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**MASTER'S DISSERTATION**

# Spatial and Temporal Variation of Atmospheric Particulate Matter in Nyanza Town and Kigali City in Rwanda

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**Ref. No. 220017893**

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## DECLARATION

I declare that this dissertation contains my work except where explicitly acknowledged.

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Date………………………………………….

**CERTIFICATION**

This is to certify that the work contained in the thesis entitled thesis "**Spatial and Temporal Variation of Atmospheric Particulate Matter in Nyanza Town and Kigali City in Rwanda**" by Francois NKUNDABAGENZI in partial fulfillment of the requirements for the award of a master's degree in Biodiversity Conservation and Natural Resource Management at the University of Rwanda, College of Science and Technology has not been submitted or published elsewhere for a degree.

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**ABSTRACT**

Exposure to atmospheric particulate matter remains the global environmental cause of premature human mortality in developing countries. This is a particular concern in African countries such as Rwanda, with rapid urbanization and population growth. However, little is known about the spatial and temporal variation of these microscopic air particles in Rwanda. This thesis provided the first spatial and temporal variation of fine and coarse particulate matter with an aerodynamic diameter ≤ 2.5 µm and ≤ 10 µm ($PM_{2.5}$ and $PM_{10}$) in two sites (urban and rural) located in a large city (Kigali) and small town (Nyanza). $PM_{2.5}$ and $PM_{10}$ data were collected using the low-cost air quality sensors for a four months' period in the wet and dry season in 2021. The results showed that the 24 hour-mean concentrations of $PM_{2.5}$ and $PM_{10}$ were higher in the dry season than in the wet season at all sites. The 24-hour-mean concentrations of $PM_{2.5}$ and $PM_{10}$ were higher in a rural site in Kigali (40.43 µg/$m^3$, 47.83 µg/$m^3$) than in a rural site in Nyanza Town (25.54µg/$m^3$, 29.57µg/$m^3$), respectively. The 24-hour means of $PM_{2.5}$ and $PM_{10}$ at all sites were more than two higher than the World Health Organization air quality guidelines for 24-hour mean. The rural site of Kigali City exhibited higher concentrations of $PM_{2.5}$ and $PM_{10}$ than the urban site, suggesting an impact of COVID-19 lockdown in Kigali City. In contrast, the higher $PM_{2.5}$ and $PM_{10}$ concentrations were observed in urban than rural site in Nyanza Town. These results prove that vehicle emissions contributed to air pollution in urban areas while biomass burning highly polluted the rural areas. Spearman correlation showed that there was no influence of meteorological conditions on air pollution at all sites and the results indicated that measures to control air pollution in large cities should be also applied in small towns. Further long-term studies are required and should cover many sites and include other meteorological conditions such as wind speed and direction.

**Keywords**: Particulate matter, $PM_{2.5}$, $PM_{10}$, urban area, rural area, Kigali City, Nyanza Town

## LIST OF SYMBOLS AND ABBREVIATIONS

PM: Particulate Matter

REMA: Rwanda Environment Management Authority

$PM_{2.5}$: Particles that are 2.5 micrometers in diameter or less

$PM_{10}$: Particles that are 10 micrometers in diameter or less

$NO_x$: Nitrogen Oxides

CO: Carbon Monoxide

$SO_2$: Sulfur Dioxide

$NO_2$: Nitrogen Dioxide

IAP: Indoor Air pollution

µg: Microgram

WHO: World Health Organization

NISR: National Institute of Statistics of Rwanda

OC: Organic Carbon

EC: Elemental Carbon

GPP: Gas Phase Photochemical Process

$NH_3$: Ammonia

BC: Black Carbon

$O_3$: Ozone

$m^3$: Cubic-meter

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# CHAP I: INTRODUCTION

## I.1. Background of the study

Air pollution is the largest global environmental cause of premature human mortality affecting urban and rural areas. Recently, the World Health Organization (WHO) indicated that about 90 % of the world population live in areas where poor air quality exceeds the limit value guidelines (WHO, 2018). The air pollutants are emitted from various sources such as transport, industries and construction activities in urban areas while biomass burning is a major source of air pollution in rural areas (Lowenthal et al., 2014). The greatest health damaging air particles possess an aerodynamic diameter of 10 or less. The exposure to those particulate matters influences air particles to enter in the lungs and cause many health problems. Particulate matter air pollution (fine particles ($PM_{2.5}$) and coarse particles ($PM_{10}$) that can penetrate into the lungs are the air pollutants of the greatest health concern. These particles are emitted from both anthropogenic and natural sources and they are used as the metric of evaluation of air pollution for countries. The WHO has set epidemiological air quality guidelines for $PM_{2.5}$ and $PM_{10}$ due to their health effects such as lung cancer, cardiovascular diseases, chronic respiratory diseases and stroke (WHO, 2020). The 2021 WHO air quality guidelines recommend that 24 hours mean concentrations of $PM_{2.5}$ and $PM_{10}$ should not exceed 15 $\mu g/m^3$ and 45 $\mu g/m^3$, respectively (WHO,2021).

While developed countries have widely monitored these particles and set air quality standards, this is of particular concern in developing countries such as Rwanda. The main concern is the lack of the long-term monitoring stations, lack of funds and qualified personnel to maintain the calibration of these reference monitors. While there are rapid urbanization and population growth, information on air pollution in Africa remains sparse. Available information indicated that the level of $PM_{2.5}$ and $PM_{10}$ are above the recommended standards. For example, in the East African region, Kalisa et al (2018) conducted a 3 months' study in Rwanda and reported that the levels of $PM_{2.5}$ and $PM_{10}$ were more than two times higher than the WHO standards. The PM is mostly known to contain a lot of toxic chemicals that have been recognized to cause cancer and mutation (Durant et al., 1996). Therefore, the long exposure to the air particles could be risky to human life and this can provoke some respiratory and heart diseases (Mabahwi et al., 2014).

### 1.2. Problem statement

In many countries, air pollution is a big problem in rural and urban areas (WHO, 2012). The air pollutants in urban areas arise mainly from industrial and traffic emissions (Ilyas et al., 2010) as well as the households during the use of fuel or energy sources for cooking and heating (Martin et al., 2013). While in rural areas, the origin of air pollutants includes the use of insecticides or pesticides sprays, dusts from unpaved roads, and burning of crop residues (Majra, 2011). The increase of air pollutants such as particulate matter is one of the global problems associated with poor air quality in rural and urban areas. Kumie et al., (2014) revealed that increased industries and motorization have raised the air pollutants in Kigali. It was also found that charcoal is highly used in urban areas and wood fuels in rural areas for cooking (MININFRA, 2018). This is consistent with the study conducted by (REMA, 2018) which indicated that a large number of people use wood fuels due to the lack of other choice and low-cost source of energy for cooking in the country. In Kigali City, the level of air particle concentrations was evidenced to increase in urban backgrounds. Henniger (2009) showed that air pollution in Kigali was at beyond belief level, the pollutants concentration was very greater than the limits value of WHO guidelines.

There are existing stations for government air quality monitoring in Kigali that can provide spatial-temporal variation of air quality data for Kigali City in previous years. To date, there has never been a study conducted in towns such as Nyanza. This will be the first study reporting air quality in that place and Nyanza is well known as it is the tourist destination (Royal capital of the Rwandan monarchy) district in Southern Province which attracts 30,000 tourists every year (Nyanza district,2018). These suggested that air pollutants may be elevated in town due to local human activities and high traffic from tourists. Thus, information of air quality status is necessary for such a touristic area. Maione et al. (2016) showed that anthropogenic works are likely to increase the emission of air particles and change the status of air in the atmosphere. Hence, the aim of the study in this thesis was to evaluate the spatial and temporal variation of particulate matter ($PM_{2.5}$, $PM_{10}$) in urban and rural areas of a city and town in Rwanda. This study will provide relevant data to the Rwanda Environmental Management Authority (REMA) to set control measures of air pollution in typical urban and rural sites from large cities and towns.

### 1.3. Research questions

What are the levels of $PM_{2.5}$ and $PM_{10}$ in urban and rural areas between small town and big city?

What human activities contribute to PM sources in urban and rural areas between small towns and big cities?

What are the levels of $PM_{2.5}$ and $PM_{10}$ concentration in the dry and wet season at sampling sites?

### 1.4. Objectives of the study

#### 1.4.1. The main goal of the study

The overall objective of this project is to investigate the spatial and temporal variation of particulate matter air pollution in Nyanza Town and Kigali City in Rwanda.

