TEMPORY VARIATION OF PM2.5 CONCENTRATION IN BENIN CITY.

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CERTIFICATION

This is to certify that this research work titled **TEMPORY VARIATION OF PM2.5 CONCENTRATION IN BENIN CITY** was carried out by OROBOR PRAISE OGHOSA and presented to the Department of Environmental Management and Toxicology, Faculty of Life Sciences, University of Benin, Benin City; in partial fulfillment of the requirements for the award of Bachelor of Science (B.Sc.) in Environmental Management and Toxicology. It was conducted under suitable conditions, was carefully supervised and subsequently approved as having met the requirements for the award of Bachelor of Science degree in Environmental Management and Toxicology.

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(HEAD OF DEPARTMENT)

DECLARATION

I, **OROBOR PRAISE OGHOSA** ” declare that the **TEMPORY VARIATION OF PM2.5 CONCENTRATION IN BENIN CITY .**” Is my own work and that all sources that I have used or quoted have been acknowledged by means of complete references and that this work has not been submitted before for any other degree at any university.

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OROBOR PRAISE OGHOSA DATE

DEDICATION

I wholeheartedly dedicate this report to The Almighty GOD and my supportive parents and siblings for helping me come this far and making this exercise a success.

ACKNOWLEDGEMENT

I sincerely want to express my genuine appreciation to my Heavenly father who has made it possible for me to successfully complete my Undergraduate Project and has always proving his love and presence in my life.I am very grateful to my project supervisor Dr.Mrs .A.Ovenseri for her support, guidance, and invaluable advice throughout the course of my project work. I am also indebted to my friends for their insightful feedback and constructive criticism, which helped me to refine and improve my work.

Finally, I am grateful to my family; my parents, siblings for their unwavering love and support throughout this journey.

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ABSTRACT

Air pollution, particularly fine particulate matter ($PM_{2.5}$), is a growing environmental and public health concern in urban areas. This study aimed to compare outdoor $PM_{2.5}$ concentrations during the daytime and nighttime in Benin City, Nigeria. $PM_{2.5}$ data were collected from three distinct locations (Ugbowo, Sapele Road, and Etete) between October to December 2024 using PurpleAir sensors, with measurements taken six times daily at intervals of 5 hours. Statistical analysis, including paired T-test and ANOVA, was conducted to assess variations between day and night as well as across location and time. Results revealed significantly higher $PM_{2.5}$ levels during the daytime, with concentrations peaking in December (170.83 µg/m^3). The lowest concentration during the day was recorded in the month of October (93.67µg/m^3,) while the highest concentration was in the month of December (183.33 µg/m^3) at Etete. At night, the least concentration was at Sapele road in the month of October (80.09 µg/m^3) with the highest in December (158.32) at Etete. A significant difference (p =1.346e-15) was recorded between the concentrations of daytime and night time PM2.5. A statistical significant difference was tested across locations (p = 0.0088) and months (p = 2e-16). The recorded concentrations far exceed WHO guidelines for $PM_{2.5}$ concentrations, suggesting a possible health risk for the inhabitants of those locations. Immediate interventions are recommended, including stricter emission regulations, better urban planning, and public awareness campaigns, to mitigate the effects of air pollution and improve public health.

CHAPTER ONE

INTRODUCTION

1.1 Background

One of the biggest threats to environmental health in the world today is air pollution, which has a big impact on ecological stability, economic productivity, and human well-being. Particulate matter (PM), or microscopic particles suspended in the air, is a significant contributor to air pollution (Daellenbach *et al.,* 2020). Due to its capacity to enter the bloodstream and deeply permeate the respiratory system, fine particulate matter ($PM_{2.5}$), which is defined as particles with a diameter of 2.5 micrometres or less, is the most dangerous of these (Thangavel *et al.,* 2022). In addition to man-made activities like automobile emissions, industrial operations, and residential burning of fossil fuels and biomass, $PM_{2.5}$ can also come from natural sources like dust storms and wildfires (Wyer *et al.,* 2022). The effects of exposure to $PM_{2.5}$ on health are widely known and reported. Chronic respiratory disorders like asthma, bronchitis, and chronic obstructive pulmonary disease (COPD), as well as cardiovascular disorders like hypertension and ischemic heart disease, have been associated with prolonged exposure (Akhbarizadeh *et al.,* 2021; Harrison *et al.,* 2021; Thangavel *et al.,* 2022). Moreover, $PM_{2.5}$ contributes to millions of fatalities globally each year, making it a major environmental risk factor for early mortality (Zhang *et al.,* 2021). The World Health Organization (WHO) estimates that $PM_{2.5}$ is a major contributor to ambient air pollution, which causes around 4.2 million deaths annually. These health hazards are even worse in urban settings with dense populations and high exposure levels from concentrated pollution sources (WHO, 2021).

Benin City in Nigeria is a historic and thriving city that has seen tremendous industrial and urbanisation growth in recent decades. Air pollution is one of the major environmental issues brought on by this growth (Eghomwanre and Oguntoke, 2022). Vehicle emissions from badly maintained cars, industrial discharges, open waste burning, and household energy consumption are the main sources of $PM_{2.5}$ in the city (Ukpebor *et al.,* 2021). A large number of Benin City families cook using biomass, such as firewood and charcoal, which contributes to the high air pollution levels in the city. Furthermore, burning waste including plastics and other dangerous materials, is a common activity that adds to pollution from $PM_{2.5}$ (Onaiwu and Okuo, 2023).

An area of increasing scientific interest is the temporal variation of $PM_{2.5}$ concentrations, or how levels change between day and night (Anjum *et al.,* 2021). As a result of increased human activity, such as traffic, industry, and building, daytime pollution levels are frequently greater. But night-time levels can also be high, especially in places where burning waste and biomass is widespread (Shen *et al.,* 2023). These diurnal variations are significantly shaped by meteorological conditions. For example, even when there is less human activity, temperature inversions, which are more prone to happen at night, can trap pollutants near the ground, increasing concentrations (Davidovic *et al.,* 2021).

Comprehensive air quality monitoring systems to regularly detect $PM_{2.5}$ levels are lacking in many Nigerian cities. Researchers, legislators, and public health authorities are unable to create focused interventions because of this gap (Abulude and Abulude, 2021). Furthermore, despite the inhabitants of the city being exposed to potentially hazardous amounts of $PM_{2.5}$ on a daily basis, there is still a lack of public knowledge regarding the risks caused by air pollution (Ukpebor *et al.,* 2021). Research on the day-night fluctuations in $PM_{2.5}$ levels in cities can reveal important information on exposure trends, assisting in the identification of high-risk times and susceptible groups (Davidovic *et al.,* 2021). The effects of pollution from $PM_{2.5}$ on the environment and the economy are equally important. By interfering with photosynthesis, fine particles can lower agricultural yield, impede visibility, and harm infrastructure (Wyer *et al.,* 2022). Air pollution might impede long-term growth and development in Benin City, where economic activities like trade and tourism are essential. Addressing air quality concerns also fits with the obligations of Nigeria under international agreements like the Paris Agreement, which focus on the need of environmental preservation and sustainable urban growth (Aidonojie *et al.,* 2020).

Studies examining the sources, health impacts, and mitigation techniques of $PM_{2.5}$ have made substantial progress worldwide (Daellenbach *et al.,* 2020; Emeka *et al.,* 2020 Sulaymon *et al.,* 2020; Thangavel *et al.,* 2022). Nonetheless, the majority of this study has been carried out in industrialised nations with strong regulatory frameworks and access to cutting-edge monitoring tools (Akhbarizadeh *et al.,* 2021). Nigeria and other developing nations, on the other hand, confront particular difficulties, such as scarce resources, conflicting developmental agendas, and lax implementation of environmental laws. These difficulties indicate how crucial localised research is to comprehending the unique dynamics of air pollution in places such as Benin City (Richard *et al.,* 2023).

This study fills a significant gap in the literature by comparing the $PM_{2.5}$ concentrations in Benin City during the day and at night. This study intends to determine the main sources of pollution at various times of the day and the meteorological conditions that affect their distribution by examining the variations in $PM_{2.5}$ levels across a 24-hour cycle. The results will help with efforts to enhance air quality and public health outcomes in Benin City by giving policymakers, urban planners, and environmental health specialists useful information. Furthermore, knowing how $PM_{2.5}$ pollution changes during the day can aid in the creation of successful solutions. Policies that promote cleaner cooking technology, limit traffic emissions during peak hours, or regulate waste-burning activities, for instance, can all greatly reduce exposure hazards. Protecting vulnerable populations can also be greatly aided by increasing public awareness of the negative health effects of $PM_{2.5}$ and promoting behavioural changes, such as staying indoors during times of high pollution.

1.2 Aim and objectives

The aim of this study is to compare the outdoor concentrations of $PM_{2.5}$ during the daytime and night-time in Benin City, Nigeria, to identify temporal variations.

1. To measure the concentration of PM2.5 during the day and at night -time in selected locations within benin city.
2. To investigate the bio buh difference in PM2.5 concentration between day and nighttime.
3. To determine the time period with the highest concentration level of PM2.5 during the study period.

