Additionally, a considerable portion of $PM_{2.5}$ comprises secondary particles that are produced in the atmosphere through well-established chemical reactions involving precursor gases [57] and[56]. Ambient $PM_{2.5}$ the levels of $PM_{2.5}$ in specific area are also influenced by the local combination of gaseous pollutants, meteorological conditions, geographical factors and seasonal variations[52]. In urban environments, $PM_{2.5}$ is typically linked to local emissions originating from vehicle exhausts.[40].

2.4.2 Exposure of people to $PM_{2.5}$

there is now a global focus on air pollution and the health issues it causes. According to the Global Burden of Disease (GBD) research[58]. Due to the extensive list of known adverse health effects, fine particulate matter ($PM_{2.5}$), which is defined as particles with a diameter of less than 2.5 micrometer, is a pollutant that is frequently studied. It is believed that approximately 90% of the global population resides in regions where the ambient $PM_{2.5}$ concentrations exceed the WHO interim target for the year 2005, which is an annual air quality guideline 10 micrograms per cubic meter[59]. On average, exposure to $PM_{2.5}$ decreases the life expectancy of the population in the areas by approximately 8,.9 months. [60]. Because the majority of the mass of PM is made up of inorganic salts like sodium chloride, ammonium sulfate, and ammonium nitrate, as well as low-toxicity minerals derived from soil dust, it is anticipated that the chemical composition of PM will play a significant role in determining its effects on health [61]. Numerous factors, including topography and local sources, can influence the relationship between PM2.5 and various health indicators; meteorology; characteristics of the house; individual variations in behavior and activity [62].

CHAPTER THREE: METHODOLOGY

3.1 Description of the Study Areas

Rubavu District is one of the seven districts of the country and is located at an altitude of 2158 m and is located in Western Province. It is approximately 145 kilometers from Kigali (1.69865S &29.37149 E) Its capital is Gisenyi.it has a total surface area of 388.4 Km^2, populations 546 683 ,1400/km^2. 294 448 live in Urban and 252 235 live in Rural. The district is situated along the shores of lake kivu, near the city of Gisenyi, and shares a border with the Congolese city of Goma. It is bounded by Nyibihu district to the east, DRC to the west and north, Rutsiro district to the south. The distance from the capital city of country is approximately 154.7km, which can be covered in 2h53 minutes' drive. The district benefits from its strategic geographic location, particularly with Lake Kivu, which facilitates its role as a business and tourism hub, especially with cross-border trade with the DRC. Rubavu district is administratively divided into 12 sectors, 80 cells, and 525 villages. Regarding its geography, the annual rainfall in the district varies between 1200 mm to 1500 mm.

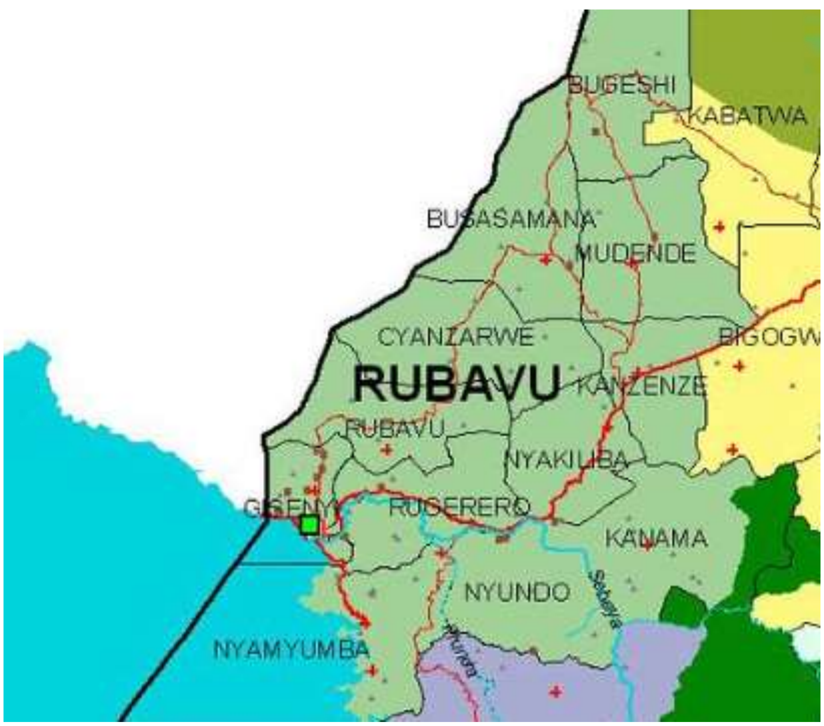


Figure 3. 1. Administrative map of Rubavu District

In the northwest part of the district, the soil is very fertile, but it is shallow, volcanic ash, and decomposed lava, On the other hand, the land in the southeast has deep but poor soil, often acidic, sandy clay, and susceptible to erosion. This area is also close to Mount Nyiragongo, an active volcano that experienced a new eruption on May 2,2021.

This site is situated in Rubavu District and represent a typical urban area, inside the Ecole D'Art de Nyundo School. There is no major source of air pollution close to the site, but from wood burning from residential area. The close main road (Musanze-Gisenyi) situated at approximately 50 m.

Gicumbi District is lies due to North of Kigali, stradding the major road of Kigali to Kampala it is a hilly District , it the one of the 5 district of the north province of Rwanda and is bordering with Uganda in north, in south Kigali city, in eastern side Nyagatare and Gatsibo District and finally Rulindo and Burera District in west.it has currently population (2022 census) 448 824; 28 131 live in urban and 420 693 live in rural, it has the total areas 828.9 sq km and population density 540 people per sq km, it has 21 sectors 109 cells and 99 planned settlement all cross the district.

Figure 3.2: Administrative map of Gicumbi

3.2 Research Design

3.2.1 Sampling locations

Daily data of $PM_{2.5}$, temperature and relative humidity recorded on daily basis over Rwanda (the selected region) between 2018 to 2021 and were collected from Rwanda Meteorological Agency and Rwanda, Environment Management Authority.

3.2.2 Experimental method

For our study, we employed Microsoft excel to organize the collected data and utilized Python as the programming language to analyze and process the data.

3.2.3 Data analysis

In this study, we used Temporal (time series) analysis, Correlation analysis and Statistical analysis.

By taking the selected regions separately, we analyzed the $PM_{2.5}$ patterns in both dry and wet seasons, by considering the diurnal variations and day of the week Patterns, seasonal patterns analysis of $PM_{2.5}$. In addition, we also plotted the temperature and relative humidity data versus time to see the variation of $PM_{2.5}$ with respect to the meteorological parameters.

3.2.3.1 Correlation analysis

To investigate the relationship between $PM_{2.5}$ concentrations and different meteorological parameters, such as temperature and relative humidity, we employed correlation analysis. This involved plotting these meteorological factors against $PM_{2.5}$ concentrations at one station in chosen region. Additionally, correlation analysis allowed us to assess the extent of association between $PM_{2.5}$ concentrations and the various meteorological parameters

The Pearson's r coefficient, also referred to as the Pearson Product Moment Correlation 'r' was utilized to quantify the strength of the relationship between the variables. This correlation coefficient (r) is determined as the ration of the Covariance of two variables representing a set of numerical data, normalized by the square root of their variances, for N pairs of observations, x and y

For a set of two-dimensional data points [X_1, X_2, X_3……. X_N] and [Y_1, Y_2, Y_3...Y_N] we have

$$\bar{x} = \frac{1}{N}\sum_i x_i$$

$$\bar{y} = \frac{1}{N}\sum_i y_i$$

$$C_{xy} = \frac{1}{N-1}\sum_i (x_i - \bar{x})(y_i - \bar{y})$$

$$C_{xx} = \sigma_x^2 = \frac{1}{N-1} = \sum_i (x_i - \bar{x})^2$$

$$C_{yy} = \sigma_y^2 = \frac{1}{N-1}\sum_i (y_i - \bar{y})^2$$

$$r = \frac{C_{xy}}{\sqrt{C_{xx}C_{xy}}} = \frac{C_{xy}}{\sigma_x \sigma_y}$$

Where:

r:is the Pearson correlation coefficient and its value ranges between – 1 and +1

x_i is the i^{th} value of the variable X

y_i is the i^{th} value of the variable y

C_{xy} is the covariance of X and Y

$\sigma_x^2\ and \sigma_y^2$ are the variance of the variable of X and Y respectively.

3.2.3.2 Statistical analysis

We used the statistical analysis to estimate the minimum, maximum, mean and standard deviation values of $PM_{2.5}$ recorded in dry season at the selected region.

3.2.3.3 Contribution estimation

We estimated the diurnal (considering the rush hour, lunchtime and dinnertime), weekly and monthly contribution of $PM_{2.5}$ concentration generated in selected areas in Rwanda.

3.2.4 Ambient $PM_{2.5}$ measurements

The analyzed data were collected over the specified time period mentioned above (in sampling location) of dry and wet seasons. Meteorological parameters were collected from Rwanda Meteorology Agency, which helped us in correlation analysis. We used tables, bar chats, pie chart; scatter plots, etc. to analyze daily, day of the week, weekend, and wet and dry season variation in $PM_{2.5}$ concentrations and to make some calculations as a way of estimating the contribution of $PM_{2.5}$ from selected areas of Rwanda.