#### 1.4.2. The specific objectives

1. To determine the levels of $PM_{10}$ and $PM_{2.5}$ in urban and rural areas in a small town.
2. To determine the levels of $PM_{10}$ and $PM_{2.5}$ in urban and rural areas in a big city.
3. To compare air pollution levels ($PM_{10}$ and $PM_{2.5}$) between urban and rural sites in a small town and big city.
4. To determine the variation of air pollution level ($PM_{10}$ and $PM_{2.5}$) between dry and wet season.
5. To investigate the impact of meteorological conditions on air pollution in urban and rural areas.

#### 1.4.3. Scope of the study

This study investigated the spatial and temporal variation of particulate matter air pollution in Nyanza Town and Kigali City. The data of $PM_{2.5}$ and $PM_{10}$ were all measured from urban and rural sites of these two areas.

#### 1.4.4. Significance of the study

This study arose with these following significances:

- This is the first study that determined spatial and temporal variation of particulate matter air pollution in Rwanda comparing small towns and big cities. This study provided useful data for Kigali City, academia, epidemiologist and policy makers, and will be relevant for urban and rural planning.

- Nyanza is a touristic district in Rwanda and information on air pollution will be useful for Rwanda Development Boards (RDB) to set measures for air pollution control in touristic areas.

# CHAP II: LITERATURE REVIEW

## 2.1. Status of particulate matter in the World with a focus on African continent

Air pollution is a key concern all over the World in developed and developing countries. Africa is a continent acknowledged to have a significant land mass in both hemispheres. The emission of air pollutants such as trace gas and aerosol is connected to its climatic conditions (Piketh and Walton, 2004). The African continent embraces various climatic regions and distinctly the climate variables could exert a strong influence on air particle levels. For instance, the countries that have wet and dry seasons, show the apparent changes in level of dust and sea spray loads (Querol et al., 2009). On the other hand, Lamri et al. (2018) indicated that the emission of air particles is associated with anthropogenic activities and natural sources. The colours in Figure 1 show where air pollutant emission is high and monitoring data is lacking in the world map. The red colour indicates the highly polluted places and blue colour shows the clean areas.

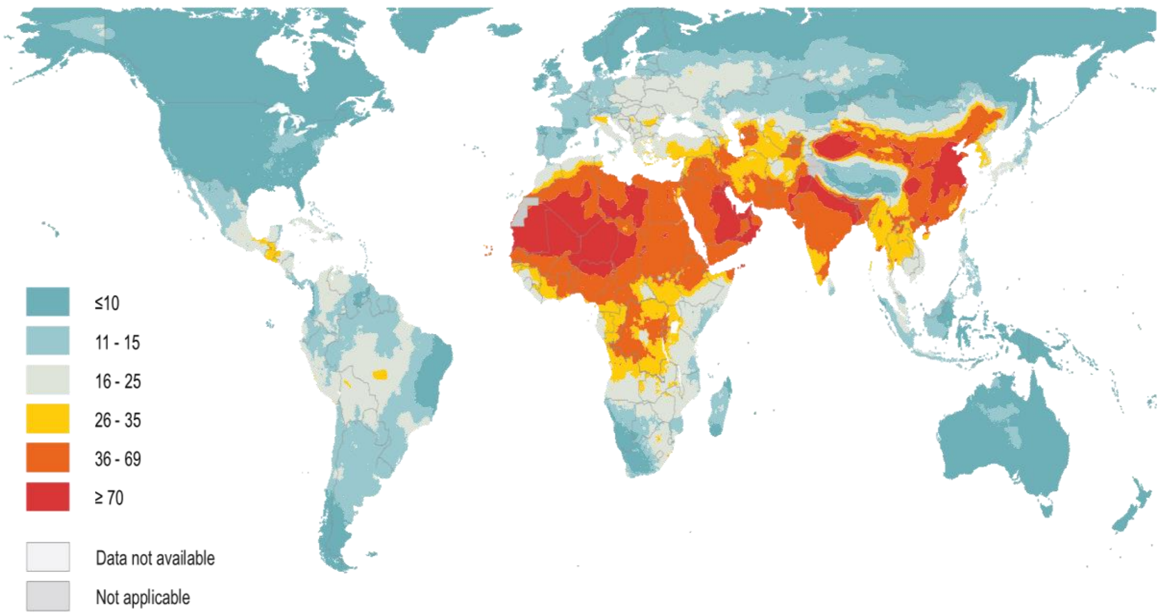


Figure 1. Global map of modelled annual median concentration of $PM_{2.5}$, in µg/m$^3$ (WHO, 2016)

## 2.2. Pollution of particulate matter in Africa according to different studies

In Africa, the particulate matter **(**PM) levels were reported to surpass the annual and 24-h WHO guidelines. PM levels were particularly high in Nigeria and large numbers of vehicles contributed to high PM concentrations in Lagos metropolis (Adeleke et al., 2011). However, the high levels of PM were also recorded in other Western African countries. Among the countries in which studies were identified in East Africa, the highest PM levels were reported in Uganda and Rwanda (Kirenga et al.,2015; Kalisa et al.,2018). Tanzania was the country with lowest recorded mean of PM levels (see Figure 2) but these pollutant concentrations exceeded the 24-h $PM_{10}$ guidelines of WHO (Mkoma et al.,2010).

Furthermore, the high concentrations of PM were found in the parts of North and South of Africa. Bouchlaghem and Nson,2012 indicated that the highest dust emission came from the Saharan desert but the high concentrations of air particles were as well spoken in cities of Egypt. The study conducted by Xu et al., 2019, in Southern West Africa showed that air pollutants were emitted from various human activities and people were exposed to those harmful pollutants. Figure 2 and 3, show the levels of particulate matters ($PM_{2.5}$ and $PM_{10}$) concentrations observed in some African countries.

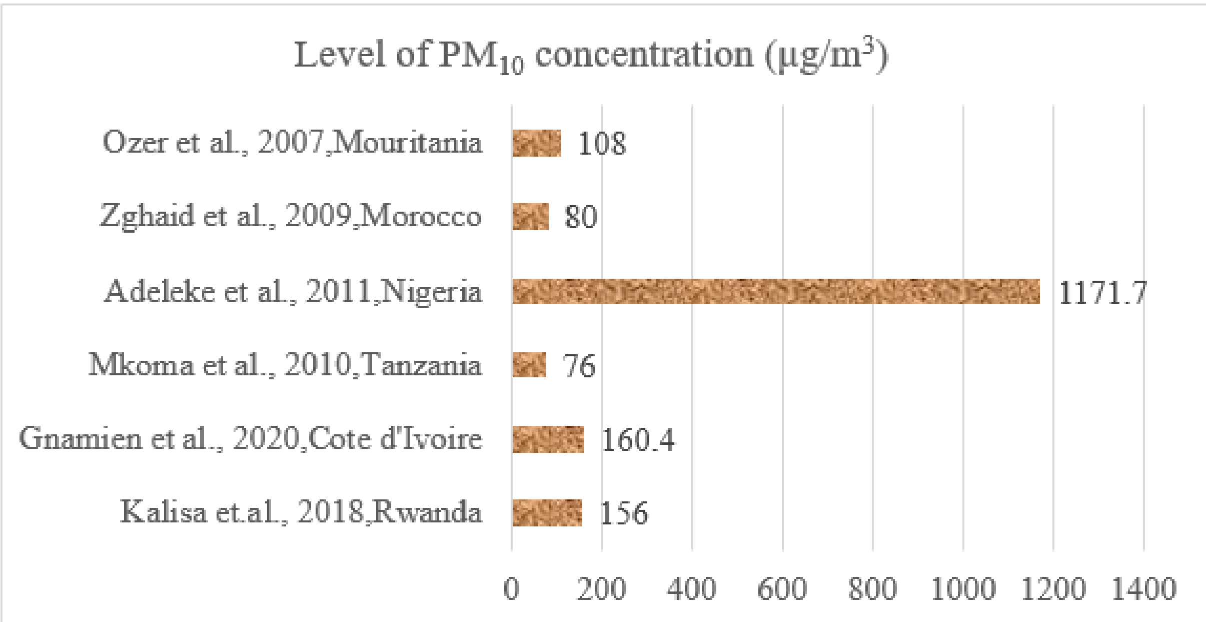


Figure 2.The studies conducted in Africa showing the level of $PM_{10}$ measured in different countries.