CHAPTER TWO

LITERATURE REVIEW

2.1 Air quality studies

Studies on air quality are important in gaining a clear comprehension and developing strategies for the management of environmental pollution, particularly as they place an emphasis on the sources, effects and strategies for mitigating air pollution (Garaga *et al.,* 2018). Fine particulate matter ($PM_{2.5}$), one of the major pollutants studied in air quality investigations, has attracted a lot of attention because of its severe effects on both the environment and human health (Daellenbach *et al.,* 2020). The ability of $PM_{2.5}$, which is made up of particles with sizes of 2.5 micrometres or less, to enter the bloodstream and penetrate deeply into the respiratory system makes it especially dangerous. Vehicle emissions, industrial processes, the burning of biomass, and natural occurrences like dust storms and wildfires are its main sources (Wyer *et al.,* 2022). Cardiovascular disorders, respiratory illnesses, and an elevated chance of dying young have all been related to $PM_{2.5}$ exposure. Additionally, it aggravates pre-existing medical disorders, increasing the susceptibility of vulnerable groups like children, the elderly, and people with chronic illnesses (Akhbarizadeh *et al.,* 2021; Harrison *et al.,* 2021). In addition to its negative effects on health, $PM_{2.5}$ damages ecosystems, alters radiative forcing, and impairs sight. To gain insights to the temporal dynamics of air pollution requires examining the diurnal fluctuations in $PM_{2.5}$ concentrations (Onaiwu and Okuo, 2023). Human activity, weather patterns, and atmospheric processes all have an impact on these changes. Due to activities in construction, industry, and heavy traffic, daytime levels are frequently higher (Shen *et al.,* 2023). However, concentrations can still be high at night, particularly in areas where burning of biomass is common or where temperature inversions trap pollutants close to the ground (Davidovic *et al.,* 2021).

2.2 PM2.5 pollution

2.2.1 Definition and characteristics of $PM_{2.5}$

Particles with an aerodynamic diameter of 2.5 micrometres or less, that is, roughly 30 times smaller than the width of a human hair, are referred to as $PM_{2.5}$. Due to their small size, $PM_{2.5}$ particles are easily inhaled and can float in the atmosphere for long periods of time (Thangavel *et al.,* 2022). Depending on where they come from, $PM_{2.5}$ particles have a variety of physical characteristics, such as differences in size, shape, and density. Sulphates, nitrates, ammonia, sodium chloride, black carbon, mineral dust, and other organic compounds are some of the complex mixture of chemicals that make up $PM_{2.5}$ (Daellenbach *et al.,* 2020). Local activities and atmospheric circumstances have an impact on the composition of $PM_{2.5}$, which varies depending on the area (Wyer *et al.,* 2022). In addition to affecting its transit and dispersion, the small size of $PM_{2.5}$ increases its capacity to enter the bloodstream and deep into the lungs, causing serious health hazards (Anjum *et al.,* 2021). Additionally, $PM_{2.5}$ particles can act as transporters of harmful compounds, such as organic pollutants and heavy metals, intensifying their negative effects (Emeka *et al.,* 2020).

$PM_{2.5}$ comes from both man-made and natural sources.

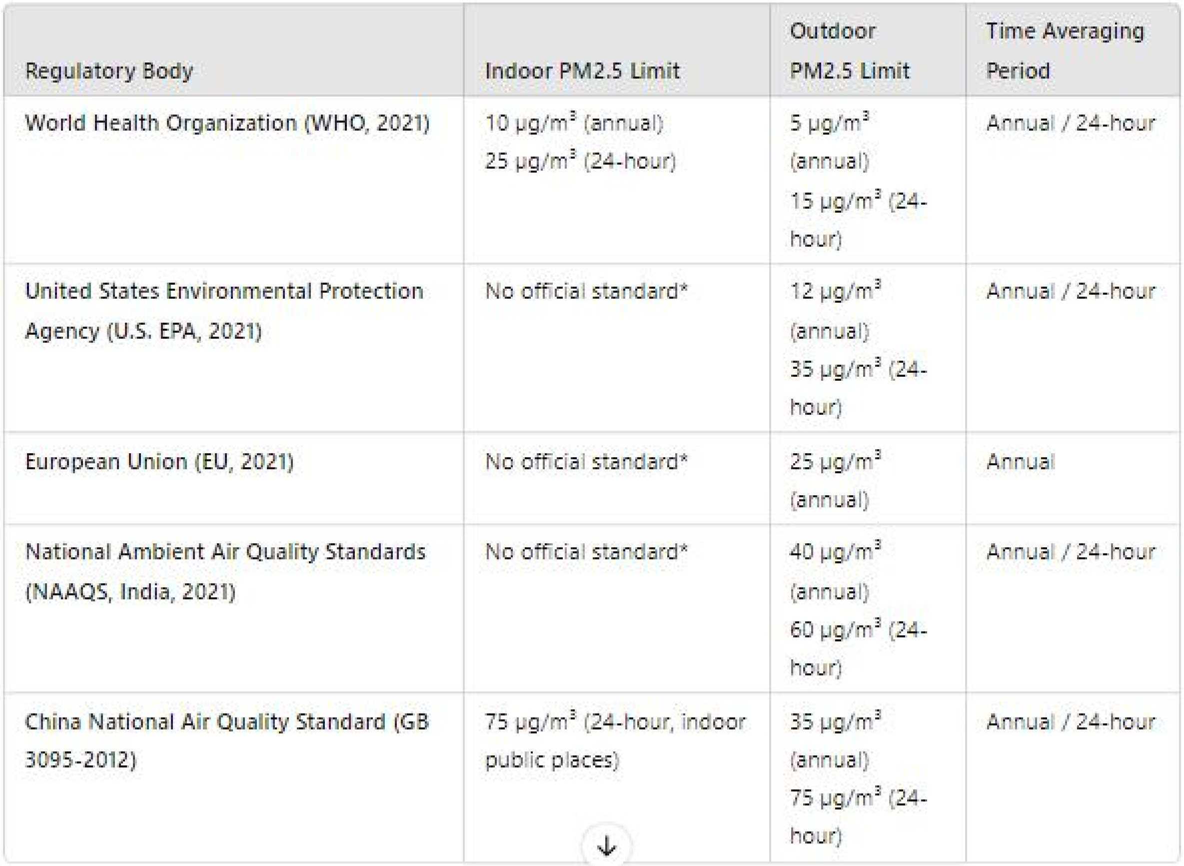
Natural Sources: These include volcanic eruptions, sea spray, wildfires, and dust storms. Although they are usually less harmful than man-made emissions, natural activities like pollen dispersal and spore release also contribute to $PM_{2.5}$ levels (Thangavel *et al.,* 2022; Nan *et al.,* 2023).

Anthropogenic Sources: The main cause of dangerous $PM_{2.5}$ pollution is human activity. Vehicle emissions, industrial operations, burning of fossil fuels, burning of biomass, and open waste incineration are some of the main sources. $PM_{2.5}$ emissions are mostly caused by traffic and industrial activity in urban areas, whereas residential energy consumption, especially the burning of biomass for cooking and heating, and agricultural practises may contribute more in rural areas (Thangavel *et al.,* 2022; Nan *et al.,* 2023).

2.2.2 Health impacts of $PM_{2.5}$ exposure

Short-term and long-term impacts on health

Human health is impacted both immediately and over time by $PM_{2.5}$ exposure. Short-term respiratory tract irritation from breathing in $PM_{2.5}$ might result in symptoms like coughing, wheezing, and dyspnoea (Sharma *et al.,* 2020). Hospitalizations and higher medical expenses may result from acute exposure that aggravates pre-existing respiratory disorders such as bronchitis and asthma (Martins and da Graca, 2023). Chronic respiratory conditions like chronic obstructive pulmonary disease (COPD) and lung cancer are among the more serious health outcomes linked to prolonged exposure to $PM_{2.5}$ (Anjum *et al.,* 2021). Significant effects are also seen in the cardiovascular system, where prolonged exposure raises the risk of arrhythmias, hypertension, ischemic heart disease, and stroke (Akhbarizadeh *et al.,* 2021). Millions of deaths per year are ascribed to illnesses linked to air pollution, and studies have demonstrated a clear link between $PM_{2.5}$ exposure and early mortality (Zhang *et al.,* 2021).



Regulatory Body	Indoor PM2.5 Limit	Outdoor PM2.5 Limit	Time Averaging Period
World Health Organization (WHO, 2021)	10 μg/m^3 (annual) 25 μg/m^3 (24-hour)	5 μg/m^3 (annual) 15 μg/m^3 (24-hour)	Annual / 24-hour
United States Environmental Protection Agency (U.S. EPA, 2021)	No official standard*	12 μg/m^3 (annual) 35 μg/m^3 (24-hour)	Annual / 24-hour
European Union (EU, 2021)	No official standard*	25 μg/m^3 (annual)	Annual
National Ambient Air Quality Standards (NAAQS, India, 2021)	No official standard*	40 μg/m^3 (annual) 60 μg/m^3 (24-hour)	Annual / 24-hour
China National Air Quality Standard (GB 3095-2012)	75 μg/m^3 (24-hour, indoor public places)	35 μg/m^3 (annual) 75 μg/m^3 (24-hour)	Annual / 24-hour

Figure 2.1: Standards for PM2.5 in air (Shen *et al.*, 2023)

Vulnerable populations and pathways of exposure

Some groups are particularly susceptible to $PM_{2.5}$ exposure because of location, socioeconomic status, or physiological characteristics. Due to their developing respiratory systems and the fact that they breathe more air per unit of body weight than adults, children are more vulnerable (Harrison *et al.,* 2021). The negative effects of $PM_{2.5}$ are also more likely to affect the elderly and people who already have health issues like asthma, COPD, or cardiovascular disorders (Wang *et al.,* 2017). Vulnerabilities are frequently increased by socioeconomic inequality, as low-income groups are more likely to reside in polluted locations or use biomass fuels for heating and cooking (Fann *et al.,* 2018). Living close to industrial zones or busy regions are examples of geographic characteristics that significantly raise exposure hazards. Although inhalation is the main pathway by which $PM_{2.5}$ particles reach the human body, some can also land on the skin or be consumed through tainted food or water (Zhang *et al.,* 2021).