CHAPTER FOUR: RESULTS AND DISCUSSIONS

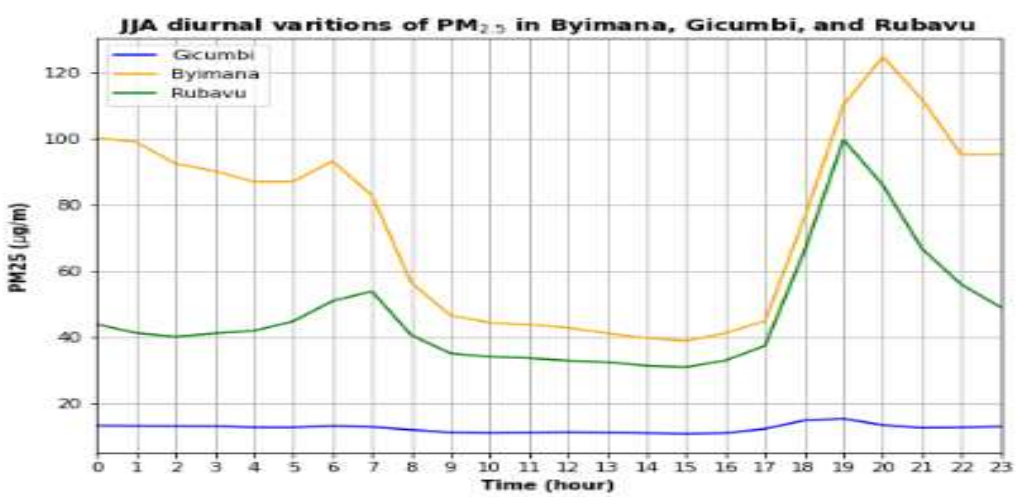
Through an analysis of the extended dry and wet seasons, we conducted a comparative evaluation of $PM_{2.5}$ concentrations in each. The primary objective of this study was to examine the diurnal fluctuations of $PM_{2.5}$ levels during both seasons, irrespective of the specific time of the year

4.1 Dry season patterns

4.1.1 Diurnal patterns of $PM_{2.5}$ concentrations at Byimana, Gicumbi and Rubavu stations in JJA

During the dry season, both the Byimana and Rubavu sites exhibited a diurnal variation of $PM_{2.5}$ with higher concentrations generally observed at night and lower values during the day. However, at the Gicumbi monitoring site, the pattern was reversed, with higher concentrations observed during the day and lower values at night.

Byimana and Rubavu monitoring site/stations have significant daytime variation in $PM_{2.5}$ concentrations in dry season, whereas Gicumbi station has relatively constant variation. Byimana and Rubavu stations experience their dry season peak exactly during rush hour between 5:00 and 7:00 in the morning and at night between 19:00 and 21:00 in the evening. Gicumbi station experiences its dry season peak during the day between 17:00 and 19:00 in the evening, with the lowest values occurring around midnight, as depicted in Figure 4.1.



Fugure 4. 1. JJA diurnal variation of $PM_{2.5}$ in Byimana, Gicumbi and Rubavu stations

Figure 4.1 shows that $PM_{2.5}$ concentrations change a lot in dry season, but the diurnal cycle stays the same from high peak in the morning to minimum in the late afternoon and rise up until around 22:00 pm at Byimana and Rubavu stations and from high peak in the day at lunchtime to minimum in the late afternoon and night at Gicumbi station between 18:00 and 20:00 pm.

When we examine the overall variations during the dry season, we can observe that there are greater $PM_{2.5}$ levels at Byimana during the night compared to those during the day, and vice versa at Gicumbi.

According to the observations, the concentrations at Gicumbi, which is installed at a high altitude from the surface, differ from those at Byimana and Rubavu station, which is located just a few meters below the surface. The peak at Byimana is caused by mobile sources and the influence of rush hour and the air pollution levels in Rubavu are expected to be significantly impacted by transboundary pollution from the nearby city of Goma, which is situated adjacent to the border with DRC and is known to have poor air quality. Moreover, the existing air quality will also be influenced by natural sources, including emissions from the active volcano on Mount Nyiragongo. whereas the peak at Gicumbi is caused by activities carried out by the local people near the location. However, the sensors may mostly record transported regional particulate matter.

Given that $PM_{2.5}$ is an air pollutant, some meteorological variables, such as temperature, precipitation, wind direction, wind speed, humidity, etc., may have an impact or be correlated with $PM_{2.5}$. All of these variables were taken into consideration for the case of Byimana and Gicumbi, including relative humidity and temperature to look into any potential relationships with $PM_{2.5}$ levels. The diluting of aerosols brought on by the deeper Planetary Boundary Layer (PBL) depth and increased wind speed may be principally responsible for the low levels during the day at Byimana, while the stability of the atmosphere is to blame for the low levels at night at Gicumbi.

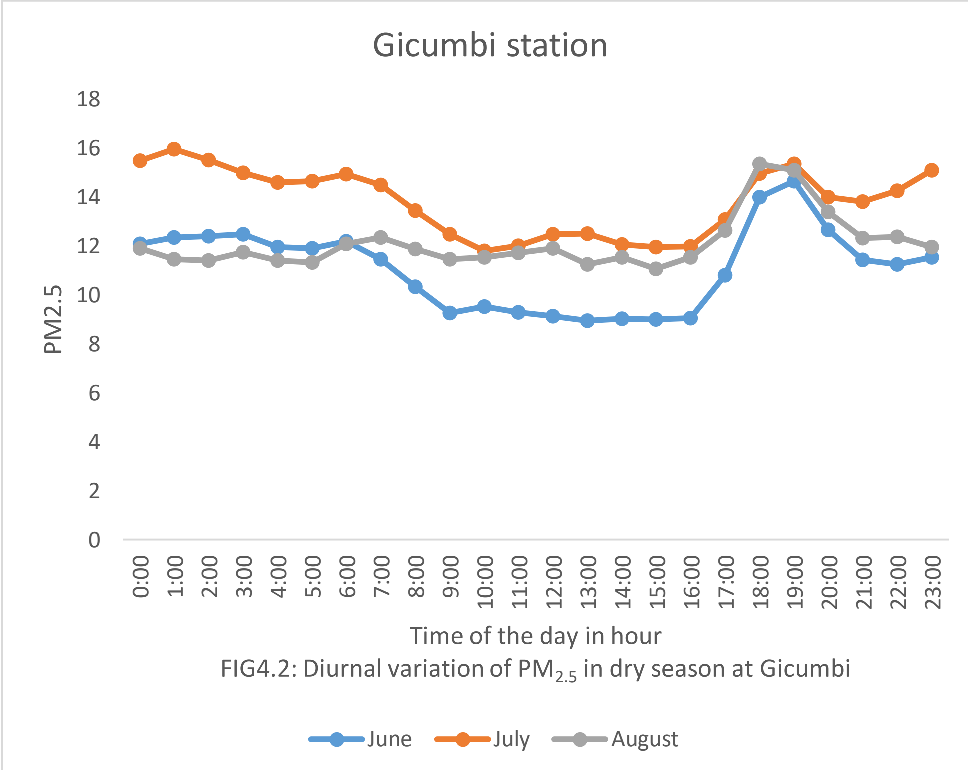
Daytime air pollution can originate from a number of anthropogenic (man-made) and natural causes. The largest human-caused air pollution sources in Rwanda, particularly are residential fuel burning and agricultural operations. Byimana levels are high in the morning, while Gicumbi values are low and stable because of their geographic locations. The Byimana station is a few meters from the ground and close to a road. However, Gicumbi station is situated at the peak of the mountain, some 20 meters below the surface. Due to trickling traffic flow and a drop in other anthropogenic activities (low emission rate), the $PM_{2.5}$ concentrations were much lower at night, specifically after 20:00 pm. There is a considerable change in concentration after midnight due to the buildup of particles during inversion circumstances and/or atmospheric stability.

Upon analyzing the overall pattern during the dry season, it becomes evident that $PM_{2.5}$ levels are higher at night compared to daytime levels. Between 10:00 AM and 15:00 PM, the concentrations remain relatively stable, but they start increasing significantly towards early morning, reaching a peak during the rush hour between 6:00 AM and 8:00 AM. After 8: 00 AM, there is a gradual decline until nearly midday. These observations suggest a strong influence of mobile sources on $PM_{2.5}$ levels, aligning with previous research, such as H.Nsengimana et al, 2011, which identified vehicle emissions as major contributors to $PM_{2.5}$ pollutions.

4.1.2. Monthly Diurnal variation of $PM_{2.5}$ in each station from the chosen ones in dry season

4.1.2.1. Gicumbi

At the Gicumbi site, during the dry season the diurnal pattern of $PM_{2.5}$ shows higher concentrations during the night and lower levels during the daytime as shown in Fig4.2, during June, July, and August, significant fluctuations in $PM_{2.5}$ concentrations are noticeable during the daytime. The highest levels occur during the dry season at night, specifically between 18:00 and 20:00 pm, while the lowest values are observed in the late afternoon.



Fugure 4. 2. JJA diurnal variation of $PM_{2.5}$ in, Gicumbi in dry season

During July, the highest recorded $PM_{2.5}$ concentration in Gicumbi was observed between 18:00 and 20:00 pm, with a mean value of 15.26 $\mu g/m^3$. In contrast , the lowest values occurred in June during the afternoon hours, specifically between 13:00 and 16:00 pm, with an average concentration of 11.61 $\mu g/m^3$. Although there were significant changes in $PM_{2.5}$ concentrations between June and August compared to July as shown in figure 4.2. the overall diurnal cycle remained consistent, with a high peak at night and a minimum during the late afternoon.

In June, the highest peak reached 14.64 $\mu g/m^3$,while in August, it was slightly higher at 15.34 $\mu g/m^3$. Both June and August experienced their maximum values during dinnertime. The lowest values in June were recorded at 9.009 $\mu g/m^3$, and in August, they were slightly higher at 11.07 $\mu g/m^3$.