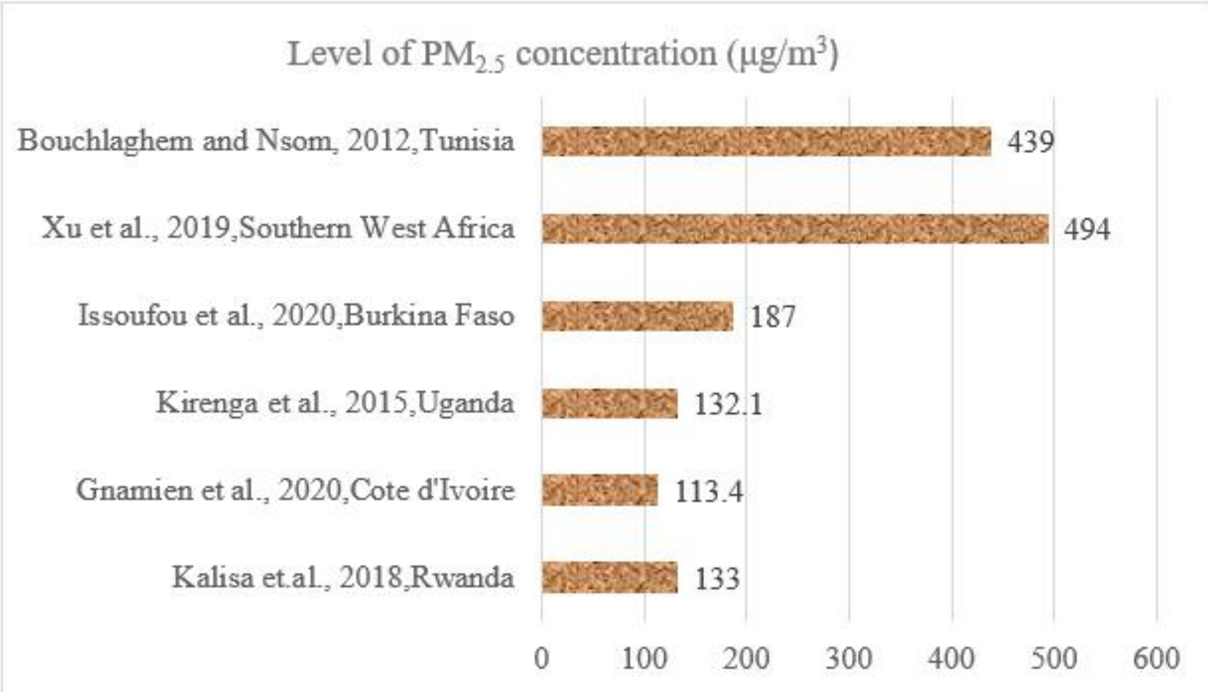


Figure 3. The studies conducted in Africa showing the level of $PM_{2.5}$ measured in different countries.

**2.3. Status of air pollution in Rwanda**

The emissions inventory on air pollution in Rwanda showed that release of vehicle exhaust is the core source of air pollution in urban centers while the use of charcoal or woods in the households and open fires in the fields increase air pollutants in rural areas (REMA, 2018). As a result, this can lead to a high load of harmful air contaminants and health effects (Musafiri et al., 2018).

Table 1.Summary of studies conducted on air pollution in Rwanda

| Study | Location | Pollutant | Findings |
|---|---|---|---|
| Henninger, 2013 | Kigali | $PM_{10}$ | The levels of $PM_{10}$ were high and surpassed those of WHO guidelines as a result that negatively affect the health of people due to the increase of air contaminants from human activities in the city. |
| DeWitt, 2016 | Musanze | BC | The anthropogenic activities stimulated the higher release of air particles. |
| Kalisa et al., 2018 | Kigali | $PM_{2.5}$ and $PM_{10}$ | The pollutant concentrations were high in Kigali and their reduction appeared during the days of rest. |
| Nduwayezu et al., 2015 | Kigali | $O_3$, $NO_2$, $SO_2$, CO | Petrol and diesel vehicles contribute to the rise of harmful air particles in different part of Kigali. |

| | | | |
|---|---|---|---|
| WHO, 2016 | Urban areas Rwanda | $PM_{2.5}$ | High rate of air pollution was observed and it burdened the economy and quality of life. |

### 2.4. Research gaps related to pollution of particulate matter in Rwanda

The size of particles and chemical constituents have been broadly known to cause health effects but further studies are required to identify the precise contributors linked to PM (Begum et al., 2009). The study conducted on particulate matter concentration in Kigali City indicated that there was poor air quality that was found to originate from vehicles emission and burning of waste materials from wood workshop (Irankunka, 2019).This study suggested that it could be conducive to use these wastes of wood materials in making other valuable products and increase electric vehicles for the environmental and human health protection. Henniger, 2009 showed that air pollution in Kigali was at beyond belief level due to the fact that the pollutant concentration was very greater than the limits value of WHO guidelines. The scholar recommended that the measurement of air pollutants should take both the dry and rainy seasons at least in one year. Furthermore, this research found that several air monitoring instruments are necessary at various locations in Kigali and across the country to improve the findings.

It was mentioned as well that many people rely on selling the reachable and low-cost wood fuel and charcoal to secure the necessities of life (Byamukama et al, 2011). Thereafter, the high concentration of particulate matter increases within homes because the households use fire woods and petrol to find lights during the darkness. The study showed that women, children and old adults are endangered by indoor particulate matters by cooking and they are affected by the inhalation of smokes in closed rooms (Irankunda, 2021). The other study conducted by REMA (2018) indicated that the air pollution in rural sites is observed from high usage of solid biomass burning. The improved infrastructure and technology for substitute cooking such as use of electric or pellet stoves can potentially reduce emission of air pollutants and other negative effects to humans and environment.

Although nature can elevate PM concentrations through the wildfire and wind, human activities such as wood and coal burning suggested higher emission of $PM_{2.5}$ and $PM_{10}$ in the urban areas (DeWitt, 2016). The pollution due to emissions from motor traffic and the development of industries own a major share in polluting the environment (Irankunda and Ishigaki, 2020). The study indicated that levels of air pollutants surpassed those of WHO guidelines in Kigali City (Kalisa et al., 2018). Correspondingly, the rural places were also reported to be highly affected by the indoor air pollution from burning substances at the time of cooking (Irankunda, 2021). Thus, there is a need to invest in liquefied petroleum gas or biogas for a long-term and increase paved roads in urban and rural areas to reduce the release of air particles especially in dry season. The use of air filters on chimneys for air pollution control and training of transforming wastes into other useful materials such as fertilizers are required to many people for improving the air quality.

**2.5. The main constituents of particulate matter**

The particulate matter consists of a significant composition of particles such as ash, dust, sea salt, organic carbon (OC), water ($H_2O$) and elemental carbon (EC). All these pollutants can be released in the atmosphere. Most particles that are frequent components of the atmosphere include nitrate (NOx), Sulfur Dioxide ($SO_2$) and primary gaseous organics, and other constituents that may develop to the particulate phase through several gas-phase photochemical (GPP) processes.

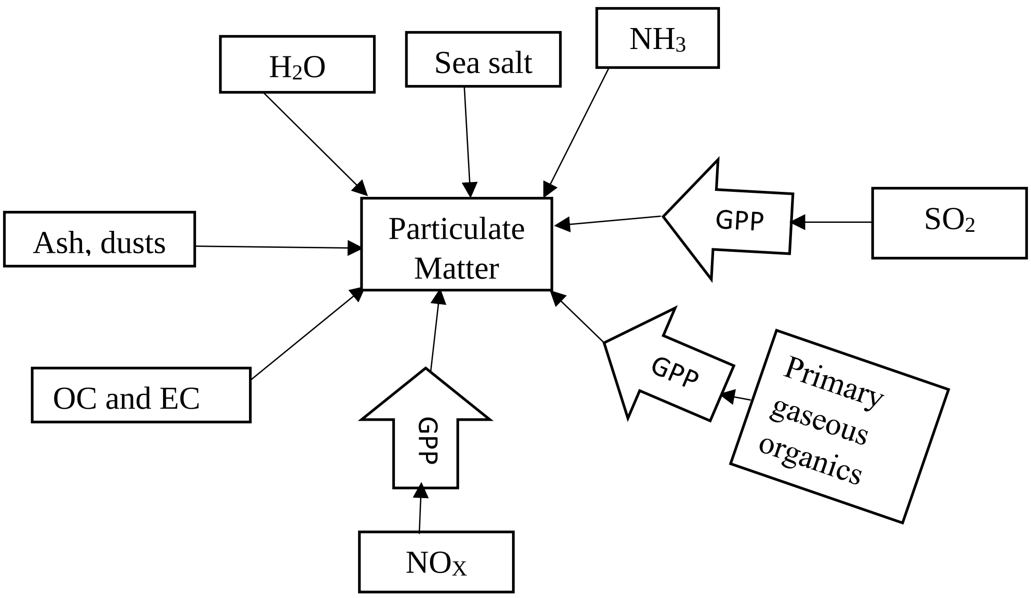


Figure 4.Composition of particulate matter, (GPP) gas-phase photochemical processes, figure adapted from Praznikar and Praznikar (2012)

Particulate air pollution is the combination of particles of mineral and carbon-based substances suspended in the air (see Figure 4). These air particles can be differentiated by their big and small size due to the fact that they are formed in a mechanical and chemical reaction manner (WHO,2003). The constituents of particulate matter are very complex because they are attributed to the state of weather and origin of emission in order to form a blend of organic and inorganic substances (Brook et al, 1997). The variation of $PM_{10}$ concentrations can be indicated by the rate of emission and the meteorological conditions but $PM_{10}$ sources are able to fluctuate by geographic latitude and longitude. As reported by various research studies (Kuang,2002, Van der Wal and Janssen ,1996, Chang et al,2000), the core atmospheric factors are wind (speed and direction), temperature, rain effect and dust storms. The largest particles are mechanically produced by the break-up of larger solid particles. These particles can include wind-blown dust from agricultural processes, uncovered soil, unpaved roads or mining operations. The road dust, pollen grains, mould spores, and plant and insect parts are all in this larger size range (WHO,2003). However, some other air particles such as N0x, and $SO_2$ can be emitted from the industries (Rabbi, 2018).