2.2.3 Environmental impacts of $PM_{2.5}$

Role in reducing visibility and effects on climate

Haze is the result of $PM_{2.5}$ particles drastically lowering air visibility. Both in urban and rural locations, these particles reduce visibility by scattering and absorbing light (Wei *et al.,* 2020). Economic effects result from decreased visibility, especially in industries like transportation, tourism, and aviation (Singh *et al.,* 2020). $PM_{2.5}$ particles have both direct and indirect effects on the climate. Climate change is made worse by black carbon, a component of $PM_{2.5}$ that absorbs sunlight and warms the atmosphere (Bhattarai *et al.,* 2024). However, $PM_{2.5}$ also contains nitrates and sulphates, which reflect sunlight and have a cooling impact (Rahman *et al.,* 2022). The overall effect of $PM_{2.5}$ on global warming is complicated by these opposing characteristics. Furthermore, $PM_{2.5}$ aids in the production of secondary pollutants like ozone, which further modify the climate and air quality (Daellenbach *et al.,* 2020).

Interactions with other pollutants

The effects on the environment and human health are increased when $PM_{2.5}$ interacts with other air pollutants. For instance, when mixed with sulphur dioxide (SO_2) and nitrogen oxides, $PM_{2.5}$ can serve as the catalyst for the development of acid rain (NOx) (Nyasulu *et al.,* 2023). Acid rain lowers agricultural production, erodes infrastructure, and harms ecosystems. Furthermore, when sunshine and volatile organic compounds are present, $PM_{2.5}$ interacts with ground-level ozone (O_3) to enhance its generation (VOCs) (Roomaney *et al.,* 2022). The health hazards associated with PM2.5 are exacerbated by ozone, a strong greenhouse gas and respiratory irritant. The intricacy of tackling air quality issues and the requirement for integrated pollution management techniques are highlighted by the synergistic impacts of $PM_{2.5}$ with other contaminants (Leite *et al.,* 2021).

2.3 Sources and contributors to $PM_{2.5}$ pollution

2.3.1 Anthropogenic sources

Traffic emissions

One of the main causes of $PM_{2.5}$ pollution in cities is vehicle emissions. Fine particles are released into the atmosphere by internal combustion engines, particularly in diesel-powered automobiles (Olukanni *et al.,* 2021). These particles, which are produced when fossil fuels burn incompletely, are made up of metallic compounds, hydrocarbons, and black carbon (Joshua *et al.,* 2023). When nitrogen oxides (NOx) and volatile organic compounds (VOCs), which are also released by automobiles, combine in the atmosphere, secondary $PM_{2.5}$ is created (Ukpebor *et al.,* 2021). Emissions are made worse by clogged roads, badly maintained automobiles, and the use of inferior fuel. Major roads, crossroads, and other urban traffic hotspots frequently have the greatest $PM_{2.5}$ levels, endangering the health of locals and commuters (Joshua *et al.,* 2023).

Industrial discharges

Large volumes of $PM_{2.5}$ are released by industrial activities through a variety of processes, such as chemical reactions, material handling, and combustion. Important sources include oil refineries, steel mills, cement factories, and power plants (Sulaymon *et al.,* 2020). These industries directly release primary $PM_{2.5}$ as well as secondary particles made of NOx and sulphur dioxide (SO_2) (Olukanni *et al.,* 2021). Outdated technologies and a lack of implementation of emission restrictions in developing nations increase industrial contributions to $PM_{2.5}$ pollution. Local communities are highly impacted by industries close to residential areas, creating localised pollution hotspots and related health issues (Suriano *et al.,* 2023).

Biomass burning and domestic energy use

In rural and peri-urban regions, burning biomass for agriculture, cooking, and heating is a major source of $PM_{2.5}$. Fine particles are released from the incomplete burning of wood, crop leftovers, and animal dung in conventional stoves and open flames used for cooking (Sulaymon *et al.,* 2020). High $PM_{2.5}$ concentrations are especially dangerous for women and children living in homes that use biomass for cooking (Gordon *et al.,* 2023). Burning crop wastes is one example of a seasonal agricultural practise that raises air particulate matter levels. Burning biomass produces precursors for secondary $PM_{2.5}$, such as carbon monoxide (CO) and volatile organic compounds (VOCs), in addition to main emissions (Saetae *et al.,* 2024).

Open waste burning

Another important anthropogenic source of $PM_{2.5}$ is the open burning of municipal solid trash, which is a prevalent practise in developing nations. Toxic pollutants including dioxins and heavy metals are released along with a combination of fine particles when plastics, paper, and organic trash burn (Saetae *et al.,* 2024). This approach is frequently used in urban areas with poor waste disposal infrastructure, which raises localised $PM_{2.5}$ levels. In addition to lowering air quality, open burning contributes to climate change by releasing greenhouse gases including methane and black carbon (Ojeaga and Okoro, 2023).

2.3.2 Natural sources

Dust storms

One of the main natural sources of $PM_{2.5}$ in arid and semi-arid areas, is dust storms (Laryea *et al.,* 2022). Fine particles from exposed soil surfaces are lifted into the atmosphere by wind erosion, resulting in high concentrations of $PM_{2.5}$ across wide areas. A variety of minerals, including silica, are frequently carried by dust storms and can be harmful if inhaled (Tariq *et al.,* 2023). Although they have a natural basis, human activities like overgrazing, deforestation, and poor land management can make dust storms more intense. The frequency and severity of dust storms are influenced by climatic factors, including droughts, and seasonal fluctuations (Olanrewaju *et al.,* 2023).

2.4 Daily variations in $PM_{2.5}$ concentrations

2.4.1 Factors influencing daytime $PM_{2.5}$ levels

Traffic density and industrial activities

Industrial activity and peak traffic hours have a significant impact on daytime $PM_{2.5}$ levels. As individuals commute to and from work in urban centres, morning and evening rush hours see an increase in vehicle emissions (Awokola *et al.,* 2022). Primary $PM_{2.5}$ particles and gaseous precursors including nitrogen oxides (NOx) and volatile organic compounds (VOCs) are produced when fossil fuels are burned in automobiles. These precursors help to build secondary $PM_{2.5}$ (Saetae *et al.,* 2024). Particulate pollution is significantly increased by daytime-operating industries. Fine particles are released into the air by factories, power plants, and building sites. In places with high population density and economic activity, the combined effect of these activities frequently leads to higher $PM_{2.5}$ concentrations during the day (Joshua *et al.,* 2023).

Resuspension of road dust

The resuspension of road dust, a major contributor to $PM_{2.5}$ levels in urban contexts, is another effect of vehicle activity during the day. Vehicle speed and wind cause debris left on road surfaces, as well as particles from tyre and brake wear, to be lifted into the air (Sidibe *et al.,* 2022). Dry weather makes this problem worse because there is not enough moisture to hold particles to the ground. Cities with high traffic loads or inadequate road upkeep are particularly affected (Leite *et al.,* 2021).

2.4.2 Factors influencing night-time $PM_{2.5}$ levels

Biomass combustion

$PM_{2.5}$ concentrations at night frequently rise as a result of activities like burning biomass. Households in rural and peri-urban areas typically use charcoal, wood, or agricultural waste for night-time heating and cooking (Abulude *et al.,* 2024). These activities contribute to increased $PM_{2.5}$ levels at night by releasing significant volumes of carbon monoxide (CO), fine particles, and other dangerous pollutants (Adeyemi, 2020).

Decreased atmospheric dispersion

Lower wind speeds and less vertical air mixing make atmospheric dispersion which dilutes and disperses pollutants is typically less efficient at night. Due to these factors, $PM_{2.5}$ particles gather close to the ground, raising concentrations (Lee *et al.,* 2024).

2.5 Meteorological factors affecting $PM_{2.5}$ levels

Temperature

Temperature affects atmospheric processes and chemical reactions, which in turn affect $PM_{2.5}$ levels (Umoh *et al.,* 2024). By speeding up photochemical reactions involving gaseous precursors including nitrogen oxides (NOx) and volatile organic substances, higher temperatures might improve the generation of secondary $PM_{2.5}$ (VOCs) (Emeka, 2020). Particle concentrations rise as a result of these reactions, which frequently take place in warm, sunny weather, particularly in cities (Emekwuru and Ejohwomu, 2023). On the other hand, low temperatures can cause more volatile organic molecules to condense and produce fine particles (Umoh *et al.,* 2024). In addition, cold weather can exacerbate emissions from home heating sources like coal stoves and wood burning, which raises $PM_{2.5}$ levels in the winter (Onaiwu and Okuo, 2023).