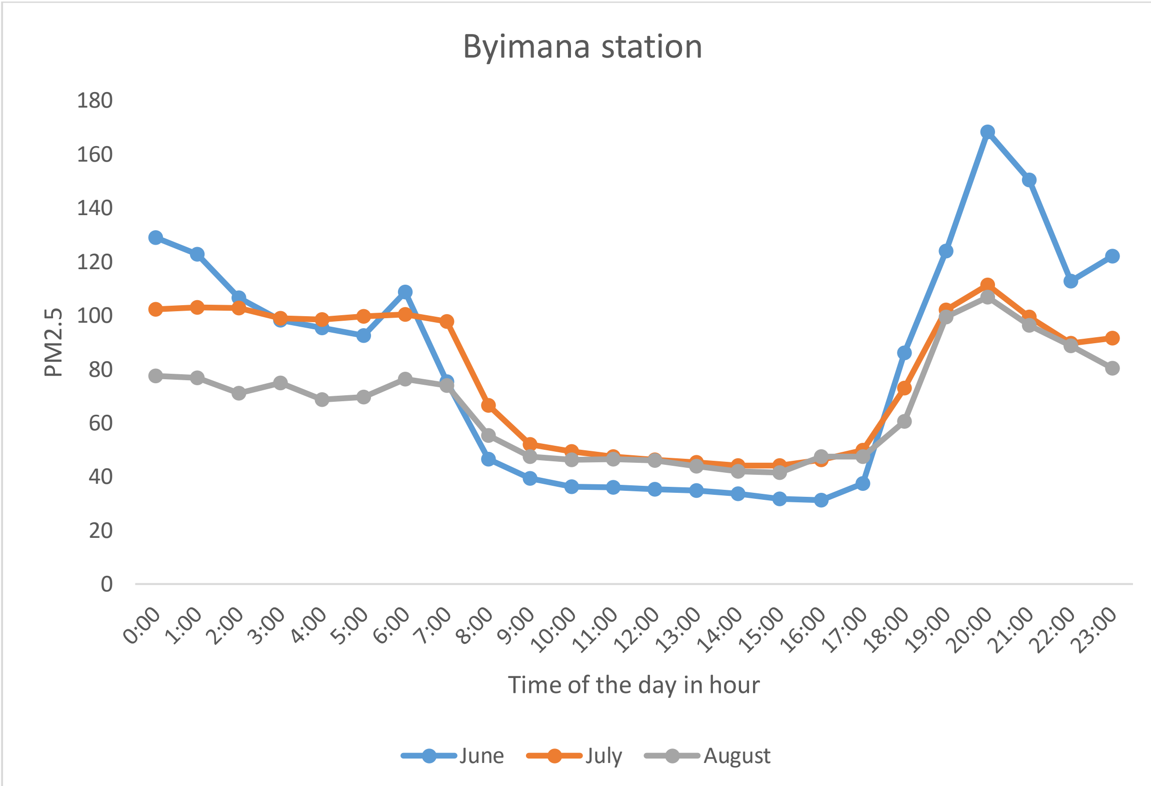
When examining the overall pattern of the dry season, it become evident that $PM_{2.5}$ levels are higher during the night compared to the daytime. Concentrations remain relatively stable from 23:00 to 16:00 pm but show a significant rise leading up to dinnertime, with the peak occurring between 18:00 and 20:00 pm. These observations suggest that cooking activities, particularly those involving domestic stoves, and atmospheric stability play a role in influencing $PM_{2.5}$ concentrations in Gicumbi.

Since $PM_{2.5}$ in an air pollutant, it is likely to have correlations with other meteorological parameters such as temperature, rainfall, wind speed, direction, and humidity. For the case of Gicumbi, investigating the potential relationship between $PM_{2.5}$ levels and specific parameters like relative humidity and temperature would be essential. The lower levels of $PM_{2.5}$ during the daytime can be attributed mainly to the dilution of aerosols facilitated by the deeper Planetary Boundary Layer (PBL) depth, higher wind speed, and reduced traffic volume in the afternoon.

Throughout the day, air pollutants originate from diverse anthropogenic (human-made) and natural origins. In the region of Gicumbi, Rwanda, the primary sources of anthropogenic air pollution are road traffic and domestic fuel burning. However, during the nighttime, specifically after 20:00pm, there is a notable decrease in $PM_{2.5}$ concentrations due to a reduction in traffic flow and other human activities with low emission rates. The peak in $PM_{2.5}$ levels at this time can be attributed to cooking activities in the intra-urban areas, which serve as the main source of air pollution in comparison to urban regions where vehicular exhaust is typically the dominant contributor to air pollution.

4.1.2.2. Byimana station

During the dry season at the Byimana site, the diurnal variation of $PM_{2.5}$ was noted, showing elevated concentrations during the night and lower levels during the day. In July and August, the Byimana station exhibited a pronounced daytime variation in $PM_{2.5}$ concentrations. The peak during the dry season occurred in the early mornings, precisely during the rush hour between 5:00 and 7:00 am, and also at night between 19:00 and 21:00 pm. On the other hand, the lowest $PM_{2.5}$ values were observed in the late afternoon.



Fugure 4. 3.JJA diurnal variation of $PM_{2.5}$ in Byimana in dry season

During July, Byimana experienced its peak value of approximately 111.31 microgram per meter cube between 7:00 pm9: 00pm, while the lowest readings during this month were observed in the afternoon hours, specifically between 2:00 pm and 4: 00 pm at Byimana station, with a measurement of 31.20 microgram per meter cube.

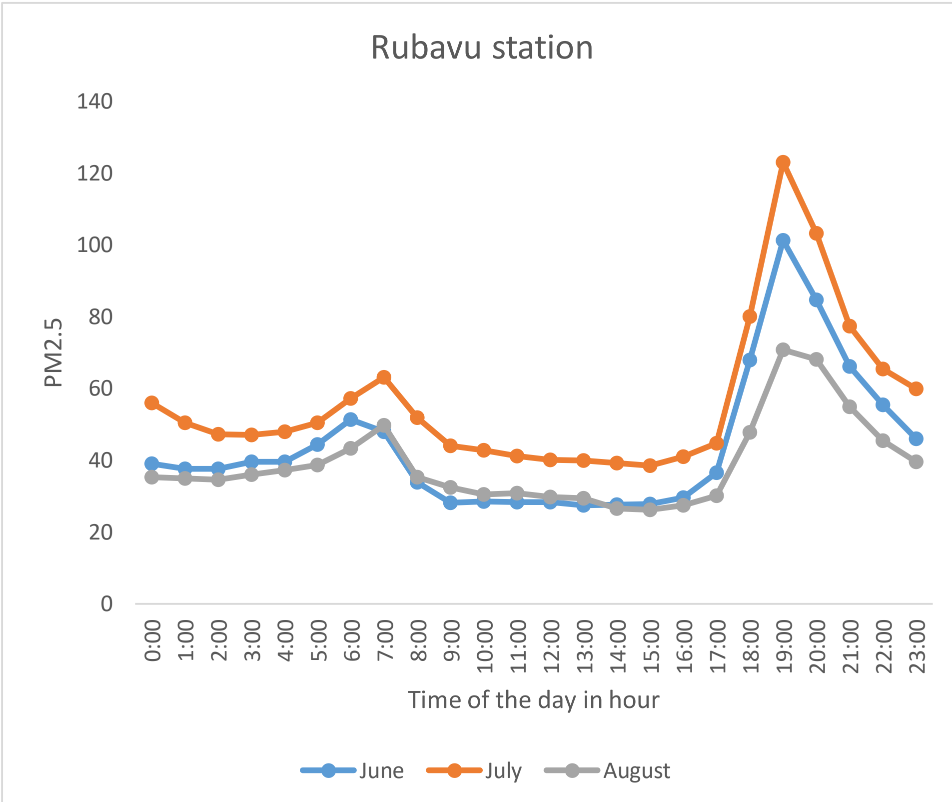
When analyzing the overall fluctuation pattern during the dry season at Byimana, it becomes evident that $PM_{2.5}$ levels are higher at night compared to the daytime levels. The observations at Byimana station, which is located just a few meters from the surface, differ from those at Gicumbi and Rubavu stations. The peak in $PM_{2.5}$ levels at Byimana is attributed to the influence of mobile sources and rush hour traffic.

Certain meteorological parameters, such as temperature, rainfall, wind speed, wind direction, and humidity, can potentially have an effect on or correlation with $PM_{2.5}$ concentrations, given that it is an air pollutant. For the case of Byimana, some of these parameters, including relative humidity and temperature, were considered to investigate their potential relationship with $PM_{2.5}$ levels. The reason for the lower $PM_{2.5}$ levels during daytime at Byimana could attributed mainly to aerosol dilution facilitated by deeper Planetary Boundary Layer (PBL) depth and increased wind speed during the day in Rwanda, air pollutants can arise from mix of human-made (anthropogenic) and natural sources. The primary anthropogenic contributors to air pollution in the country are agricultural activities and the burning of domestic fuels. In the morning, Byimana experiences higher $PM_{2.5}$ levels due to its proximity to a road and its location only a few meters above the surface.

4.1.2.3. Rubavu station

During the dry season at Rubavu station, $PM_{2.5}$ follows a diurnal patter with elevated concentrations at night and lower levels during the day. Notably, both June and July show a significant variation in $PM_{2.5}$ concentrations throughout the daytime. The peak during the dry season in Rubavu is observed in the early morning, particularly during the rush hour from 5:00 to 8:00 am, as well as at night between 6:00 and 9:00 as illustrated in figure 4.4.

conversely, the lowest values are observed in the late afternoon. During July, the highest recorded PM2.5 value at Rubavu was observed at night between 18:00 and 21:00 pm, reaching around 122.99 µg/m^3. In contrast, the minimum values in July were measured in the afternoon hours btn 14:00 and 16:00 pm at Rubavu station, with a concentration of 38.43 µg/m^3.



Fugure 4. 4. JJA diurnal variation of $PM_{2.5}$ in Rubavu in dry season

During August, there is a noticeable variation in $PM_{2.5}$ concentrations compared to July (see figure 4.4). however, the general diurnal cycle remains consistent, with peak in the morning followed by a minimum in the late afternoon, and a rise until around 22:00 pm at Rubavu station. The highest peak in August recorded a value of 70.77 µg/m3. at Rubavu station, during August, the maximum$PM_{2.5}$ values are observed between 18:00 and 21:00 pm, precisely during dinnertime, as indicated in the table below.

The elevated hourly averaged PM mass concentrations are likely associated with automobile sources and anthropogenic activities, which directly emit pollutants and contribute to summer heating. These anthropogenic activities include cooking in nearby households during breakfast preparation in the morning, as well as supper preparation during nighttime, using low-quality energy sources such as charcoal, petrol, and wood. Additionally, the increased traffic from vehicles commuting to and from work and tourists' vehicles may contribute to the higher $PM_{2.5}$ levels during these hours.