### 2.6. Categories of particulate matter

The polluted air has many particles of different sizes that consist of:

- $PM_{2.5}$ which refers to particles of 2.5 micrometers in diameter or less and $PM_{10}$ that refers to particles of 10 micrometers in diameter or less.

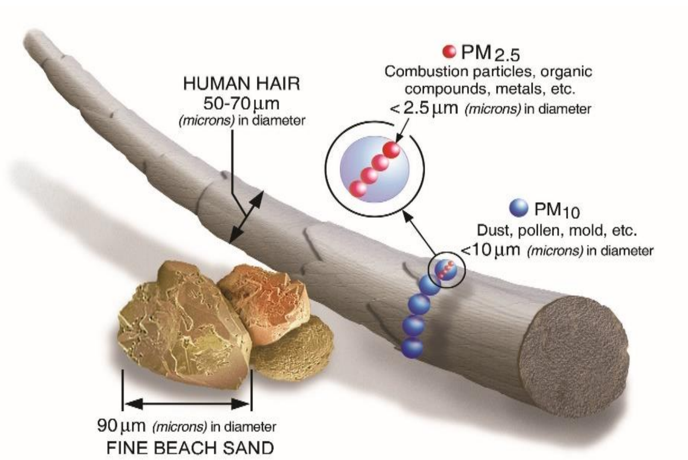


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Figure 5:Illustration of the size of particulate matter (Source: United States Environmental Protection Agency, 2016)

### 2.7. Sources of $PM_{2.5}$ and $PM_{10}$ in urban and rural sites

#### 2.7.1. Indoor and outdoor air pollution

The ambient air pollution includes emitted harmful pollutants and this is able to change atmospheric air in its natural state (see Figure 6). Because of that and the matter of household air pollution related to the concentration of air contaminants in buildings, the scholars decided to conduct different studies on air pollution. The study of Bruce et al., 2000 showed that smoke emissions from burning wood, coal, cattle dung, and other biomass fuels are significant sources of indoor air pollutants in many different nations. For outdoor air pollution, Karagulian et al., 2015 found that biomass burning and vehicle emission were among the leading causes of outdoor air pollutants. They added that a lot of risks on health can increase in rural places and cities. The published study on biomass burning in households described that domestic emission of smoke is considerably high and this spread a lot of air particles in rural and urban zones (Fullerton et al.,2009).


Figure 6.Source of PM. a) Indoor air pollution, b) open fire burning of substances , c) road dusts, and d) industry (Wright et al., 2019)

The capital of Kigali has an increase in population growth (Rajasheka et al., 2019) and anthropogenic activities such as transportation and fire wood burning can be expected to raise air pollutants with an extreme danger to the health of citizens (Henninger, S. 2009). A study carried out by (Nsengimana et al,.2011) indicated that the elevated accumulation of air pollutants in Kigali is due to an increase of vehicles, especially old vehicles with insufficient care facilities and poor traffic management systems. (Nahayo et al, 2019) also revealed that the first contributors to air pollution in Kigali City were automobile and stationery sources and as a result that can cause many disasters and complications to health.

The study conducted in Kigali for three months in 2018, showed that the levels of $PM_{2.5}$ and $PM_{10}$ surpassed the recommended WHO guidelines (Kalisa et al.,2018). They added that high concentration of the pollutants was contributed by vehicle emissions and reduced during holidays and car-free days. However, there has not yet been a study carried out in the southern province such as Nyanza. This is the first study conducted in Nyanza Town and will show the contributors and levels of PM in urban and rural areas. The available report of Nyanza district showed that the contamination of air in this place is attributed to the dust emissions due to the vehicle speed in the working area and watering during the soil works *(*ESMP, 2019).

## 2.8. Particulate matter and effects

### 2.8.1. Human health effects of exposure to particulate matter

Human health has suffered from the high concentration of PM and the collaborative study described that air particles of ten aerodynamic diameter ($PM_{10)}$ are deadly across all ages of people (Samoli et al,.2008) as shown in Figure 7. The heart and lung diseases were proved to increase due to elongated exposure to fine air particles (Pope et al.,2002). Disastrous effects of PM exposure to health include the increase of both acute and chronic disease (Bruce et al.,2000).

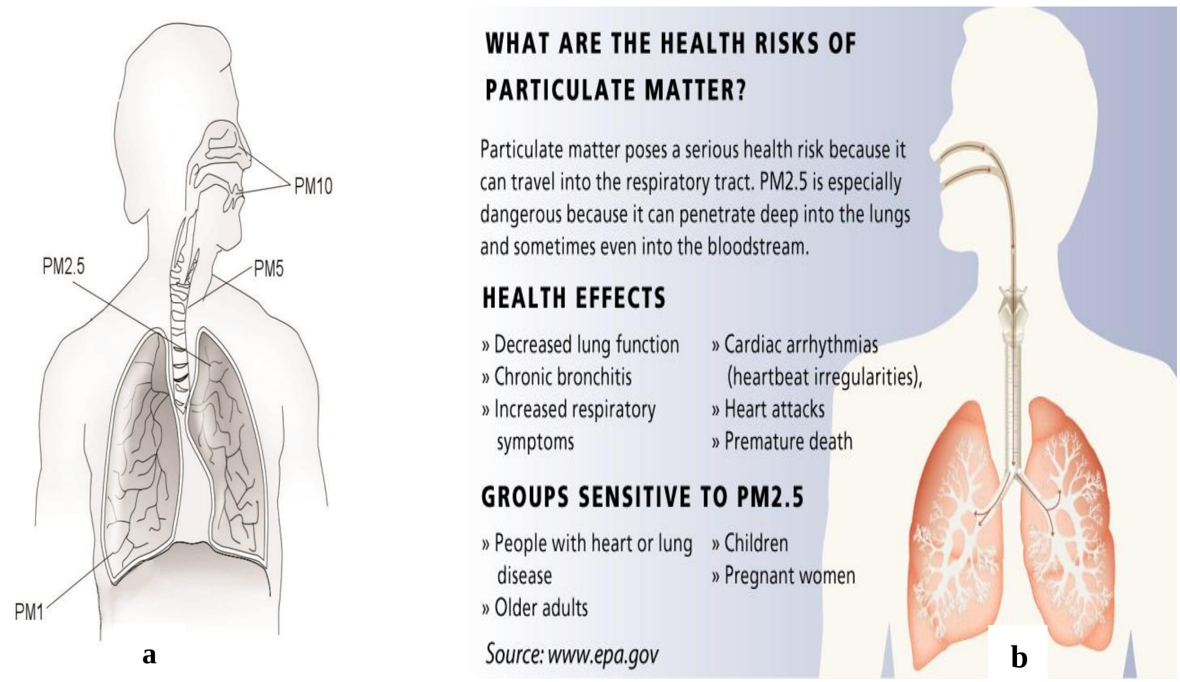



Figure 7. PM in the respiratory system. a) Deposition site (Praxsnih ,2011), b) Health risks

The health problems attributed to long duration of PM exposure in the worldwide condition comprise a high diminution in life expectancy of humans (Abbey De et al., 1999). The study indicated that there are several deaths, cardiovascular and respiratory diseases linked to short duration of exposure to high PM level such as exacerbation of asthma (Brunekreef and Forsberg ,2005). This agrees with the study of Gauderman et al 2004 which showed that PM harmfully affects lung development in children and adolescents. They also revealed that high concentration of PM causes the loss in respiration growth among children and that leads to malfunction of the lungs. Table 2 shows some effects that air particles cause to human lives.