Humidity

By changing the physical characteristics of the particles, humidity influences $PM_{2.5}$ levels. Particles grow hygroscopically, that is, they absorb water and get bigger, when the relative humidity is high (Zender-Swiercz *et al.,* 2024). This may increase light dispersion, making it harder to see and making hazy conditions worse. Furthermore, the health effects of bigger particles may be amplified due to their extended air residence duration (Iroegbulem *et al.,* 2022). Conversely, dry particles that are more likely to resuscitate can result from low humidity. Regions with substantial natural dust sources may see higher $PM_{2.5}$ concentrations due to arid conditions that exacerbate dust emissions (Panchal *et al.,* 2024). Temperature and humidity together frequently influence how $PM_{2.5}$ forms and persists in the atmosphere. For example, while cold and dry circumstances can increase primary emissions from heating sources, warm and humid conditions may result in high amounts of secondary particles (Abulude and Abulude, 2021).

Wind speed

A key element in the dilution and dispersion of $PM_{2.5}$ is wind speed. Air contaminants are mixed and transported more effectively by strong winds, which lowers their concentrations close to emission sources (Omokungbe *et al.,* 2020). In open spaces or places with few obstacles, this impact is more apparent. On the other hand, extremely high winds have the potential to briefly raise $PM_{2.5}$ levels by re-suspending fine particles from the ground, such as soil and road dust (Iroegbulem *et al.,* 2022). On the other hand, stagnation events, in which pollutants build up in the lower atmosphere, are linked to low wind speeds (Amooli *et al.,* 2024). High $PM_{2.5}$ concentrations are frequently caused by these factors, especially in cities with high emission density. Additionally, calm wind conditions intensify the impacts of neighbouring sources, generating hotspots for pollution and raising health hazards for those in the vicinity (Abulude *et al.,* 2021).

Wind direction

The direction of the wind affects how $PM_{2.5}$ is transported and dispersed from its sources to the surrounding surroundings. Long-distance transport of polluted air masses can impact areas distant from the original emission sites (Onaiwu and Okuo, 2023). For instance, because of transported pollutants, $PM_{2.5}$ levels are frequently greater in metropolitan areas downwind of industrial zones or locations where substantial amounts of biomass are burned (Akinwumiju *et al.,* 2021). $PM_{2.5}$ concentrations can also be influenced by regional weather patterns like trade winds or monsoons. For example, dust particles may be carried by winds from arid regions, which raises $PM_{2.5}$ levels in nearby areas (Lucky *et al.,* 2021).

Temperature inversions

When a layer of warmer air covers cooler air close to the ground, the normal temperature gradient is reversed, causing temperature inversions. By preventing vertical mixing and trapping pollutants like $PM_{2.5}$ in the lower atmosphere, this phenomenon produces a stable atmospheric layer (Akinwumiju *et al.,* 2021). Inversions are most frequent at night and in the early morning, particularly when there are clear skies and gentle winds. The earth cools the air directly above it by radiative cooling, which affects the formation of inversions. On long, clear nights when heat from the earth escapes into space, this cooling effect is most pronounced. As a result, the cooler air close to the surface gets denser and is trapped beneath a layer of warmer air (Usman *et al.,* 2022).

By restricting the dispersion of fine particles, temperature inversions make $PM_{2.5}$ pollution worse. Localized pollution episodes are caused by emissions that build up within the inversion layer from industrial processes, domestic heating, and traffic (Jonah *et al.,* 2024). Particularly in cities with high emission density, these circumstances frequently cause abrupt increases in $PM_{2.5}$ concentrations. By generating stationary circumstances that allow for chemical reactions, inversions also contribute to the generation of secondary $PM_{2.5}$ (Okimiji *et al.,* 2021). For example, these conditions facilitate the conversion of sulphur dioxide (SO_2) and nitrogen oxides (NO_x) into sulphate and nitrate particles (Muhammad *et al.,* 2022). In winter, when longer nights and less solar radiation enhance the probability and duration of inversion events, the effects of inversions are most noticeable. Inversions help create prolonged haze in metropolitan areas, which impairs visibility and results in extreme air quality episodes (Ayua *et al.,* 2023).

2.6 PurpleAir Sensors

The PurpleAir sensor is a widely used low-cost air quality monitoring device designed to measure airborne pollutants in real time. It has grown in popularity because of its high spatial resolution, cost, and simplicity of deployment, making it a vital instrument for environmental study, monitoring, and public awareness (Mousavi and Wu, 2021; Farooqui *et al.,* 2023). In contrast to conventional regulatory-grade air quality monitors, which are costly and scarce, PurpleAir sensors offer a dense network of data points that provide insights into the local air quality (Barkjohn *et al.,* 2021).

2.6.1 Geographic range and coverage

With dense networks in major cities including Los Angeles, New York, London, Beijing, and Sydney, PurpleAir sensors are extensively distributed throughout North America, Europe, and portions of Asia (Barkjohn *et al.,* 2021). Large-scale air quality monitoring networks are supported by robust environmental regulations, public awareness, and technology infrastructure in these areas (Mousavi and Wu, 2021). Although they are still relatively few in number as compared to other continents, PurpleAir sensors are progressively becoming more widespread across Africa. PurpleAir is actively monitoring many major African cities, including Johannesburg, Cape Town, Lagos, Abuja, Nairobi, Accra, and Cairo (Awokola *et al.,* 2022). Researchers, environmentalists, and neighbourhood associations mostly utilise these sensors to monitor air pollution caused by dust storms, industrial operations, open burning, and vehicle emissions. However, due to obstacles including expense, lack of internet connectivity, and a lack of government activities, rural regions in Africa continue to go mostly unmonitored (McFarlane *et al.,* 2021).

2.6.2 Pollutants detected by PurpleAir Sensors

The main substance that PurpleAir sensors monitor is particulate matter (PM), which is made up of microscopic liquid or solid particles that are floating in the atmosphere. PurpleAir sensors are excellent at identifying particulate matter, but they are unable to monitor gaseous pollutants like sulphur dioxide (SO_2), nitrogen dioxide (NO_2), ozone (O_3), or volatile organic compounds (VOCs) (Lawal and Mohammed, 2022). Among the main contaminants found are:

1. $PM_{1.0}$: Fine particles from vehicle exhaust, industrial emissions, and urban pollution. These particles pose significant health risks as they can penetrate deep into the lungs.
2. $PM_{2.5}$: A major air quality concern in many regions, particularly in cities with heavy traffic, industrial zones, and areas affected by wildfires. In Africa, $PM_{2.5}$ pollution comes from transportation, power generation, cooking with biomass fuels, open waste burning, and desert dust. Exposure to high $PM_{2.5}$ levels increases the risk of respiratory and cardiovascular diseases (Awokola *et al.,* 2022).
3. PM_{10}: Larger particles commonly found in dust storms, unpaved roads, construction sites, and agricultural activities. In North and West Africa, Saharan dust is a major source of PM_{10} pollution, affecting air quality over long distances (Awokola *et al.,* 2022).

2.7 $PM_{2.5}$ assessments

2.7.1 Studies from Nigeria

Owoade *et al.* (2021) used low-cost sensors for the identification of variations and source of air pollutants in a semi-urban Nigerian settlement. Between June 8 and July 31, 2018, low-cost sensors were placed at five points in a developing semi-urban community in southwest Nigeria to record climatic variables, gaseous pollutants (CO, NO, NO_2, O_3, and CO_2), and particulate matter ($PM_{2.5}$ and PM_{10}) (air temperature, relative humidity, wind speed and wind-direction). The observed temporal and spatial variations of the pollutants were identified, and a conditional bivariate probability function was used to identify the likely origins of the pollutants (CBPF). There was a range of 20.7±0.7 to 36.3±1.6μg m^{-3} for $PM_{2.5}$ and 47.5±1.5 to 102.9±5.6μg m^{-3} for PM_{10} values per hour. From 348±132 to 542±200 ppb CO, 21.5±7.2 ppb NO_2, and 57.5±11.3 to 64.4±14.0 ppb O_3, the hourly concentrations of gaseous pollutants varied. Spatial variations in the hourly-average pollutant concentrations were shown to be statistically significant using Kruskal-Wallis ANOVA on ranks. Diel variation analysis showed that O_3 peaked at noon, NO, NO_2, and CO peaked in the evening, and CO_2, $PM_{2.5}$, and PM_{10} peaked in the early hours of most days. At the majority of sampling sites, the southwest contributed the greatest pollutants, which were primarily of anthropogenic origin. Two of the monitoring locations, which were in residential neighbourhoods with a paved road that was often used, showed significant similarities in the sources which contributed to the pollution.