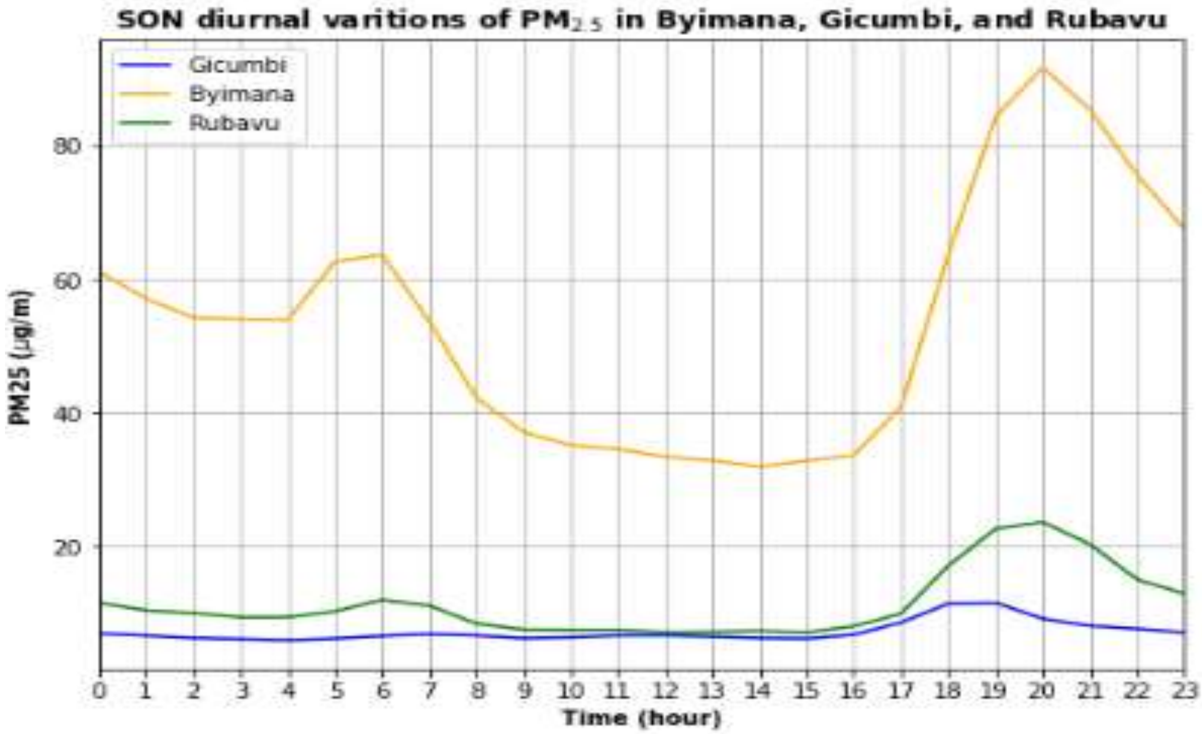
Table 1. $PM_{2.5}$ Maxima and Minima values recorded in dry season of Rubavu station

RUBAVU_STATION EXTREMA RECORDS OF 2021_DRY SEASON						
Month	MINIMUM		MAXIMUM		MEAN	STD
	value in µg/m3	time of the day the value was recorded	value in µg/m3	time of the day the value was recorded		
JUNE	9.83	Btn 13:00and 14:00	84.64	Around 20:00	43.95	25.2
JULY	21.38	Btn 13:00 and 15:00	122.99	Around 19:00	56.41	26.52

4.1.2. Wet season patterns

4.1.2.1. Diurnal patterns of $PM_{2.5}$ concentrations

on the other hand, there are no differences between the dry season' s morning, afternoon, and nighttime fluctuations and the rainy season's diurnal pattern of $PM_{2.5}$ (September, October, and November). only the variations in the peak times and the times at which the extrema were observed with their accompanying values changed; otherwise, the overall picture of the day remained unchanged.



Fugure 4. 5. SON diurnal variations of $PM_{2.5}$ in Byimana,Gicumbi and Rubavu in wet season

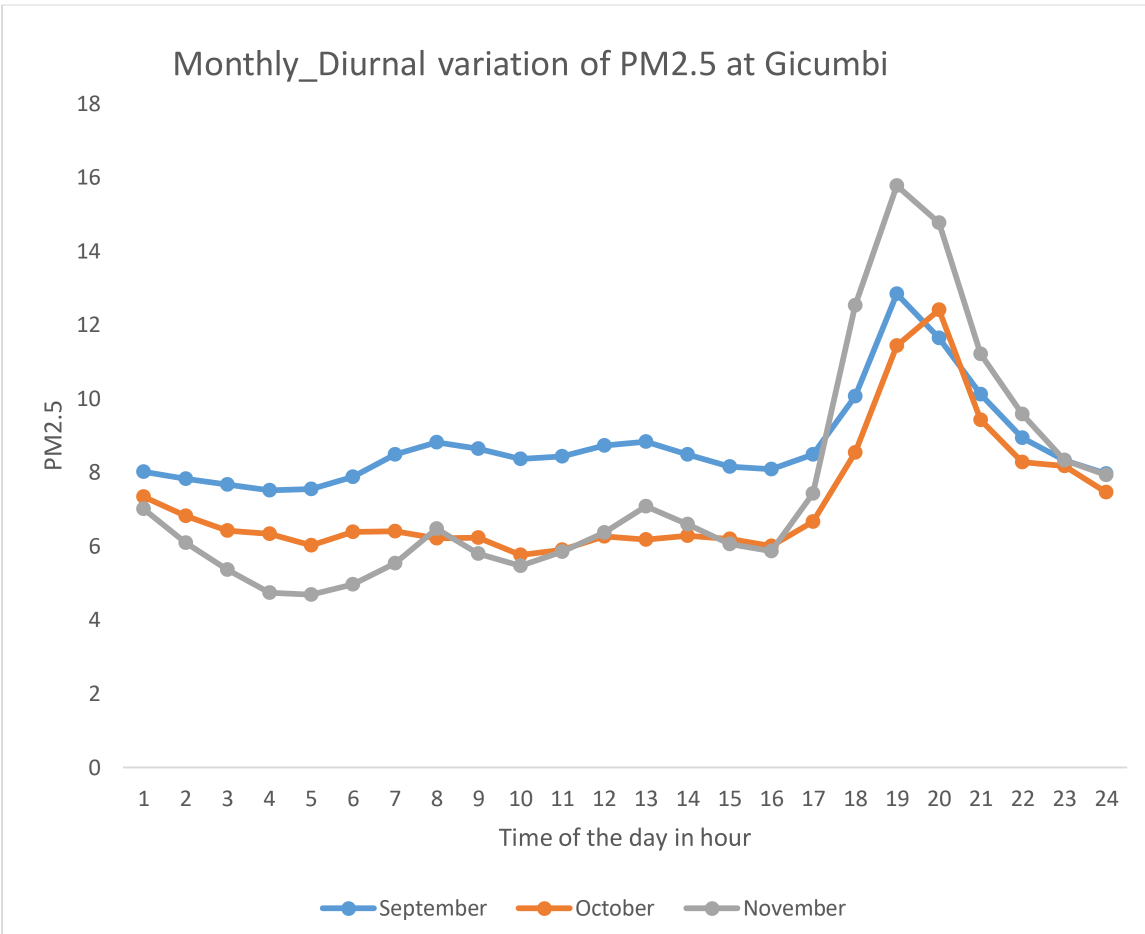
4.1.2.2. Monthly Diurnal variation of $PM_{2.5}$ in each station from the chosen ones in dry season

4.1.2.2.1. Gicumbi

However, during the wet season (September, October, and November), the daily variation of $PM_{2.5}$ does not show any significant divergence from the dry season in the mornings, afternoons, and nights. The fluctuations follow a similar pattern, with only variations observed in peak hours and the specific values of the extrema. Overall, the overall daily trend remains consistent between the two seasons.

During the wet season, specifically in November, Gicumbi experiences a noteworthy peak in $PM_{2.5}$ levels, reaching an average concentration of 15.77 $\mu g/m^3$. This particular value is observed precisely during the night between 18:00 and 20:00 as depicted in fig:4.3. the elevated levels of $PM_{2.5}$ in the vicinity of Gicumbi center can be attributed to its geographical location and numerous human activities taking place in the area. These factors collectively contribute to the increased concentrations of $PM_{2.5}$ in the region.

Likewise, the minimum $PM_{2.5}$ concentration observed in November, which was approximately 4.6 $\mu g/m^3$, occurred 3:00 -4:00 am. This decrease in $PM_{2.5}$ levels during that time might be attributed to reasons similar to those seen in the dry season, such as reduced traffic volume in the afternoon, aerosol dilution due to the deeper planetary boundary layer depth, and higher wind speeds. During the night, the $PM_{2.5}$concentrations tend to rise due to certain household activities and the accumulation of particles under inversion conditions or atmospheric stability.