Table 2.Mechanisms by which particulate matter particles increase the threats of breathing and other health effects ( Bruce et al.,2000).

| **Pollutants** | **Mechanism** | **Potential health effects** |
|---|---|---|
| $PM_{10}$ and $PM_{2.5}$ | Lung infection and irritation | Illness of asthma |
| | Reduced mucociliary transport | Infection of throat |
| | | |
| | Reduction of white blood cells | Persistent bronchial diseases |
| | Fibrotic response | Permanent pulmonary diseases |

**2.8.2. Impacts of particulate matter on wildlife species**

**2.8.2 .1. Plants**

The plants have many uses and can provide the leaf surface for absorption and storage of air pollutants to reduce the level of these contaminants in the atmosphere (Liu and Ding 2008). The study also showed that urban plants contribute to a reduction of polluted air (Selmi et al., 2016). However, the deposition of particulate matter on leaf area may reduce chlorophyll due to a shading effect (Singh et al,2002). The coarse particulate matters have the impacts on the upper areas of leaves more (Kim et al., 2000) while finer particulate matters impact lower surfaces (Beckett at al. 2000). The air pollutants may cause harm to plants by changing the host physiology or direct toxicity as a result the greater damage can cause total loss of plants (Iqbal and Shafig,2000) as shown in Figure 8.


Figure 8.Particulate matter on plant leaf, a) $PM_{10}$ on a plant leaf, b) $PM_{2.5}$ on a plant leaf (Supe and Gawande, 2013)

**2.8.2.2. Animals**

The accumulation of air pollutants in the environment causes a lot of health risks. Exposure to particulate matter is well-known to increase adverse health effects including morbidity, organ disturbances and death (Coogan et al,2012). The stress, change in species distribution and anemia are also connected to emission of toxic air pollutants on wildlife species (Newman et al.,1979). The weak animals such as young or old, are highly affected by air particles (Humphreys,1991). The pollutants of particulate matters affect animals like humans, various breathing and long-lasting diseases can attack them. Thus, typically the body inflammation, oxidative damage, and other biological effects appear (Osornio-Vargas et al. 2003).

Air pollutants can influence acidic rain formation (Kumar, 2017) and indirectly affect animal health and habitat (Newman et al.,1992). Furthermore, these pollutants including PM can cause global warming and climate change, therefore there is the loss of many animals' species (PAL,2015).

## CHAP III. MATERIALS AND METHODS

### 3.1. Study sites description

This study was conducted in Kigali City and Nyanza Town (see Figure 9). Kigali City is the capital city of Rwanda, it covers an area of 730 $km^2$ and is composed of three districts which are Kicukiro, Nyarugenge and Gasabo. This city has the population size of 1,132,686 and the population density of 1552 /$km^2$ (NISR, 2012).Rwanda has two main seasons. These are wet season (March, April, and May) and dry season (June, July, August).

Nyanza, is the small town of the southern province in Rwanda compared to Kigali, located in 90 km from Kigali City. Nyanza Town is in Nyanza district which covers a land area of 672 $km^2$ with a population size of 323,719 people and population density of 482 /$km^2$ (NISR, 2012). In all seasons, the temperature typically changes. July is the driest month while April is the wettest month (www.weatherspark.com).

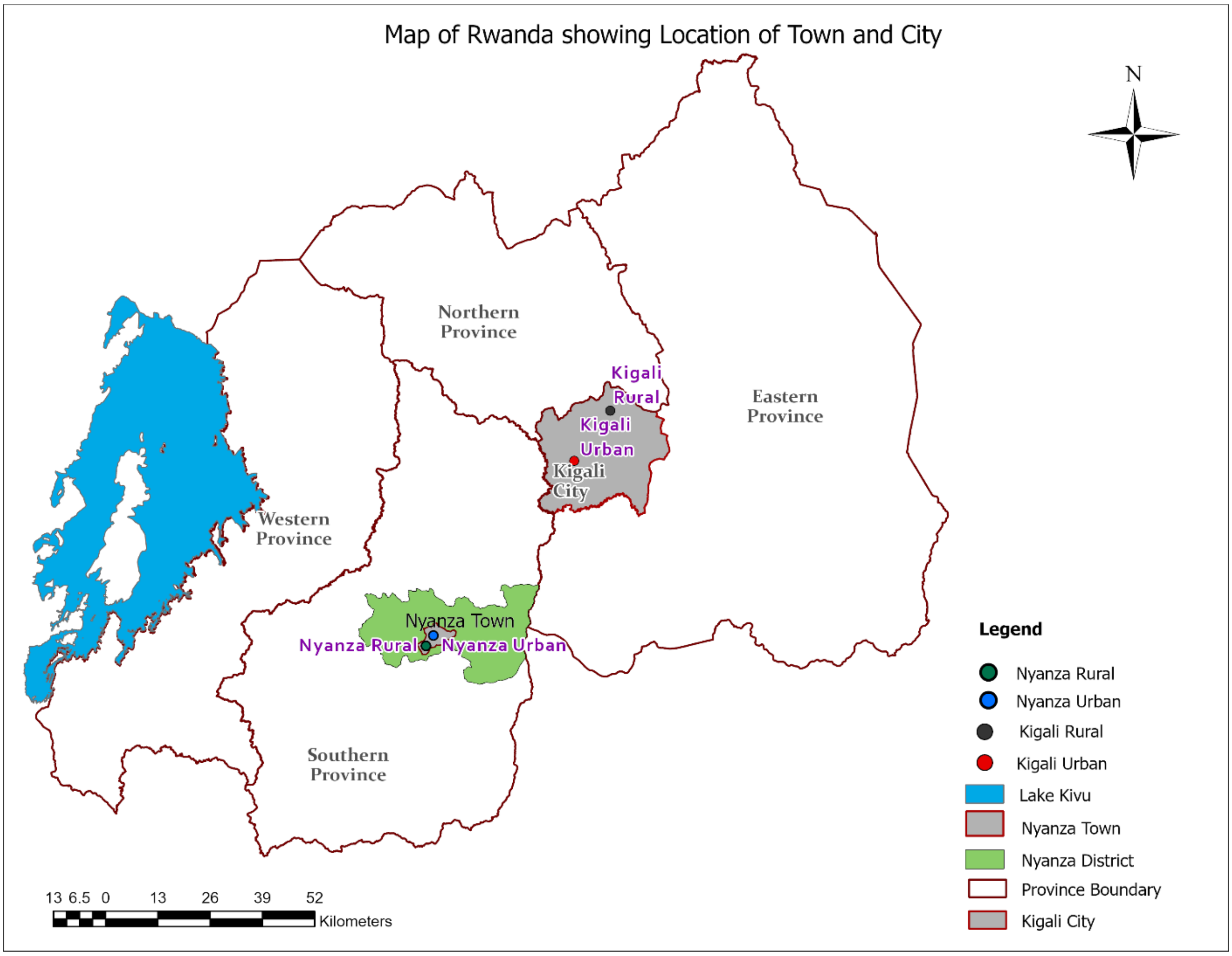



Figure 9.Showing the sampling points in Kigali City and Nyanza Town.

### 3.2. Particulate matter collection ($PM_{2.5}$ and $PM_{10}$)

The real-time data of $PM_{2.5}$ and $PM_{10}$ were collected using low-cost air quality sensors (Purple Air, USA) over 4 months from 1st April to 31st July, 2021 reflecting two seasons (wet season: April and May, and dry season: June and July). The PM monitors were mounted at different buildings in urban and rural areas in Kigali and in Nyanza at approximately 5 m above ground. The distance between two sampling sites was 1.3km in Nyanza Town and 15.32km in Kigali City respectively. The parts of town and city with many agricultural lands and low population density indicated the rural areas while many infrastructures and high population density showed urban areas. These places were also considered because the buildings were in the open space to facilitate the sensors detect the pollutants of $PM_{2.5}$ and $PM_{10}$. All measured data were downloaded and saved on the flash disk every month until the end of study when they were transferred to the computer and analysed through SPSS software.

### 3.3. Measurement of meteorological parameters

Meteorological data (temperature and relative humidity) recorded during the sampling period were obtained from both Rwanda weather stations close to our sites and from portable weather stations embedded with low-cost air quality sensors.

### 3.4. Data Analysis

The meteorological and PM data were exported into excel and combined into one SPSS file. SPSS software was used to analyse data of air particles and provide the descriptive statistics of all measured parameters that summarized the standard deviation, mean, minimum and maximum values. Kruskal Wallis test was used to test significance differences between the sites at a significance level of 5% and compare the means of PM concentrations between urban and rural areas.