Awokola *et al.* (2022) determined the ambient concentrations of $PM_{2.5}$ by way of PurpleAir sensors in fifteen locations distributed over 8 sub-Saharan African countries. Between February 2020 and January 2021, a network of simple, low-cost air quality sensors (PurpleAir-II-SD) was utilised to monitor fine particulate matter ($PM_{2.5}$) concentrations at 15 sites in 11 cities across eight Sub-Saharan African (SSA) countries. The annual $PM_{2.5}$ concentrations, as well as seasonal and temporal fluctuation, were determined. Time patterns were modelled using harmonic regression. Annual $PM_{2.5}$ values at research sites varied from 10 to 116 μg/m3, exceeding the current WHO annual mean recommended level of 5 μg/m^3. Nigeria experienced the greatest degree of seasonal variation, with seven sites reporting greater $PM_{2.5}$ levels during the dry season than during the wet season.

Ishaya *et al.* (2023) conducted a diurnal assessment of the quality of air at Zuba Motor Park, Abuja, Nigeria. For seven days in December 2022, the air pollutants were measured three times a day (morning, afternoon, and evening) to obtain a comparative result that would demonstrate the intensity at different times of the day and how they contribute to air pollution. Utilizing the Statistical Package for Social Sciences (SPSS) Version, statistical analysis was carried out (22.0). AQI was computed using the US EPA formula. In the morning and evening (6 a.m. to 7 a.m. and 6 p.m. to 7 p.m.), when traffic volumes were high within the Motor Park, the concentrations of CO, SO_2, $PM_{2.5}$, and PM_{10} were higher, according to the results. The morning ambient concentrations of CO and SO_2 at the motor park are higher than the NESREA permissible limit, endangering human health. Similarly, $PM_{2.5}$ at the motor park is higher than the NESREA permissible limit only on working days, but PM_{10} is within the NESREA permissible limit at all times of the day and on all days of the week.

Onaiwu and Okuo (2023) quantified $PM_{2.5}$ and its association with meteorological factors around an automobile workshop in Benin City, Nigeria. The research was carried out in Benin City from January to December of 2019. Four zones were established for the city: North West (NW), North East (NE), South East (SE), and South West (SW). During the wet and dry seasons, 180 representative samples for $PM_{2.5}$ were taken from the workshops of craftsmen using an Apex2IS Casella standard pump equipped with a conical inhalable sampling (CIS) head. The samples were collected for eight hours at a flow rate of 3.5 L/min. Alongside $PM_{2.5}$, meteorological indicators were gathered. The dry season has $PM_{2.5}$ levels between 37.9 and 735.1 (µg/m3), whereas the wet season has $PM_{2.5}$ levels between 60.6 and 313.9 (µg/m^3). The estimated $PM_{2.5}$ concentration was higher above the limits set by the National Ambient Air Quality Standard (NAAQS) and the World Health Organization (WHO), which are 250 and 25 ug/m^3, respectively. The study estimated the following meteorological parameters: temperature, relative humidity, pressure, wind speed, wind direction, solar radiation, and ultraviolet radiation: 27.9–33.4 (°C), 59.8–78.9 (percent), 748.4–754.3 (mmHg), 2.8–6.9 (km/h), 154.9–205.4 (o), 425.1–1,073.4 (W/m^2), and 717.3–

1,133.7 (µW/m2), respectively. The relationship between PM2.5, temperature, sun radiation, and UV radiation was found to be significantly positive. In contrast, pressure showed a negative association. Particularly during the rainy season when temperatures are low and wind speeds are low, this positive association may contribute to the poor dispersion of $PM_{2.5}$ and have a detrimental effect on human health.

Sulaymon *et al.* (2023) modelled $PM_{2.5}$ variability, sources and impacts of meteorological factors during severe episodes of atmospheric pollution. In January 2021, during a prolonged severe atmospheric pollution episode (APE) in Lagos, the contributions of eight emissions sectors to fine particulate matter ($PM_{2.5}$) and its major components were measured using the Integrated Source Apportionment Method (ISAM) tool in the Community Multiscale Air Quality (CMAQ) model (CMAQ-ISAM). It was also clarified how the weather affected the production and spread of $PM_{2.5}$ during the APE. Geographically, the northwest part of Lagos, an urban area with higher levels of human emissions, has higher PM2.5 concentrations. The two main sources of $PM_{2.5}$ were industry and residential areas. The largest contributor to total PM2.5 (about 40 µg/m^3) was residential, followed by industry (approximately 20 µg/m^3). The residential and industrial sectors were primarily responsible for the high concentrations of secondary inorganic aerosols (SIA) in the northwest and upper northern regions of Lagos. Furthermore, the main sources of sulphate, which made up the biggest portion of $PM_{2.5}$, were electricity, industry, and homes. While residential and industry were the main sources of ammonium, the on-road, residential, and industrial sectors were the main donors to nitrate. Furthermore, adverse weather conditions during the APE significantly increased the elevated $PM_{2.5}$ concentrations.

Tariq *et al.* (2023) evaluated the spatiotemporal trends and health risks associated with the concentration of $PM_{2.5}$ in Nigeria between 2001 and 2019. According to the findings, $PM_{2.5}$ concentrations rose in the majority of Nigerian states, especially in the southern and mid-northern regions. The lowest concentration of $PM_{2.5}$ in Nigeria is significantly higher than the intermediate target-1 set by the World Health Organisation (35 $\mu g/m^3$). The average $PM_{2.5}$ concentration rose from 69 $\mu g/m^3$ to 81 $\mu g/m^3$ over the course of the study, growing at a rate of 0.2 $\mu g/m^3/yr$. Each region had a different growth rate. With a mean concentration of 77.9 $\mu g/m^3$, the quickest growth rate was 0.9 $\mu g/m^3/yr$ in Kano, Jigawa, Katsina, Bauchi, Yobe, and Zamfara. The northern states had the greatest $PM_{2.5}$ concentrations, as indicated by the median centre of the national average $PM_{2.5}$ moving northward. The main source of $PM_{2.5}$ in northern regions is the dust from the Sahara Desert. Furthermore, poor rainfall combined with agricultural practises and deforestation activities exacerbated air pollution and desertification in these areas. In the majority of the southern and mid-northern states, health hazards rose. The percentage of 8×10^4–7.3×10^6 $\mu g\cdot person/m^3$ that corresponded to ultra-high health risk (UHR) locations grew from 1.5% to 2.8%. UHR areas primarily include Kano, Lagos, Oyo, Edo, Osun, Ekiti, southeastern Kwara, Kogi, Enugu, Anambra, northeastern Imo, Abia, River, Delta, northeastern Bayelsa, Akwa Ibom, Ebonyi, Abuja, Northern Kaduna, Katsina, Jigawa, central Sokoto, northeastern Zamfara, central Borno, central Adamawa, and the northwest Plateau.

Adianimovie and Ogunlowo (2024) monitored and assessed the concentrations of particulate matter in relation to variations in relative humidity in Federal University Otuoke. For six months, spanning both the rainy and dry seasons, sampling was conducted using Dustmate, Kane 100-1, and 3.5.1 RS-1361C Humidity/Temperature metres from 8 a.m. to 5 p.m., five days a week. For compliance and regulation, the measured concentrations of PM_{10} and $PM_{2.5}$ were compared to the The National Ambient Air Quality Standard criteria set by the USEPA. Data analysis employed descriptive statistical methods. The findings showed that $PM_{2.5}$ concentrations were 27.52 $\mu g/m^3$ and 32.21 $\mu g/m^3$, respectively, while PM_{10} averages are 116.71 $\mu g/m^3$ and 107.25 $\mu g/m^3$. Additionally, relative humidity readings of 55.53 $\mu g/m^3$ and

73.74 µg/m^3 were noted. According to the data, the overall average of PM_{10} in both seasons is 100.19 µg/m^3 and 110.07 µg/m^3, $PM_{2.5}$ is 23.88 µg/m^3 and 23.37 µg/m^3, and the relative humidity is 55.78 µg/m^3 and 68.18 µg/m^3, respectively. The relative humidity of the area around Federal University Otuoke had a major impact on the concentrations of pollutants.

Suriano *et al.* (2024) assessed the concentrations of PM2.5 and associated air quality index in 8 selected points in Lagos, Nigeria. The concentration levels and spatial distribution of $PM_{2.5}$ and AQI in the eight locations that were chosen for this investigation were evaluated using AirQo data. AirQo sensors were placed in eight key places throughout Lagos to collect data on $PM_{2.5}$ concentrations. To compare the findings with both national and international air quality standards, the spatial distribution of $PM_{2.5}$ levels and AQI was examined. According to the findings, there are serious health hazards because $PM_{2.5}$ levels in many parts of Lagos which range from a minimum of 6.28 µg/m^3 (Ikeja) to a maximum of 204.68 µg/m^3 (Banana Island) exceeded the WHO and national air quality recommendations. Hotspots for pollution were found by the spatial analysis, especially in areas with high population densities and industrial activity. According to the statistics, industrial operations and vehicle emissions were the main causes of elevated $PM_{2.5}$ levels.

2.7.2 Studies from other parts of the world

Cao *et al.* (2020) carried out an investigation of the spatiotemporal trends in concentrations of $PM_{2.5}$ with the aid of the distributed air sensor network. The findings revealed that $PM_{2.5}$ daily fluctuations occurred in four stages: accumulation, continuing pollution, dispersion, and cleanup. In general, dispersion happened faster than accumulation, and $PM_{2.5}$ accumulated quickly in warm, humid conditions with low wind speeds. However, heavy winds and precipitation had the most impact on the dispersion stage. Furthermore, the findings revealed that the four variation stages did not closely correlate to seasonal divides. The spatial distribution of $PM_{2.5}$ revealed that the primary pollution source was found in a south-eastern industrial park, which had a major influence throughout the four stages.