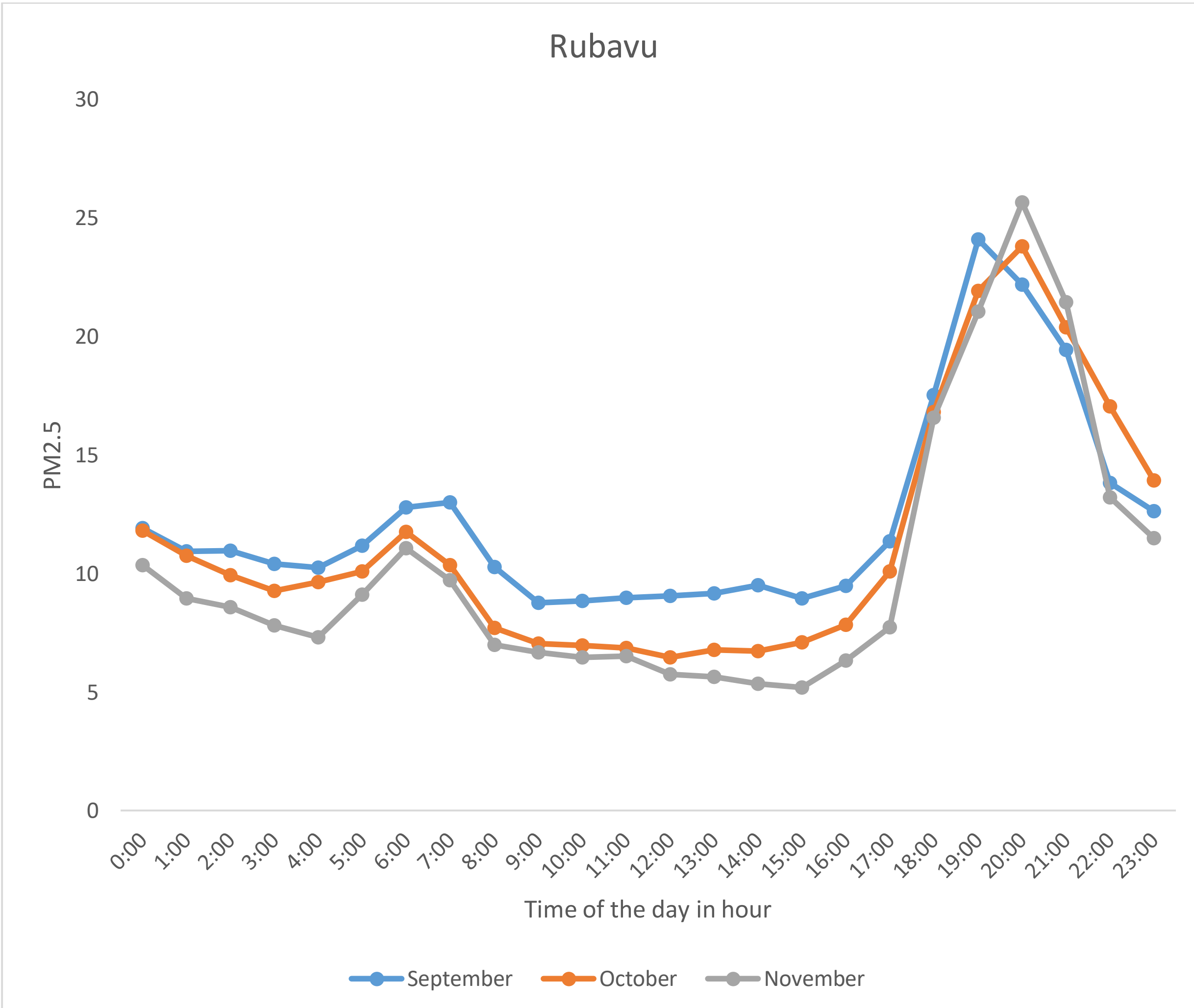
Fugure 4. 6. SON monthly diurnal variations of $PM_{2.5}$ at Gicumbi in wet season

4.1.2.2.2. Rubavu

According to the observations, the concentrations at Rubavu station, which is located just a few meters below the surface

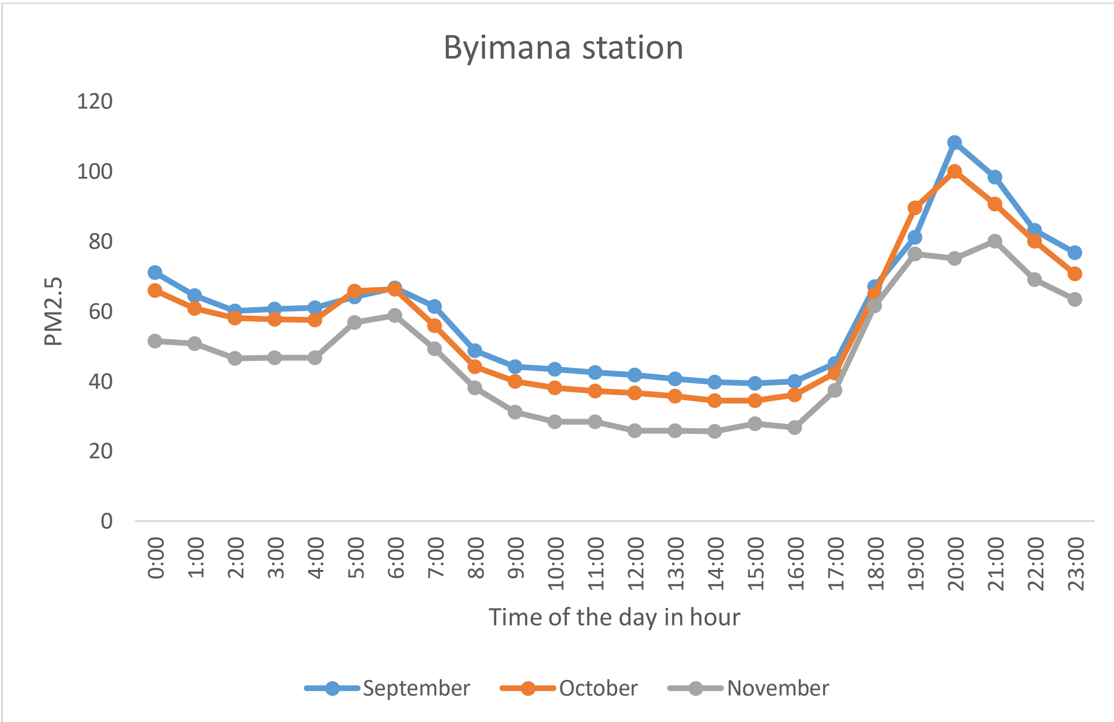
The air pollution levels in Rubavu are likely to be significantly impacted by transboundary pollution originating from the nearby city of Goma, situated adjacent to the border with the DRC, known to have poor air quality. Moreover, natural sources, including the active volcano on Mount Nyiragongo, also play a role in influencing the existing air quality in the area. During the wet season (September, October and November), the diurnal pattern of particulate matter less 2. 5 micros are similar to that of the dry season in the mornings, afternoons, and night fluctuations. The only noticeable differences are observed in the peak hours and timing of extreme values along with their corresponding concentrations. Apart from these specific changes, the overall daily pattern remains consistent between the two seasons. For individual months, it is found that in wet season, Rubavu has one significant peak in November with the average concentration 25.6 μg/m3 and this value has been observed exactly during the night between19:00-21:00 PM (Fig 4.7.). the reason behind, during the evening and night hours, people tend to engage in indoor activities that can release $PM_{2.5}$ particles into the air. These activities may include cooking, burning candles or incense, using certain household products, and smoking indoors. These activities contribute to the buildup of $PM_{2.5}$ indoors, which can then escape to the outdoor environment.

Likewise, in October, the minimum recorded value (approximately 5.5 microgram per meter cube) was observed during the time frame of 2:00 to 3:00 pm. This could be attributed to factors similar to those influencing the reduction in air pollution dry season, such As decreased traffic volume in the afternoon and aerosol dilution facilitated by a deeper Planetary Boundary Layer depth and increased wind speed.



Fugure 4. 7. SON monthly diurnal variations of $PM_{2.5}$ at Rubavu in wet season

Byimana station was selected as one of the monitoring sites to investigate the variations in $PM_{2.5}$ levels due to its consistent data recording through the entire study period and its advantageous geographical location. The average diurnal variation of $PM_{2.5}$ for each month is shown in figure 4.8. and the table 4.2 shows the maxima and minima in wet season, it shows a very little difference when comparing the similar seasons, all maximum levels appeared during dinnertime between 19:00- 21:00 pm with the main reasons discussed in previous sections; and all have been recorded in dry and wet seasons. The highest level (around 108.3 $\mu g/m^3$) appears in September, while October and November (wet season) are associated with the minimum levels in the late afternoon with the values around 40$\mu g/m^3$ each.



Fugure 4. 8.SON monthly diurnal variations of $PM_{2.5}$ at Byimana in wet season

Table 2. $PM_{2.5}$ Maxima and Minima values recorded in long wet season of Byimana station

BYIMANA_STATION EXTREMA RECORDS OF 2021_LONG WET SEASON						
MONTH	MINIMUM		MAXIMUM		MEAN	STD
	value in µg/m3	time of the day the value was recorded	value in µg/m3	time of the day the value was recorded		
SEPTEMBER	39.34	AROUND 15:00	108.23	AROUND 20:00	59.33	28.96
OCTOBER	34.37	Btn 13:00 AND 14:00	100.04	AROUND 20:00	55.69	31.37
NOVEMBER	25..61	Btn 12:00 AND 14:00	80.04	AROUND 21:00	46.70	27.

4.1.3 Day-of-Week Pattern in dry season

The three months of dry season are slightly different in both concentration level and fluctuation in day of the week behavior. A pronounced days of the week variation in $PM_{2.5}$ concentrations is observed in both July and August for Byimana, Rubavu stations, while for Gicumbi station we have fairly constant variation. The peak in July for Byimana and Rubavu stations are observed in Monday (85.13µg/m^3) and Wednesday (65.58µg/m^3) respectively, while the lowest peak appears in Wednesday(66.69µg/m^3) and Monday (51.69µg/m^3) respectively and the peak for Gicumbi station is observed in Wednesday (16.77µg/m^3), while the lowest peak appears in

Saturday (12.08µg/m^3), On the other hand, August was characterized by lower values in $PM_{2.5}$ compared to July. the peak in August for Byimana and Rubavu Stations are observed in Wednesday(75.67µg/m^3) and Tuesday (42.32µg/m^3) respectively while the lowest peak appears in Friday(48.61µg/m^3 for Byimana and 34.95 µg/m^3 for Rubavu) and the peak and the lowest peak are fairly constant for Gicumbi (≅ 12.50µg/m3)station as shown in Figures below.