## CHAP IV. RESULTS AND DISCUSSION

### 4.1. Descriptive results

Table 3. Weather conditions and PM concentrations on an average of 24 hours at sampling sites in four months.

| Measured parameters | N | Location | Site Type | Min | Mean | Max |
|---|---|---|---|---|---|---|
| $PM_{2.5}$ (µg/m$^3$) | 122 | Kigali | Rural | 17.27 | 40.43 | 76.60 |
| $PM_{10}$ (µg/m$^3$) | 122 | Kigali | Rural | 18.16 | 47.83 | 81.37 |
| Temperature ($^0$C) | 122 | Kigali | Rural | 16.43 | 24.36 | 34.65 |
| Relative Humidity (%) | 122 | Kigali | Rural | 31.34 | 50.17 | 72.28 |
| $PM_{2.5}$ (µg/m$^3$) | 122 | Kigali | Urban | 10.33 | 23.35 | 40.53 |
| $PM_{10}$ (µg/m$^3$) | 122 | Kigali | Urban | 18.08 | 39.21 | 70.22 |
| Temperature ($^0$C) | 122 | Kigali | Urban | 16.43 | 24.36 | 34.65 |
| Relative Humidity (%) | 122 | Kigali | Urban | 31.34 | 50.17 | 72.28 |
| $PM_{2.5}$ (µg/m$^3$) | 122 | Nyanza | Rural | 4.50 | 25.54 | 92. 69 |
| $PM_{10}$ (µg/m$^3$) | 122 | Nyanza | Rural | 4.60 | 29.57 | 98. 20 |
| Temperature ($^0$C) | 122 | Nyanza | Rural | 10.25 | 17.93 | 26. 93 |
| Relative Humidity (%) | 122 | Nyanza | Rural | 41.90 | 62.22 | 84. 50 |
| $PM_{2.5}$ (µg/m$^3$) | 122 | Nyanza | Urban | 6.35 | 39.19 | 240.91 |
| $PM_{10}$ (µg/m$^3$) | 122 | Nyanza | Urban | 6. 61 | 43.01 | 251.10 |
| Temperature ($^0$C) | 122 | Nyanza | Urban | 10.25 | 17.93 | 26.93 |
| Relative Humidity (%) | 122 | Nyanza | Urban | 41.9 | 62.22 | 84.50 |

The air pollutants concentrations by sampling sites are presented in Table 3. The 24 hour-mean concentrations of $PM_{2.5}$ and $PM_{10}$ were higher in rural site in Kigali (40.43 µg/m$^3$, 47.83 µg/m$^3$) than rural site in Nyanza Town (25.54µg/m$^3$, 29.57µg/m$^3$). The results also indicated that the level of $PM_{2.5}$ and $PM_{10}$ at all sites in Kigali City and Nyanza Town exceeded 15 µg/m$^3$ and 45 µg/m$^3$ values of the WHO standard respectively (WHO, 2021). The low concentration of $PM_{2.5}$ and $PM_{10}$ was found in urban area compared to rural area in Kigali City and could be explained by reduction of these air pollutants emissions in urban area during COVID-19 lockdown. Data of $PM_{2.5}$ and $PM_{10}$ were collected at an urban site in Kigali from April to July and these times, Rwanda imposed measures such as curfew to avoid the spread of COVID-19 infection. Kalisa et al. (2021) indicated that the total COVID-19 lockdown in 2020 decreased air contamination about 33% and the limited lockdown reduced air pollutants emission just about 21% in Kigali City. Also, the pollutant concentrations were higher at urban Nyanza than urban Kigali. This could reveal that the areas such Nyanza, where human activities continued to operate in the partial COVID-19 lockdown were probable to have an increase of air pollutants, suggesting their high level during the study period. These results were also consistent with previous studies conducted in Rwanda that indicated that biomass burning and vehicle emissions are major contributors to air pollution in Rwanda. In agreement, the studies conducted by Irankunda, (2019) and; Nduwayezu et al., (2015) reported that air pollutants come from the fuel combustion, motor vehicle emissions and waste material decomposition in Kigali. The recent study published by REMA in 2018 also indicated that human activities such as agriculture, construction or biomass burning, which happened in rural areas, have contributed to the emission of many air pollutants. As already mentioned, the minimum concentrations of $PM_{2.5}$ and $PM_{10}$ (4.50 µg/m$^3$, 4.60 µg/m$^3$) were observed in Nyanza rural site and maximum values of $PM_{2.5}$ and $PM_{10}$ (240.91 µg/m$^3$, 251.10 µg/m$^3$) in Nyanza urban site respectively across all sites. Furthermore, relative humidity and temperature were measured to indicate the conditions of weather during the sampling days. The results showed that the daily average of relative humidity and temperature were 17.93$^0$C and 62.22% for Nyanza Town, and 24.36$^o$C and 50.17% for Kigali City during the entire period of data collection.

### 4.2. Comparison of $PM_{2.5}$ and $PM_{10}$ between rural and urban areas

Table 4.The P value of level of $PM_{2.5}$ and $PM_{10}$ at different sampling sites

| Pollutants | N | Kigali-Urban | Kigali-Rural | P Value |
|---|---|---|---|---|
| $PM_{2.5}$ | 244 | 23.35 ± 7.10 | 40.43 ± 9.82 | 0.001 |
| $PM_{10}$ | 244 | 39.21 ± 11.80 | 47.83 ± 12.50 | 0.001 |
| **Pollutants** | | **Nyanza-Urban** | **Nyanza-Rural** | **P value** |
| $PM_{2.5}$ | 244 | 39.19 ± 14.96 | 25.54 ± 20.65 | 0.002 |
| $PM_{10}$ | 244 | 43.01 ± 16.77 | 29.57 ± 24.78 | 0.002 |

The measured pollutant concentrations between urban and rural areas can be shown by Table 4. The results indicated that the levels of $PM_{10}$ and $PM_{2.5}$ pollutants in Kigali rural site were significantly higher compared to all other sampling sites. This study also indicated that there were higher levels of PM in Nyanza urban site than rural site. However, the findings showed that PM concentrations in Kigali urban site were lower than those of rural area and similarly, the lower air pollutant concentrations appeared in Nyanza rural site than urban site. The occurrence of higher PM concentrations suggested that there could be some activities performed on those sites that promoted release of a lot of air contaminants.

This is in line with a study conducted by Monn et al. (1997) which indicated that anthropogenic activity is the greatest contributor to the increase of PM formation. Bhaskar and Mehta, 2010 also acknowledged that the air pollutants concentrations in urban areas come from emission of human activities. Although no study on particulate matter was conducted in Nyanza, it can be estimated that people are more vulnerable to adverse air pollutants because their activities release air pollutants. This is evidenced in recent studies conducted by Kalisa et al. (2018) and DeWitt et al. (2019) reported that both rural and urban areas of Rwanda have air pollutants connected to emission sources and natural surroundings. Furthermore, Barnes et al.,2009 indicated that the exposure to air pollutants might lead to diseases and deaths on the globe.

Considering Nyanza Town and Kigali City only at sampling sites, the results showed a proven and statistical significant difference between urban and rural site in Nyanza Town at (p-value = 0.002) as well as in Kigali urban and rural sites at (p-value = 0.001). When looking at the whole dataset for both Kigali and Nyanza sites, again urban and rural sites were different at (p-value = 0.001). The results of this study suggest that the emission of moving vehicles could be the main source of $PM_{2.5}$ and $PM_{10}$ in urban and domestic biomass burning in rural areas. However, it was noted that the levels of PM measured in all areas exceeded the recommendations of the WHO.

Table 5. Levels of PM concentration of this study and other studies conducted in Rwanda

| **Study** | **Site (Kigali)** | **Pollutant** | **Level [µg/m$^3$]** |
|---|---|---|---|
| This study | Urban | $PM_{2.5}$ &$PM_{10}$ | 23.35&39.21 |
| | Rural | $PM_{2.5}$ &$PM_{10}$ | 40.43 & 47.83 |
| Subramanian et al., 2020 | Urban | $PM_{2.5}$ &$PM_{10}$ | 52 & 4 |
| Kalisa et al., 2018 | Urban | $PM_{2.5}$ &$PM_{10}$ | 185.3 & 214.0 |
| REMA, 2018 | Rural | $PM_{2.5}$ &$PM_{10}$ | 6.4 & 17.5 |
| | Urban | $PM_{2.5}$ &$PM_{10}$ | 8.5 & 19.5 |
| Henninger, 2013 | Urban | $PM_{10}$ | 650 |

Table 5 shows the 24 hour -mean concentrations of particulate matters measured in rural and urban areas by this study and the findings of different studies conducted in Rwanda.