Zhang *et al.* (2020) determined the spatiotemporal differences in $PM_{2.5}$ concentrations and the factors influencing these trends between 2013 and 2018. This study used a variety of statistical approaches, including conventional Kriging interpolation, spatial autocorrelation analysis, time-series analysis, and the Bonferroni test, to assess regional and seasonal changes in $PM_{2.5}$ concentrations using long-term monitoring data. The results showed that $PM_{2.5}$ concentrations reduced on an annual basis, indicating that air pollution management efforts have had some initial effectiveness. Furthermore, $PM_{2.5}$ concentrations were higher throughout the winter and in the southern regions. Diurnal variation showed a bimodal distribution that varied somewhat with the season. The distribution of $PM_{2.5}$ concentrations was mostly influenced by relative humidity and wind speed, with precipitation having little effect. A strong positive connection between $PM_{2.5}$ and gaseous pollutants (SO_2, NO_2, and CO) indirectly represented the role of automotive exhaust and coal-fired emissions. In general, $PM_{2.5}$ concentrations showed significant spatiotemporal fluctuation, which was influenced by meteorological conditions and pollutant emissions.

Rahman *et al.* (2021) employed the clustering method in identifying the patterns of $PM_{2.5}$ levels in Malaysia. A tapered element oscillating microbalance was used to continually measure $PM_{2.5}$ concentrations. The Agglomerative Hierarchical Cluster (AHC) approach was used for the cluster analysis. The daily average $PM_{2.5}$ values ranged from 8 to 31 $\mu g\ m^{-3}$, according to the data. Based on the AHC analysis, the cluster regions were divided into three categories: high pollution regions (HPR), medium pollution regions (MPR), and low pollution regions (LPR). HPR had the highest average $PM_{2.5}$ concentration (23.04 $\mu g\ m^{-3}$), followed by MPR and LPR. The results also revealed that the 2019 haze event had the highest concentration of $PM_{2.5}$ in all three zones, with the air pollutant index indicating extremely harmful and dangerous levels.

Casallas *et al.* (2022) analysed the spatiotemporal trends in $PM_{2.5}$ in north-western South America. Reanalysis and ground-based data revealed that high $PM_{2.5}$ levels in the majority of the cities within the region, including the capitals of Venezuela, Ecuador, Colombia, and Panama, are caused by wildfires and local emissions. Two peaks in daily $PM_{2.5}$ fluctuations (related to vehicle emissions) were found, as well as a sharper fall around noon (associated with an increase in wind speed and boundary layer height). The trend analysis demonstrates that Bogotá and Medellín have a decreasing yearly $PM_{2.5}$ trend (between -0.8μgm^{-3} and -1.7μgm^{-3}), indicating effective interventions. Cali shows a positive yearly trend (0.8μgm^{-3}), perhaps due to Short-Range Transport caused by a northerly flow from a highly polluted nearby city, which also impacts the diurnal cycle of $PM_{2.5}$ diurnal cycle.

Tariq *et al.* (2023) assessed the variations in $PM_{2.5}$ and the associated human health impacts in Niger Republic 1998 - 2019. The study used remotely sensed satellite data to show that $PM_{2.5}$ concentrations in Niger increased from 68.85 $\mu g/m^3$ in 1998 to 70.47 $\mu g/m^3$ in 2019. During the study period, the yearly average concentration of $PM_{2.5}$ was significantly higher than the WHO standards and interim target-1 (35 $\mu g/m^3$). The yearly increase rate of $PM_{2.5}$ concentrations in Niger is 0.02 $\mu g/m^3$/year. The health risk (HR) from exposure to $PM_{2.5}$ has also increased in Niger, particularly in Southern Niger. Extremely high-risk locations with concentrations of 1×10^4 - 9.4×10^5 $\mu g.persons/m^3$ have increased from 0.9% in 2000 to 2.8% in 2019. Long-term exposure to $PM_{2.5}$ has resulted in high HR in Niamey, southern Dakoro, Mayahi, Tessaoua, Mirriah, Magaria, Matameye, Aguié, Madarounfa, Groumdji, Madaoua, Bouza, Keita, eastern Tahoua, eastern Illéla, Bkomnni, southern Dogon-Doutchi, Gaya, eastern Boboye, central Kollo, and western Tillabéry. These findings suggest that $PM_{2.5}$ poses a significant health concern throughout Niger.

Cholianawati *et al.* (2024) determined the daily and diurnal differences in $PM_{2.5}$ concentrations and its association with meteorological factors in seven Indonesian cities in 2021. The study made use of half-hourly $PM_{2.5}$ concentrations derived from an air quality monitoring system (AQMS), radiosonde estimates of planetary boundary layer height (PBLH), and meteorological data received from meteorological stations. Padang, Manado, Palu, and Pangkalpinang show a bimodal pattern with two peaks, whereas Jakarta, Surabaya, and Pontianak exhibit a unimodal pattern with one peak from night to morning. In general, cities have greater diurnal $PM_{2.5}$ concentrations in the dry season than in the wet season. The link between $PM_{2.5}$ concentration and PBLH demonstrates that Jakarta, Surabaya, Padang, and Pontianak have substantial anti-correlations for different seasons, with Padang having an unusually positive correlation. The Pearson correlation between $PM_{2.5}$ concentration and each meteorological component is substantial in monthly data but insignificant in daily data. The application of Multiple Wavelet Coherence (MWC) with various meteorological factors demonstrates that the combination of four characteristics has a greater influence on $PM_{2.5}$ concentration in all examined sites. From May to September, wavelet analysis reveals discrete scale periods characterised by increased haze concentrations in Jakarta and Surabaya. The examination on the high rise of $PM_{2.5}$ in Pontianak owing to peatland forest fires using HYSPLIT demonstrates that emission from the surrounding area greatly rises the maximum half-hourly in Pontianak to 700 $\mu g/m^{-3}$.

Kurniawati *et al.* (2024) characterised the temporal variations in $PM_{2.5}$ concentrations using the PurpleAir sensor. To evaluate the low-cost PA-II, co-location sampling with the filter-based Super Specification Air Sampling System (SuperSASS) was used from June 2022 to May 2023. The measurements taken from the low-cost PA-$PM_{2.5}$ II were compared to SuperSASS data. The annual average mass concentration of $PM_{2.5}$ measured by SuperSASS and the low-cost sensor were 31.51±15.53 $\mu g/m^3$ and 39.04±15.16 $\mu g/m^3$, respectively, exceeding the regulation limit of 15 μg/m^3 set by the Indonesian government. The two approaches were compared using R2 = 0.96, and low-cost PA-II data outperformed SuperSASS by 1.24. Differences in sensor technology, calibration, location, and data processing may all contribute to the disparity. Seasonal variations recorded revealed that there was an increment in concentrations of pollutants in the dry season while in the wet season, they decreased. According to the identified diurnal trends, it was seen that the stagnant conditions and low temperatures were the cause of the morning peak (06:00 to 08:00) and that of the evening (18:00 to 23:00). A variety of meteorological, climatic, and human activity factors influence the diurnal pattern of $PM_{2.5}$, which frequently reaches its lowest point at midday.

CHAPTER THREE

METHODOLOGY

3.1 Study area

Benin City, the capital of Edo State in southern Nigeria, lies at approximately 6.34° N latitude and 5.63° E longitude. Famous for its historical significance as the seat of the former Benin Kingdom, the city is a major centre of culture and the economy. There are two distinct seasons in the tropical climate characteristic of the city: the wet season (April to October) and the dry season (November to March). The city has high humidity levels all year round, with average temperatures ranging from 24°C to 31°C. Local air quality is affected by seasonal changes, such as harmattan winds during the dry season (Efe and Eyafia, 2014). The use of biomass for home energy, open waste burning, vehicle emissions, and industrial operations are some of the economic activities in Benin City that have an effect on the quality of the air (Onaiwu and Okuo, 2023). These lead to higher levels of $PM_{2.5}$, especially in locations that are industrial and heavily inhabited. The problems of air pollution in the city are made worse by rapid urbanisation and traffic congestion (Onaiwu and Okuo, 2023).

3.2 Sampling locations

Ugbowo (6.3435° N, 5.6037° E) is a busy neighbourhood that is home to the University of Benin as well as residential and business districts. Due to the fact that cars, buses, and motorbikes emit $PM_{2.5}$, the high population density and heavy traffic contribute significantly to $PM_{2.5}$ levels. Furthermore, the existence of roadside markets and small-scale industrial operations like auto repair and welding shops contributes to particle pollution. The prevalent practise of open waste burning in this region makes air quality issues much worse.

One of the main commercial and industrial roads in Benin City is Sapele Road (6.3176° N, 5.6145° E). Numerous industries, warehouses, and business establishments are located here.

Trucks and tankers, among other heavy-duty vehicles, regularly use this route, producing large amounts of $PM_{2.5}$ and other pollutants. The air quality is further deteriorated by street vendors cooking outdoors and by the burning of biomass in adjacent residential neighbourhoods.