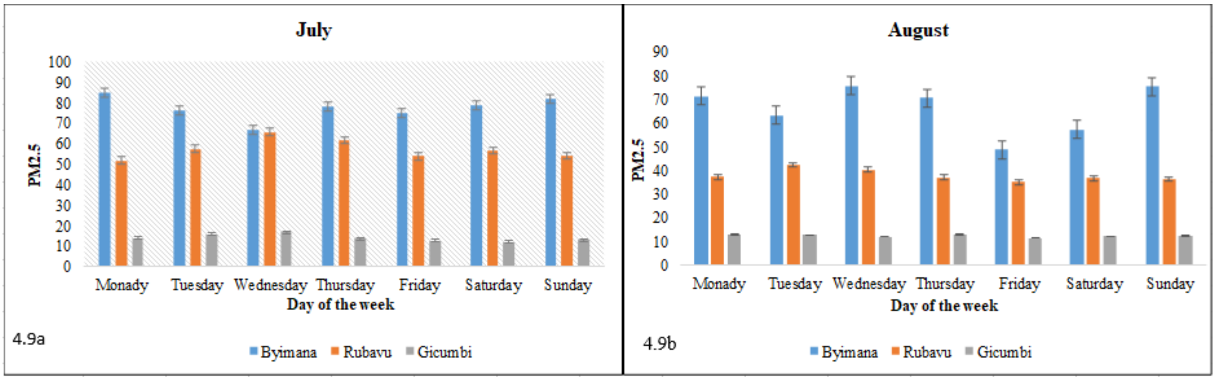


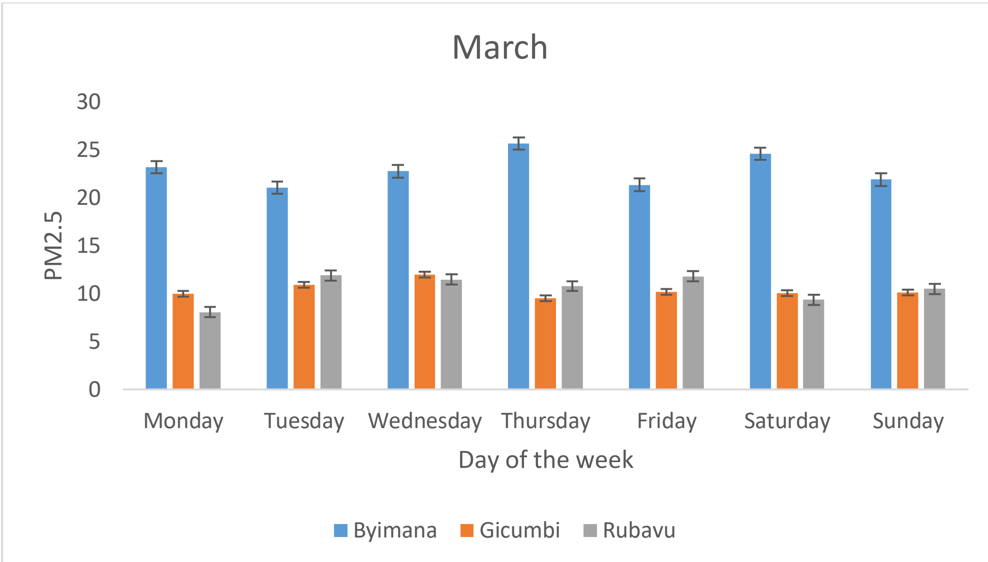
Figure 4.10 variation of PM2.5 (a) in July and (b) in August

These findings indicated that human activities play a significant role in the daily fluctuations of $PM_{2.5}$ levels. Additionally, meteorological factors have a crucial impact on $PM_{2.5}$ concentrations. According to Chen et al. (2015), wind speed has a negative influence on $PM_{2.5}$ concentrations as it aids in plume dispersion and dilution, resulting in lower $PM_{2.5}$ levels. Atmospheric horizontal mixing has been recognized as an effective dilution mechanism. (Marcazzan et al., 2001; Zhang et al., 2015; Wen et al.,2018). Furthermore, high humidity conditions can lead to the rapid formation of haze weather. Researchers like Sum et al. (2013) and Fang et al. (2017) have found that RH is a significant factor in explaining the daily variations of $PM_{2.5.}$

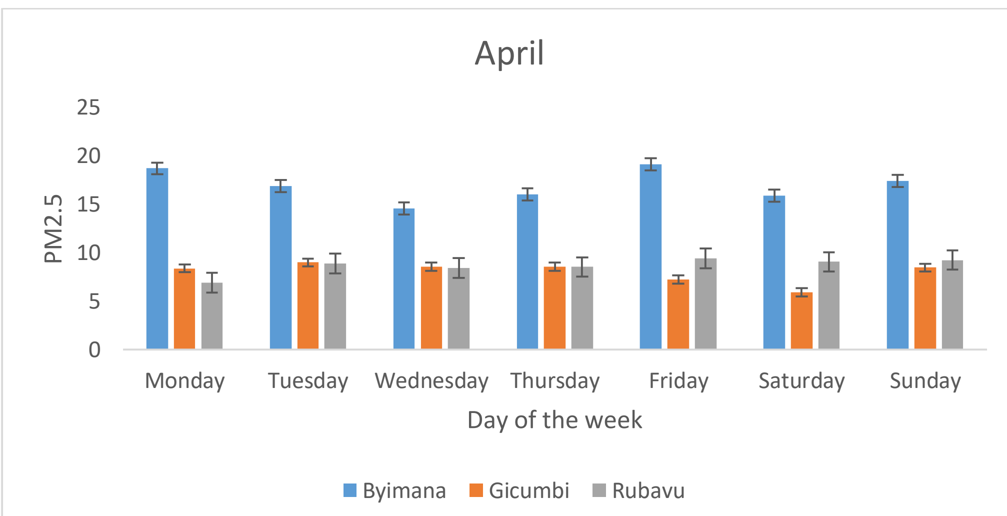
.4.1.4Wet season patterns

4.1.4.1. Day of the week in MAM

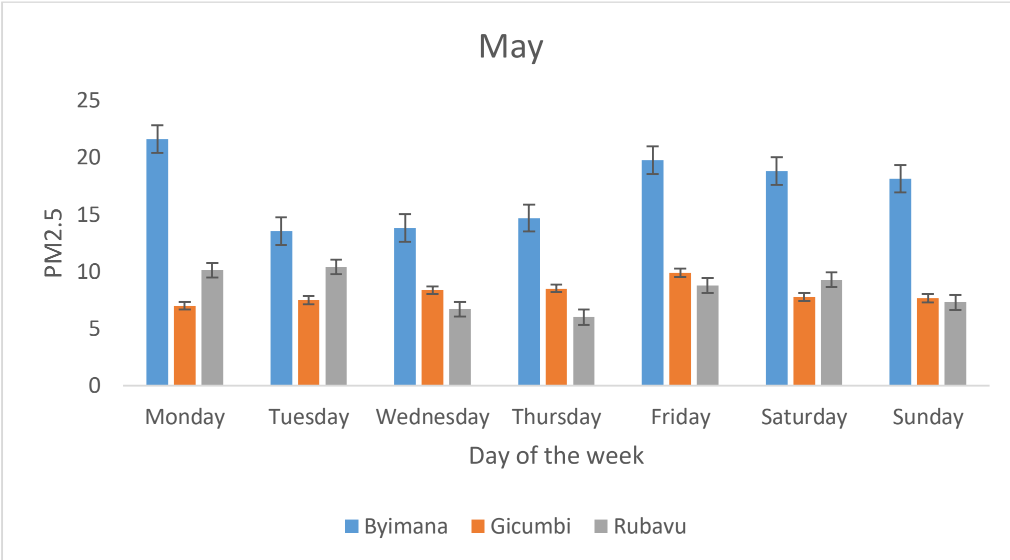
According to the fluctuations in wet season shown in the figure 4.11, 4.12 and 4.13 it is seen that $PM_{2.5}$ concentrations are generally lower compared to the dry season. This decrease can be attributed to several factors, with meteorological influences, such as abundant rainfall during the wet season, playing a significant role. The rainfall effectively washes out particles from the atmosphere through a process known as wet deposition.



Fugure 4. 9.variation of $PM_{2.5}$ in March



Fugure 4. 10. variation of $PM_{2.5}$ in April



Fugure 4. 11. Variation of $PM_{2.5}$ in May

The variation of $PM_{2.5}$ on the weekday and weekend levels on March where the Byimana station we have peak and Rubavu station we have on Tuesdays and the lower values for Byimana is on Tuesday for Rubavu is on Monday. For April the highest values are on Friday for Byimana and Rubavu, the lower value is on Wednesday and Monday for Byimana and Rubavu respectively. On May the highest value is obtained on Monday for Byimana and Tuesday for Rubavu, the lowest value is on Tuesday for Byimana and Thursday for Rubavu

MAM months exhibit the lowest values of $PM_{2.5}$ when compared to the other months in the wet season. The reduced $PM_{2.5}$ concentrations during this period can be Attributed to the abundant rainfall. The consistent $PM_{2.5}$ levels throughout the week in MAM are a result of regular washout due to precipitation, which indicates that the emissions have a minimal impact during the weekend in contrast to the dry season.