These results indicated that there is a severity of air particle emissions that exceeded the updated WHO air quality guideline of 15 μg/m$^3$ for $PM_{2.5}$ and 45 μg/m$^3$ for $PM_{10}$ (WHO,2021). The PM concentration levels obtained in this study were lower than those measured at urban roadside by Kalisa et al. (2018) in dry and wet months in Kigali City. This could be due to the reason that this study was conducted during COVID-19 pandemic whereby human activities were restricted in the Kigali urban area. The other cause might be the use of air quality sensors compared to the high air volume samplers for data collection. They also indicated that rural area of Northern Province released more air pollutants in the wet season than this study. Furthermore, the higher magnitude of air pollutants has been shown in the studies conducted by Henninger, 2013; Subramanian et al., 2020 which reported that the level of polluted air was higher in Kigali, which agrees with the results of this study.

In contrast, the study conducted in October to December by REMA ,2018 indicated that the particulate matter concentrations were lower in the urban background of Kigali than this study. This lower level of air pollutants might have been associated with the time and monitors used for data collection. Nevertheless, these studies have been carried out in dissimilar conditions. The results showed that the air quality in urban and rural areas of Kigali City is unsafe to human life.

### 4.3. Seasonal variation of particulate matter in Nyanza and Kigali

This study was aware of air pollutants concentration in dry and wet months and showed the variation of these pollutants between dry and wet season as presented in Figure 10.

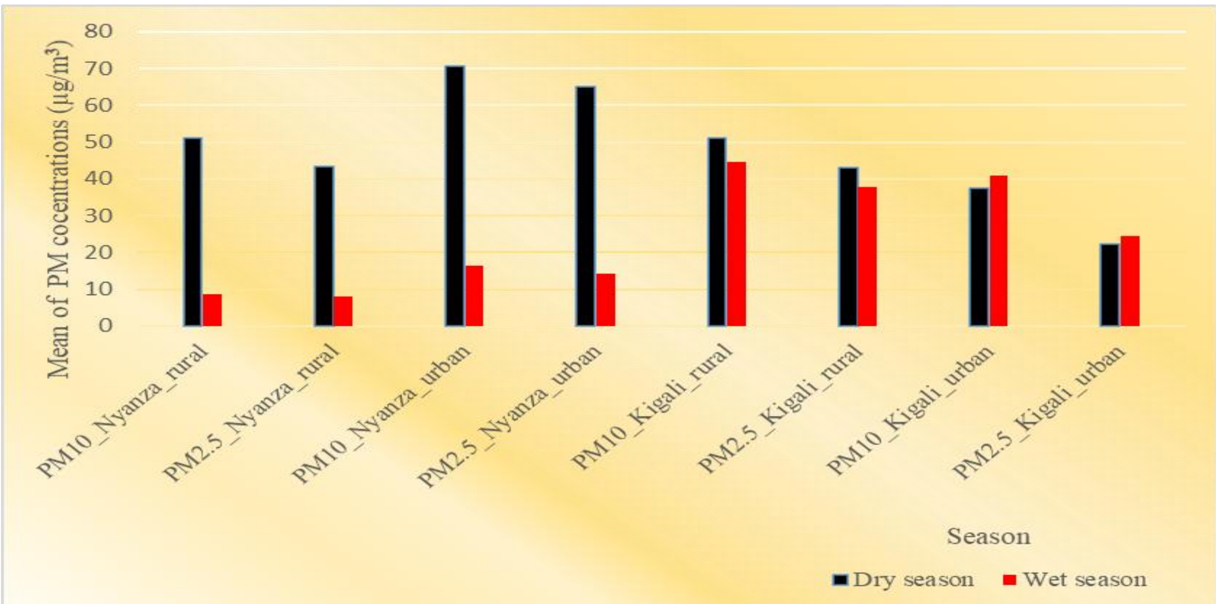



Figure 10: The comparison of PM concentrations by season at sampling sites

The results from Figure 10, showed that the PM-values were remarkably higher in dry than wet season at all sites except in Kigali urban area. This could suggest that Kigali rural and Nyanza urban had a lot of emissions of air pollutants in the period of dry months. DeWitt et, al. (2019)

found that the high concentration of air pollutants was present in rural areas of Rwanda and they also indicated that air pollution is a huge problem in the East African region.

On the other hand, the African continent is correspondingly known to have a lot of savanna plants and the air pollutants can spread in different areas regardless of the boundaries. Therefore, the high emissions are expected from biomass burning and dust resuspension in dry season (Gnamien et al., 2020). This increase could be as well due to the weather conditions such as high temperature and speed of wind occurring in dry season which are recognised to increase the deposition of air pollutants. This is in line with the studies reported that the meteorological conditions such as temperature and relative humidity were observed to promote the PM concentrations in some regions (Cheng and Li ,2010; Gualtieri et al., 2015). Considering the sampling sites in the dry and wet season, the concentrations of $PM_{2.5}$ and $PM_{10}$ were higher in Nyanza urban area compared to all other sampling sites in the dry season. However, the higher emissions of $PM_{2.5}$ and $PM_{10}$ pollutants were also found in Kigali rural area than other sampling sites in the wet season.

Apart from that, the low level of PM in the dry season has been found in Kigali urban site compared to wet season and that could be due to the COVID-19 lockdown that existed in Kigali urban areas in July,2021. Therefore, this reduced pollutants emission from human activities. This decrease of air pollutants was consistent with the study conducted by Kalisa et al., 2018 which reported that the diminution of anthropogenic activities resulted in a reduction in air pollutants concentration in Kigali. Moreover, the recent study affirmed that COVID-19 lockdowns reduced the level of air pollutants concentration in Kigali City (Kalisa et al., 2021).

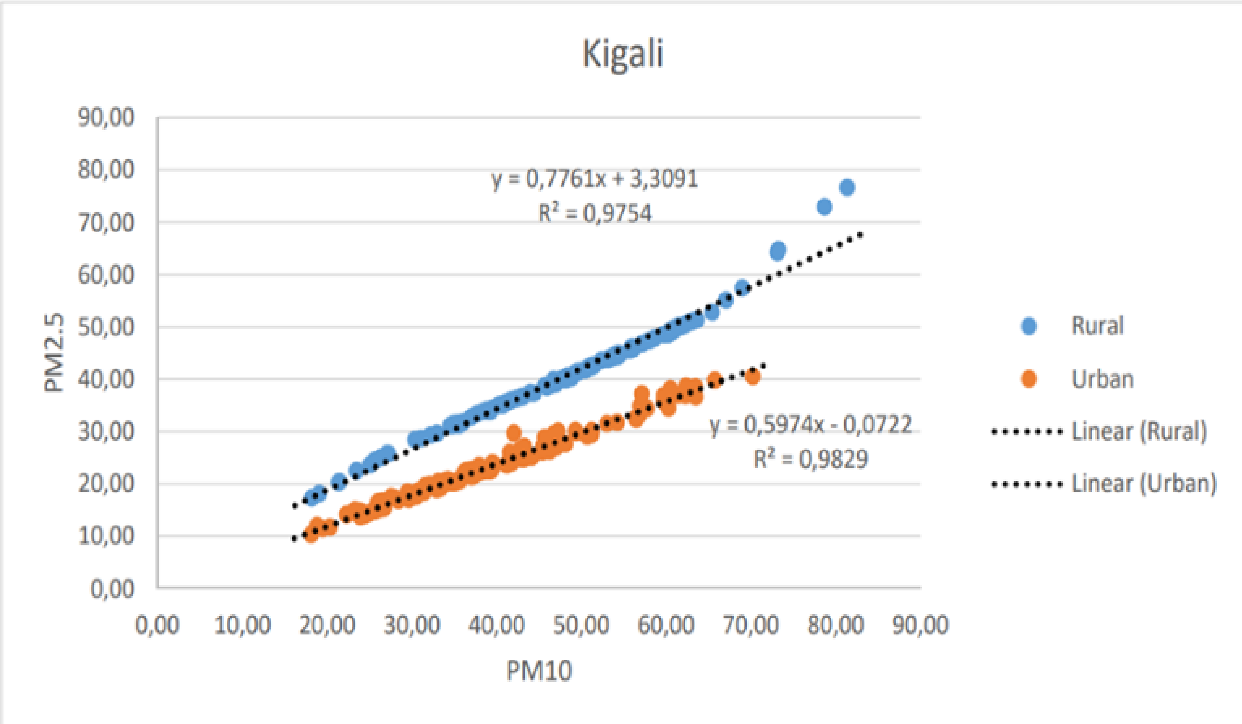
### 4.4. The relationship between particulate matter and weather station parameters