The mixed-use neighbourhood of Etete (6.3452° N, 5.6140° E) is home to restaurants, small businesses, and residential buildings. In this area, biomass combustion is commonly used for home energy needs, including firewood cooking. Additionally, open burning from nearby informal waste disposal facilities raises $PM_{2.5}$ levels. Air quality is further impacted by local building projects and moderate vehicle activity.

3.3 Data collection period

The data collection period for the study was three months from October to December of 2024. $PM_{2.5}$ readings were taken every day during this period from the three sample points that were selected: Ugbowo, Sapele Road, and Etete.

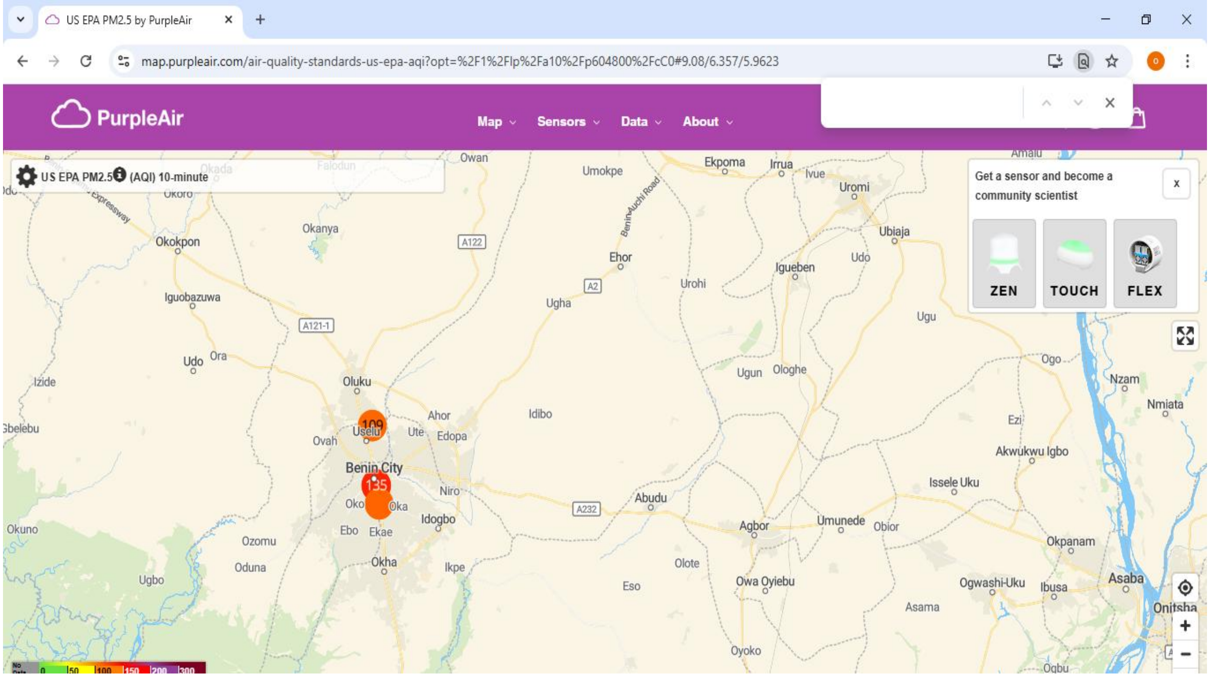
3.4 $PM_{2.5}$ measurements

To record diurnal fluctuations, measurements were recorded 6 times a day: thrice during the day (12:00 AM, 05:00 AM and 08:00 AM) and trice at night (12:00 PM, 05:00 PM and 08:00 PM), using PurpleAir sensors that can be accessed through the PurpleAir website. In addition to providing a thorough dataset for examining variations in $PM_{2.5}$ concentrations between day and night, this strategy guaranteed regular monitoring.

3.5 Statistical analysis

The $PM_{2.5}$ values for every sampling location was analysed with descriptive statistics and visualized with a boxplot using the statistical software R Differences between concentrations throughout the day and at night was evaluated using Inferential statistics such as the *paired T-test was used to evaluate the variations in the concentration of PM2.5 during the day and at night*. Analysis of variance (ANOVA) was performed to compare $PM_{2.5}$ levels across the three locations and Time (Months).

DDDD



US EPA PM2.5 by PurpleAir

map.purpleair.com/air-quality-standards-us-epa-aqi?opt=%2F1%2Flp%2Fa10%2Fp604800%2FcC0#9.08/6.357/5.9623

US EPA PM2.5 (AQI) 10-minute

Get a sensor and become a community scientist

FIGURE 3.1 The Data Collection Process, Photo Credit : Orobor Praise

CHAPTER FOUR

RESULTS PRESENTATION

4.1 Daytime levels of $PM_{2.5}$

Daytime concentrations of $PM_{2.5}$ in Ugbowo ranged from 114.27µg/m^3 in October to 174.98µg/m^3 in December; in Sapele road, it ranged from 113.35µg/m^3 in October to 177.19µg/m^3 in December; and in Etete, it ranged from 93.67µg/m^3 in October to 183.33µg/m^3 in December. The concentrations of $PM_{2.5}$ in daytime (Figure 4.1) showed that in the three sampling locations, the concentrations showed the following trend: December > November > October.

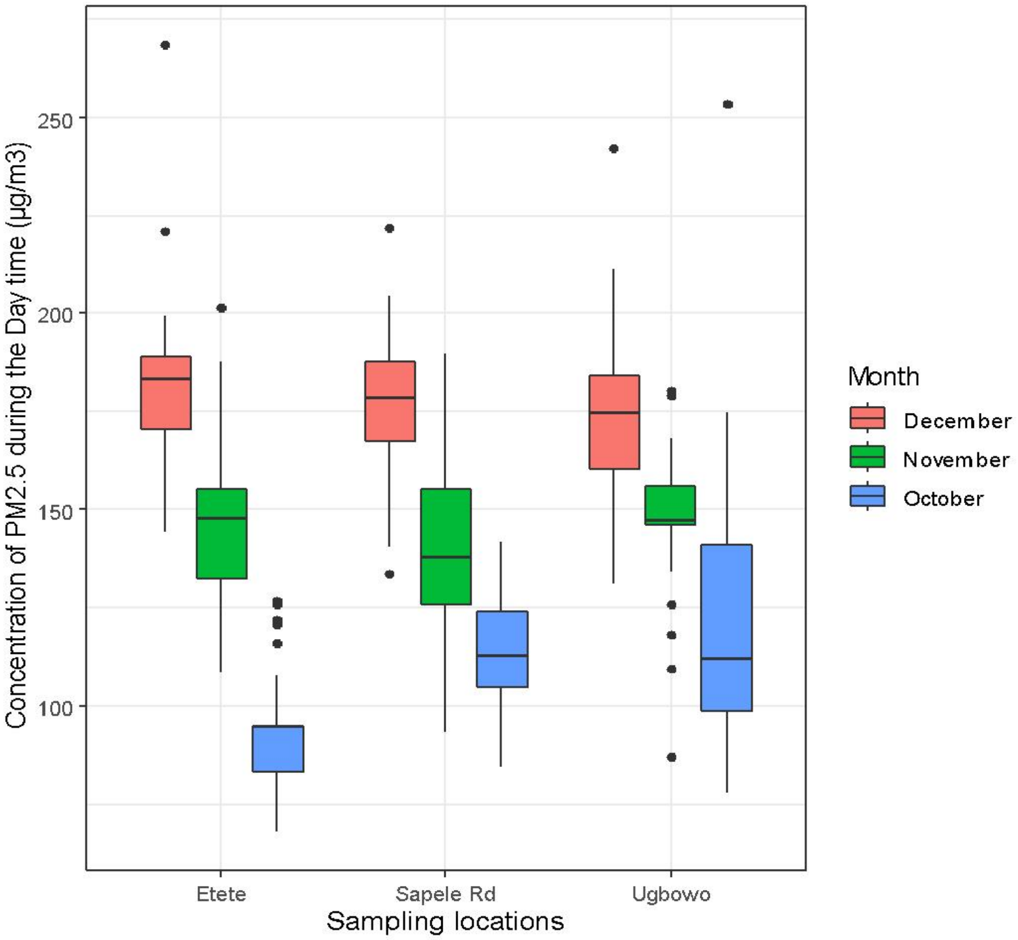


Figure 4.1: Concentrations of $PM_{2.5}$ in daytime

4.2 Night-time levels of $PM_{2.5}$

Night-time concentrations ranged from 114.17µg/m^3 in October to 153.51µg/m^3 in December (Ugbowo); 80.09µg/m^3 in October to 135.4µg/m^3 in December (Sapele Road); and 81.58µg/m^3 to 158.32µg/m^3 in December (Etete). For night-time concentrations (Figure 4.2), they were highest in December in all sampling locations.