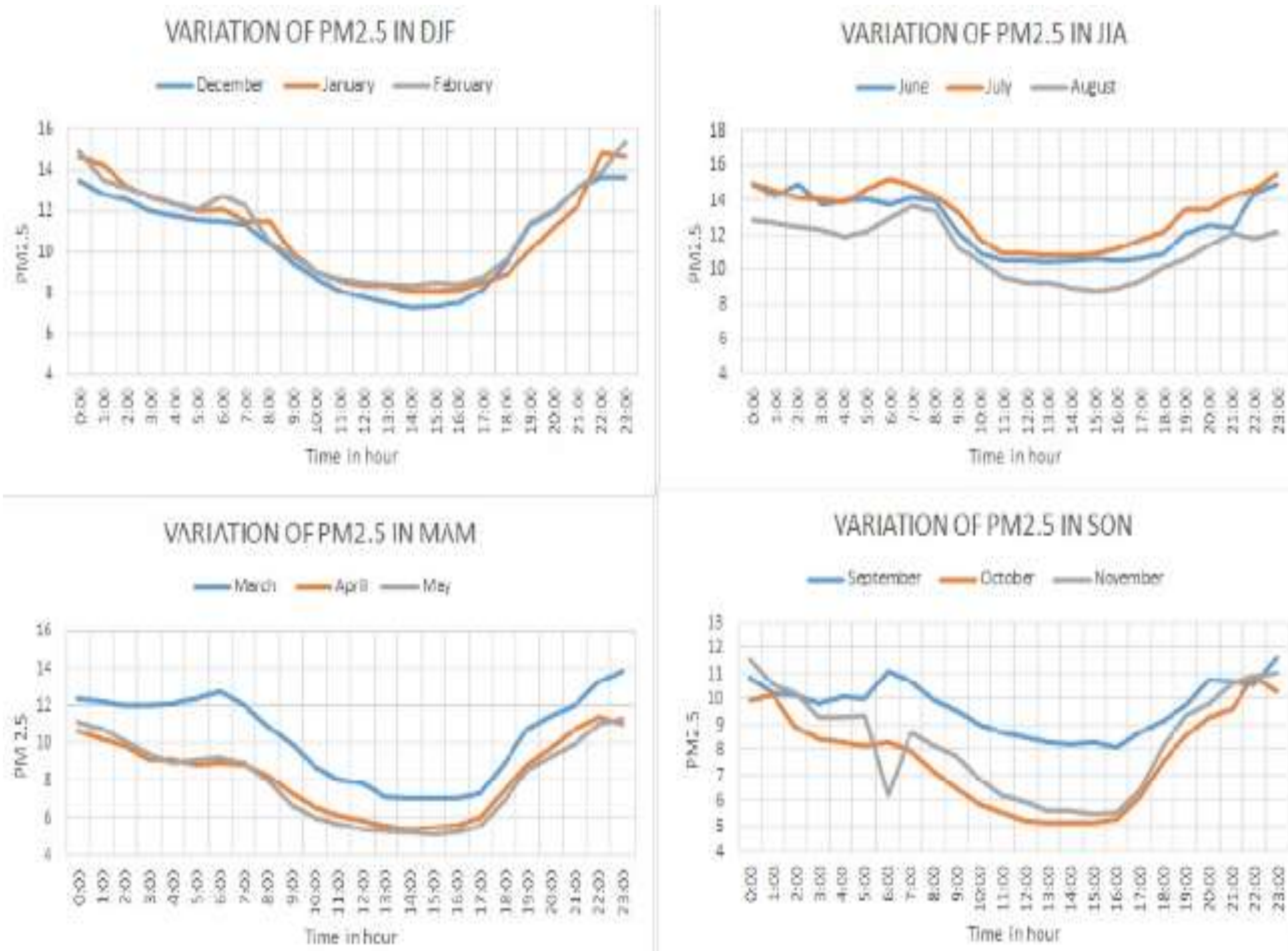
4.1.2.2. Seasonal patterns comparison of $PM_{2.5}$ concentrations.

Gicumbi station was selected to analyse the seasonal variations in $PM_{2.5}$ concentrations because it consistently recorded data throughout the entire period of study. Figure 4.14 displays the average daily fluctuations of $PM._{2.5}$ for each month. Interestingly, there is very little difference observe between the similar seasons, such as the dry periods (June, July &August) and (December, January & February) or the wet seasons (SON and MAM).

During the overall study period, Gicumbi exhibited two significant peaks in $PM_{2.5}$ concentrations: one in February and the other in July. These peaks consistently occurred during dinnertime, between 19:00 to 21:00 pm. Previous sections have discussed the primary reasons behind these peaks, and it is worth noting that all maximum levels were recorded during the dry seasons.

Notably, the highest level of $PM_{2.5}$ concentrations around 16 μg/m3, was observed in February, while the lowest levels, approximately 5 μg/m3 were associated with the wet season, particularly in May during the afternoon.

Although the diurnal patterns show some similarities, there are significant differences in $PM_{2.5}$ concentrations between wet and dry seasons. Figure 4.14 and table 3,4,5, and 6 make it clear that $PM_{2.5}$ levels are consistently higher during the dry seasons compared to the wet seasons, as well as across all four seasons.



Fugure 4. 12. Seasonal patterns of $PM_{2.5}$

The $PM_{2.5}$ concentrations in December are significantly lower compared to January and February within the same season see figure 4.14. this can be attributed to the fact that December marks the beginning of the dry season (December, January, February) following the wet season (September, October, November). Although December, January, February is generally a dry season, December still retains some meteorological characteristics from its preceding season, which greatly influence the variation of $PM_{2.5}$ levels, as discussed in section 4.2. this is also the reason why September exhibits higher $PM_{2.5}$ levels compared to the rest of the wet season (September, October, November).

Table 3. $PM_{2.5}$ Maxima and Minima values recorded in wet season (DFJ) of Gicumbi station

GICUMBI_STATION EXTREMA RECORDS OF 2019_(DFJ) SEASON						
MONTH	MINIMUM		MAXIMUM		MEAN	STD
	value in µg/m3	time of the day the value was recorded	value in µg/m3	time of the day the value was recorded		
December	3.5412	AROUND 17:00	27.3859	AROUND 22:00	10.4539	3.6628
January	5.4438	AROUND 15:00	21.3112	AROUND 22:00	10.8054	2.84
February	3.889	AROUND 14:00	28.82067	AROUND 23:00	11.02428	4.0135

Table 4. $PM_{2.5}$ Maxima and Minima values recorded in wet season (MAM) of Gicumbi station

GICUMBI_STATION EXTREMA RECORDS OF 2019_(MAM) SEASON						
MONTH	MINIMUM		MAXIMUM		MEAN	SDT
	value in µg/m3	time of the day the value was recorded	value in µg/m3	time of the day the value was recorded		
MARCH	4.3569	AROUND 14:00	22.0736	AROUND 23:00	10.3697	3.245
APRIL	3.319	AROUND 14:00	19.393	AROUND 22:00	8.2165	2.753
MAY	3.172	AROUND 15:00	17.6496	AROUND 23:00	7.890	2.813

Table 5. $PM_{2.5}$ Maxima and Minima values recorded in dry season (JJA) of Gicumbi station

GICUMBI_STATION EXTREMA RECORDS OF 2019_(JJA) SEASON						
MONTH	MINIMUM		MAXIMUM		MEAN	SDT
	value in µg/m3	time of the day the value was recorded	value in µg/m3	time of the day the value was recorded		
JUNE	6.2267	AROUND 13:00	27.0181	AROUND 2:00	12.4989	3.5583
JULY	6.411	AROUND 13:00	35.6338	AROUND 23:00	13.1354	4.101
AUGUST	5.1052	AROUND 15:00	41.036	AROUND 7:00	11.1558	3.518

Table 6. $PM_{2.5}$ Maxima and Minima values recorded in wet season (SON) of Gicumbi station

GICUMBI_STATION EXTREMA RECORDS OF 2019_(SON) SEASON						
MONTH	MINIMUM		MAXIMUM		MEAN	SDT
	value in µg/m3	time of the day the value was recorded	value in µg/m3	time of the day the value was recorded		
SEPTEMBER	3.3139	AROUND 16:00	18.011	AROUND 23:00	9.6703	2.339
OCTOBER	2.993	AROUND 14:00	42.3353	AROUND 22:00	7.5942	3.052
NOVEMBER	3.1499	AROUND 15:00	25.144	AROUND 0:00	8.403	2.814

4.2. IMPACT OF METEOROLOGY ON PM2.5 CONCENTRATIONS

Selected meteorological parameters, including temperature, relative humidity and wind speed has been chosen for evaluation to understand their impact on $PM_{2.5}$ concentrations. This illustrates the significant increase in $PM_{2.5}$ levels during nighttime and early morning hours compared to the rest of the day. Conversely, $PM_{2.5}$ concentrations tend to decrease as wind speed and temperature rise, indicating a negative correlation. This trend could be attributed to the rise in boundary layer height throughout the day, which is typically associated with higher temperatures and drier weather conditions.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

We evaluate the levels of $PM_{2.5}$ concentrations by analyzing hourly observations from three stations in each region as we said above between June 2019 and March 2021

According to all plots, there is a distinct diurnal cycle in the concentrations of $PM_{2.5}$ at all three locations during both dry and rainy seasons. In general, we observe a diurnal fluctuation in the chosen areas, with higher concentrations being present during the nighttime compared to daytime., Typically, the lowest $PM_{2.5}$ concentrations is observed during the late afternoon, specifically between 14:00 and 16:00, while the highest concentration peaks during dinnertime, between 18:00 and 20:00. Human activities and complicated climatic elements, such as strong wind speeds during the day that recede at night when the air becomes stable and the wind speed lowers, are responsible for the changes in $PM_{2.5}$ concentrations.

In the wet season, due to the plentiful rainfall results in washout or wet deposition of pollutants and higher relative humidity, leading to lower $PM_{2.5}$ concentrations compared to the dry season.

5.2 Recommendations

Evaluation of all relevant sources that are known to produce $PM_{2.5}$ is necessary. decreased sources of $PM_{2.5}$ include but are not limited to vehicle emissions, particularly from older vehicles, and industries, which have been proven to be substantial sources in certain locations. Cooking with firewood and charcoal should also be decreased in these places.

Local authorities should be responsible for monitoring and evaluating the air quality within their jurisdiction. To effectively manage air quality, environmental protection agencies can create regional air quality management districts by taking into account the unique characteristics of each area. This approach will allow the government to establish priorities for gradually reducing air pollutant concentrations and developing a comprehensive air quality management plan,

The government, in collaboration with local authorities, should disseminate information to the public regarding local air pollutant levels, potential health effects, and recommended actions to mitigate health risks. This effort aims to enhance the public's awareness and understanding of air pollution issues, fulfilling an important education role.

Implanting emission control technology involves assessing the accessibility and cost-effectiveness of electric transportation options, ensuring sufficient electricity production, establishing widespread charging infrastructure, and incorporating environmentally-friendly sources of energy.