Table 6:Spearman analysis of the parameters in Nyanza sites

| | | RH_ Nyanza | T_ Nyanza | $PM_{10}$_ Nyanza _rural | $PM_{2.5}$_ Nyanza _rural | $PM_{10}$_ Nyanza _urban | $PM_{2.5}$_ Nyanza _urban |
|---|---|---|---|---|---|---|---|
| Spearman's rho | RH_Nyanza | 1.000 | **-0.938** | -0.479 | -0.493 | -0.431 | -0.432 |
| | T_Nyanza | **-0.938** | 1.000 | 0.407 | 0.422 | 0.265 | 0.265 |
| | $PM_{10}$_Nyanza_rural | -0.479 | 0.407 | 1.000 | **0.999** | 0.570 | 0.572 |
| | $PM_{2.5}$_Nyanza_rural | -0.493 | 0.422 | **0.999** | 1.000 | 0.569 | 0.571 |
| | $PM_{10}$_Nyanza_urban | -0.431 | 0.265 | 0.570 | 0.569 | 1.000 | **0.999** |
| | $PM_{2.5}$_Nyanza_urban | -0.432 | 0.265 | 0.572 | 0.571 | **0.999** | 1.000 |

Table 7:Spearman analysis of the parameters in Kigali sites

| | | RH_ Kigali | T_ Kigali | $PM_{10}$_ Kigali_ rural | $PM_{2.5}$_ Kigali_ rural | $PM_{10}$_ Kigali_ urban | $PM_{2.5}$_ Kigali_ urban |
|---|---|---|---|---|---|---|---|
| Spearman's rho | RH_Kigali | 1.000 | **-0.950** | 0.290 | 0.292 | 0.160 | 0.185 |
| | T_Kigali | **-0.950** | 1.000 | -0.379 | -0.381 | -0.177 | -0.198 |
| | $PM_{10}$_Kigali_rural | 0.290 | -0.379 | 1.000 | **0.999** | 0.064 | 0.048 |
| | $PM_{2.5}$_Kigali_rural | 0.292 | -0.381 | **0.999** | 1.000 | 0.070 | 0.055 |
| | $PM_{10}$_Kigali_urban | 0.160 | -0.177 | 0.064 | 0.070 | 1.000 | **0.991** |
| | $PM_{2.5}$_Kigali_urban | 0.185 | -0.198 | 0.048 | 0.055 | **0.991** | 1.000 |



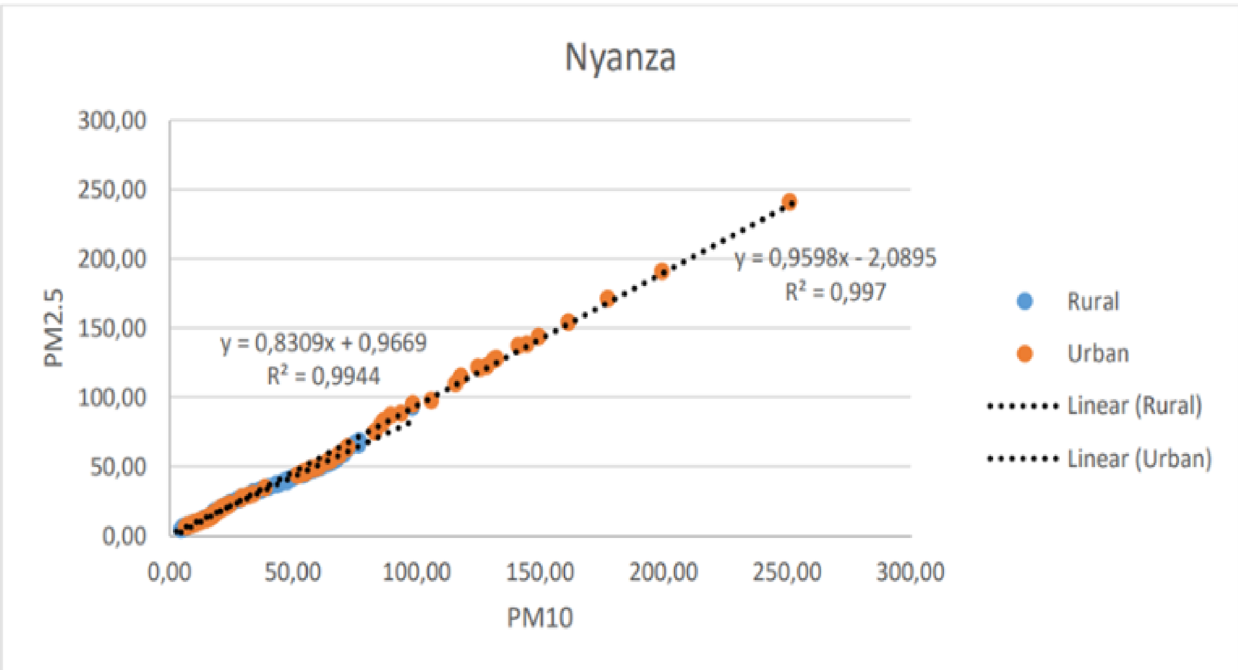




Figure 11:Relationship between particulate matters at different sites

Meteorological and particulate matter data were collected for the dry and wet season to assess the relationship between them. The RH and temperature have been measured to indicate weather conditions during the sampling period at both rural and urban areas. The Spearman correlation and regression analysis were performed as it is shown in Table 6,7 and Figure 11.

The processed data were from April to July,2021. The Spearman's results showed a positive correlation of 99% between $PM_{10}$ and $PM_{2.5}$ for Nyanza and Kigali sites. But, the negative correlation of 93% and 95% were observed at Nyanza and Kigali sites respectively between RH and T. However, there was no significant correlation between weather parameters and PM concentration. In this study, significant correlations have been found between $PM_{2.5}$ and $PM_{10}$ as well as T and RH when only looking at each study site. The positive correlation observed on PM concentrations indicated that when one parameter increased, the other one increased as well like it is shown on Figure 11. This indicated that there was no effect of meteorological parameters on PM concentrations measured at all sites and weather conditions did not greatly vary during the entire sampling period. This is quite consistent with the study conducted by Zhou et al., (2016) which reported that there is a high relationship between $PM_{2.5}$ and $PM_{10}$ due to the fact that they come from the same source of emission. As already mentioned, this might be indicated by supplemental sources of air pollutants happening at the study sites such as dust from unpaved roads and the fuel combustion. The findings were evidenced in the study of Arkouli et al., (2010) which showed that the high correlations between $PM_{2.5}$ and $PM_{10}$ exhibited that the pollutants had short term change of weather conditions as well as the similar behaviour and origin. However, the negative correlation was observed between relative humidity and temperature as shown in Table 6 and 7 suggesting that when temperature increases, the RH reduces and vice - versa, and this has been indicated to promote the formation of heavy precipitation in the future (Denson et al., 2021). Another study reported that higher relative humidity can increase the level of air ambient particulate matter concentrations but this was different from the results observed in this study (Elminir ,2005).

# CHAP V. CONCLUSION AND RECOMMENDATIONS

## 5.1. CONCLUSION

This study aimed to compare the particulate matter concentrations in urban and rural site of a town and large city in dry and wet season using the low-cost sensors. The results showed that except in Kigali urban area, the daily average concentration of $PM_{2.5}$ and $PM_{10}$ were higher in dry than wet season at all sites. The 24hour-average concentration of $PM_{2.5}$ and $PM_{10}$ were higher in rural site in Kigali than rural Nyanza Town and exceeded the World Health Organization standard. Comparing the sites within a city and town, the concentration of $PM_{2.5}$ and $PM_{10}$ were found to be higher in rural than urban site in Kigali. In contrast, the urban $PM_{2.5}$ and $PM_{10}$ concentrations were higher than rural in Nyanza Town. However, when the whole dataset was considered to compare all sites. The findings indicated that rural and urban site of Nyanza Town seemed to be similar, and urban Nyanza and urban Kigali also seemed to be similar for $PM_{10}$ level. Considering $PM_{2.5}$, the results also showed that rural site of Nyanza and Kigali seemed to be similar, as well as rural or urban site of Nyanza and site of urban Kigali or urban Nyanza.The findings indicated that this similarity was caused by data distribution within the whole dataset due to the fact that similar values constituted the same group in the data set. In fact, the rural and urban areas were dissimilar when only testing the PM data of Nyanza and/or Kigali sampling sites.

## 5.2. RECOMMENDATIONS

This study used a limited data set of 4 months, therefore future long term study should be conducted in all provinces of Rwanda spanning four seasons. This thesis demonstrates that air pollution in a town and city, exceeded the WHO recommended safe limit. Therefore, the control measures of air pollutants emission are required and should cover many sites and include other weather parameters such as wind speed and direction. Future long-term epidemiological studies are also essential in both urban and rural areas to assess the impact of air pollution on Rwanda population.

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