Lastly, it is crucial to emphasize the significance of maintaining continuous air pollution monitoring and conducting further research in this field. Decision makers in the country should actively seek opportunities, such as launching innovation calls, to support novel and advanced research and technologies related to air quality. The insights gained from such initiatives will prove invaluable in shaping our strategies to enhance air quality in country, Rwanda

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APPENDICES

Apendix 1: Gicumbi station,2021

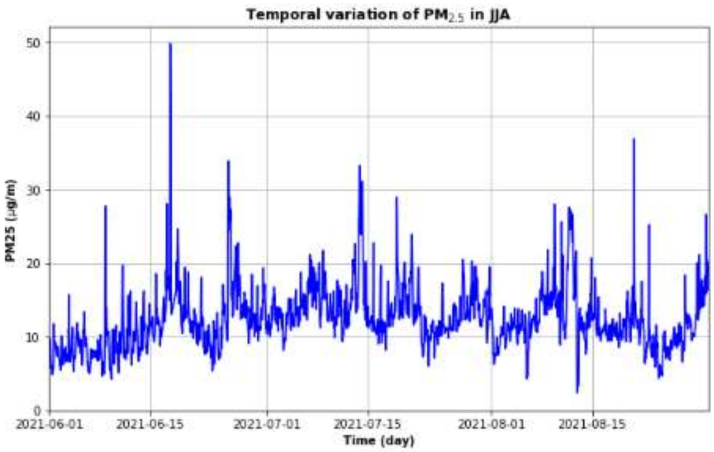

Figure A. 1 PM$_{2.5}$ variations in JJA

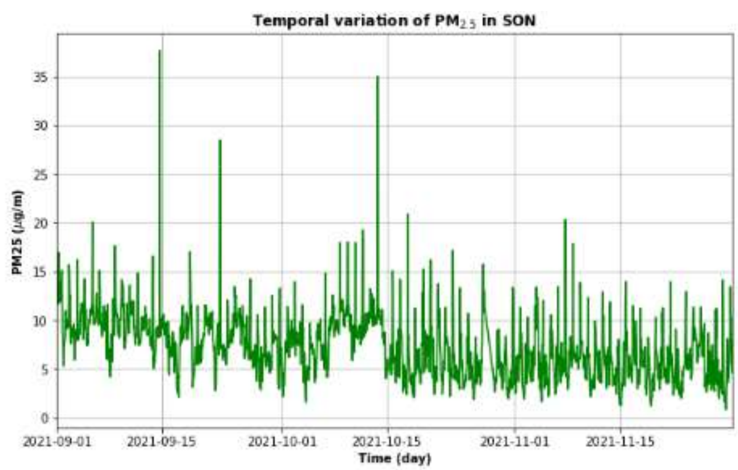

Figure A. 2 PM$_{2.5}$ variations in SON

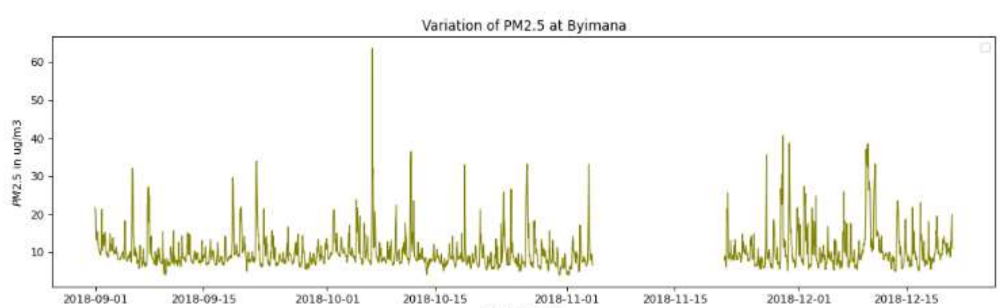

Figure A. 3 PM$_{2.5}$ variations

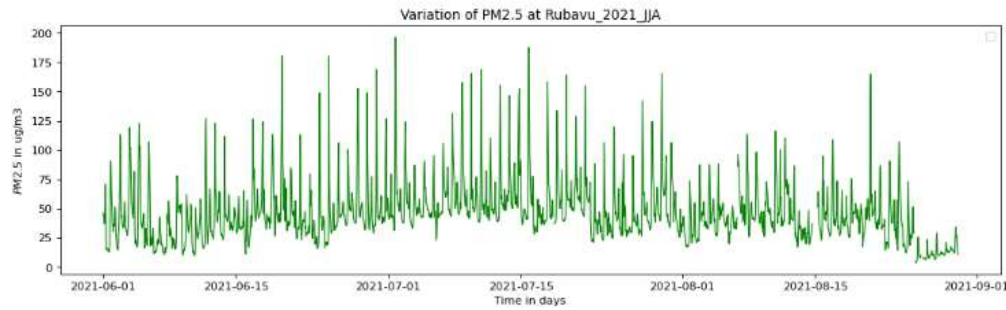

Figure A. 4 PM2.5 variations at Rubavu station, 2021 JJA

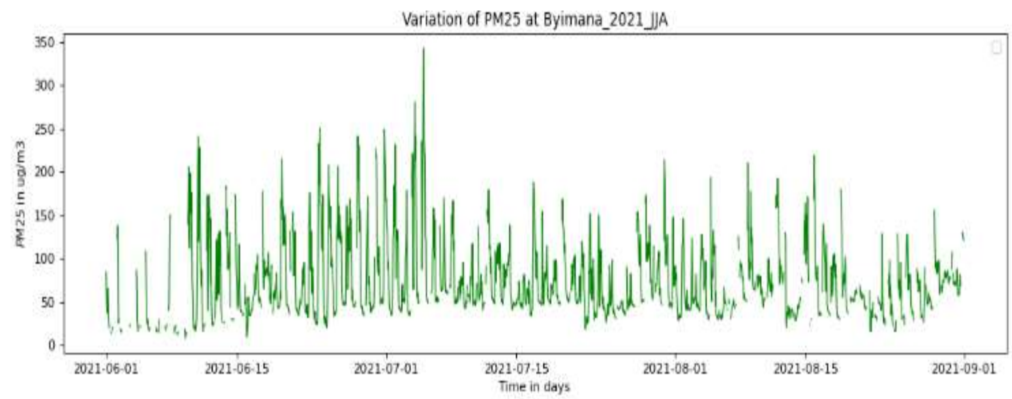

Figure A. 5 PM2.5 variations at Byimana

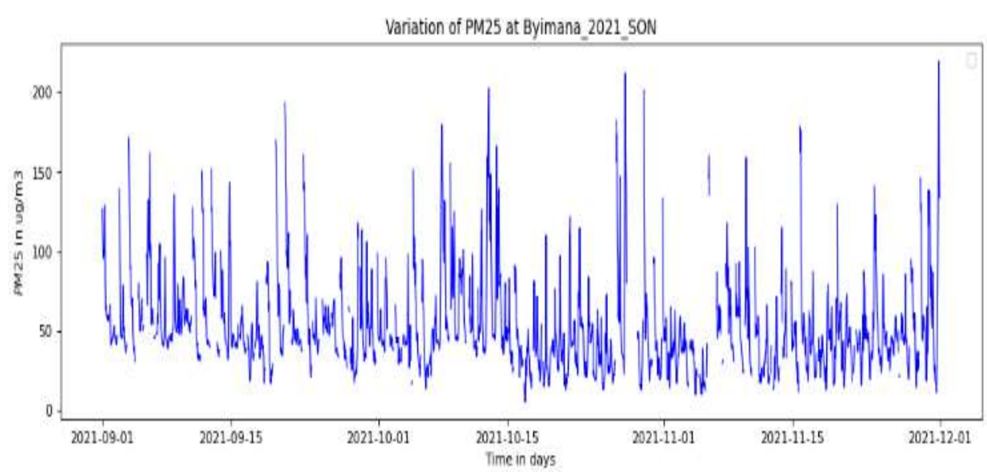

Figure A. 6 PM2.5 variations at Byimana

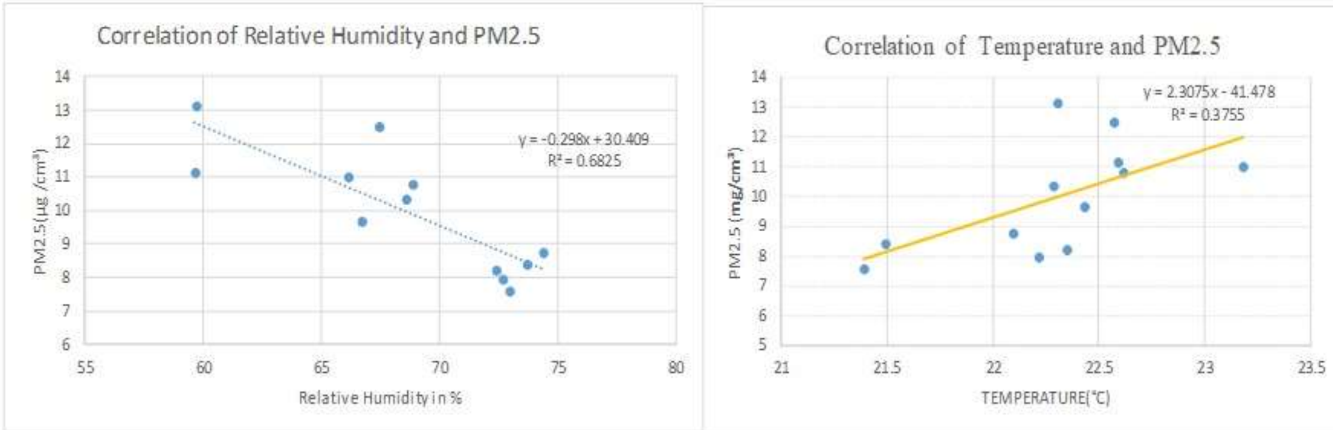

Figure A.7 Correlation of PM2.5 with RH and T