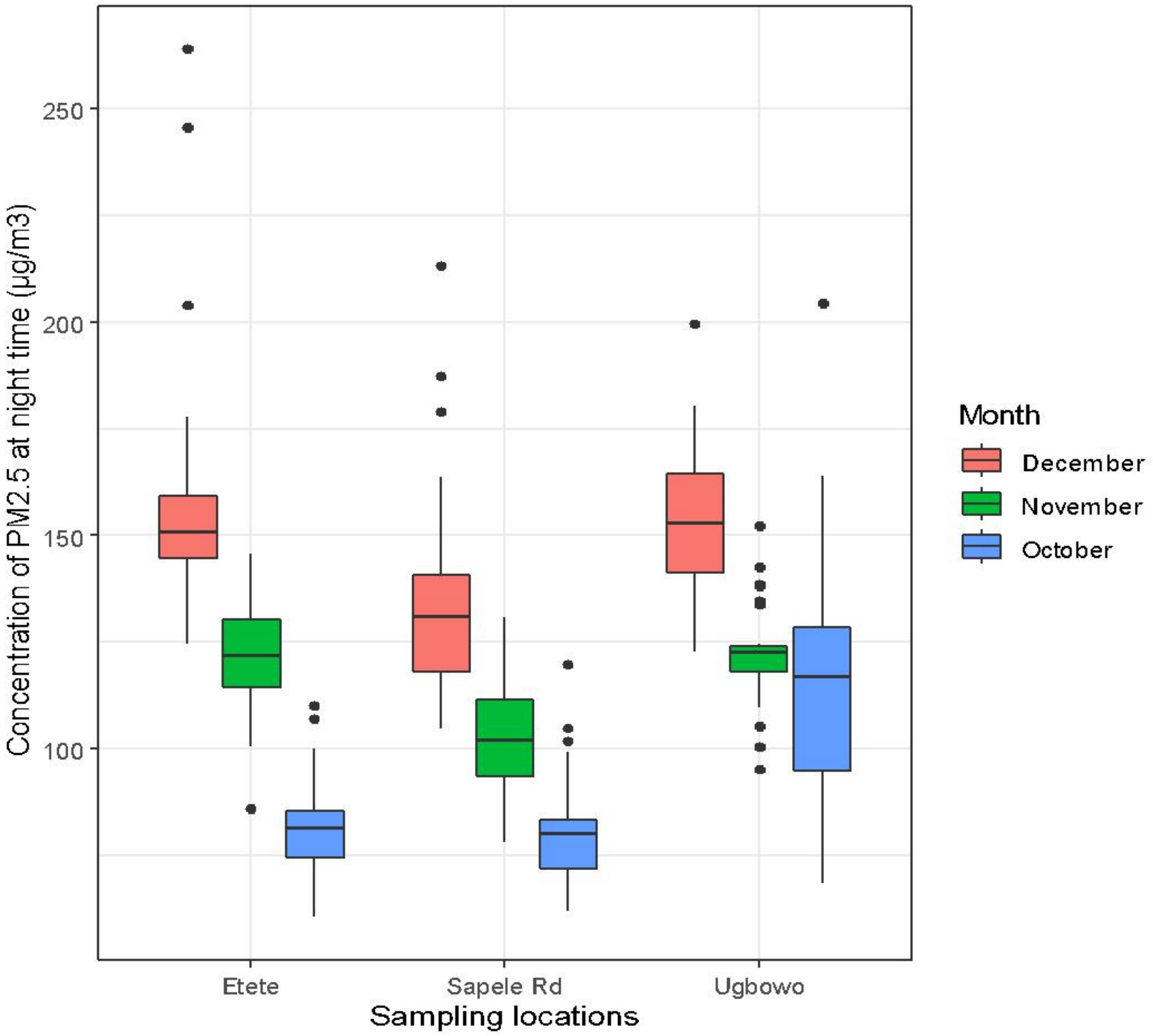


Figure 4.2: Concentrations of $PM_{2.5}$ in night-time

4.3 Total $PM_{2.5}$ concentrations

Mean day and night concentrations of $PM_{2.5}$ in Ugbowo ranged from 117.67µg/m^3 in October to 164.25µg/m^3 in December; in Sapele road, it ranged from 96.72µg/m^3 in October to 156.29µg/m^3 in December; and in Etete, it ranged from 87.62µg/m^3 in October to 170.83µg/m^3 in December. The total concentrations recorded for $PM_{2.5}$ (Figure 4.3) showed that overall, the highest concentrations were recorded in December and the lowest in October for all three sampling points.

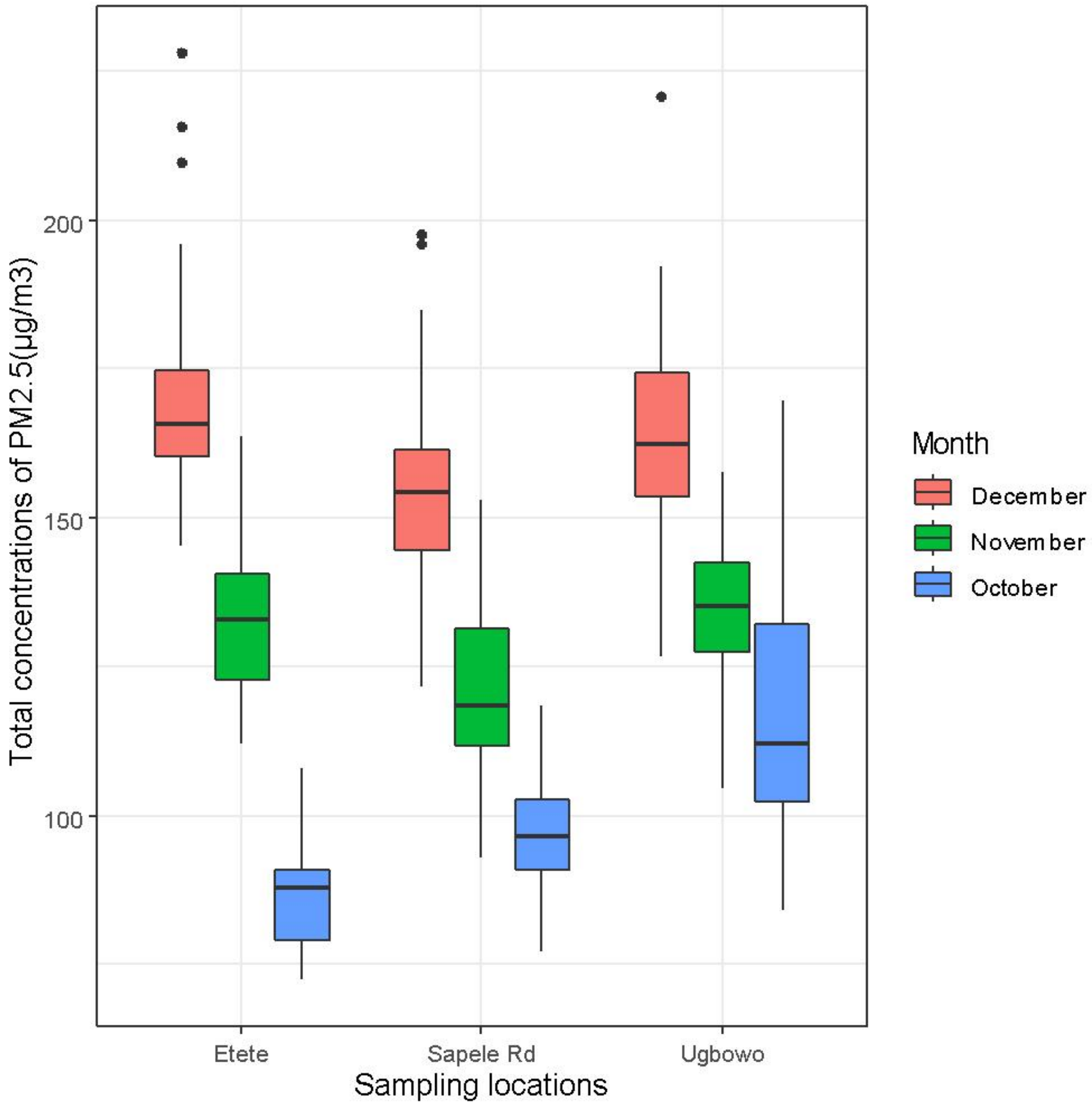


Figure 4.3: Total concentrations of $PM_{2.5}$

The concentrations of $PM_{2.5}$ between the day and night were significantly different with a p-value of 1.346E-15. Also, ANOVA showed that the concentrations of $PM_{2.5}$ over the three months were significantly different with a p-value of 2E-16. Also, when pairing the months using the Tukey test, the differences in concentrations were found to be significant ($p=0$). The results of ANOVA revealed significant differences ($p = 0.0088$) between the concentrations of $PM_{2.5}$ across all sampling locations. Pairing up location in the Tukey test showed that there were no significant differences in concentrations based on location except for the Ugbowo-Sapele road pairing with a p-value of 0.006.

Table 4.1: $PM_{2.5}$ concentrations compared with WHO standards

Location	Month	Mean PM2.5 (µg/m^3)	24-hour exposure	
			WHO Standard (µg/m^3)	NAAQS (µg/m^3)
Ugbowo	October	117.67	15	60
Ugbowo	November	135.16	15	60
Ugbowo	December	164.25	15	60
Sapele Rd	October	96.72	15	60
Sapele Rd	November	120.75	15	60
Sapele Rd	December	156.29	15	60
Etete	October	87.62	15	60
Etete	November	133.93	15	60
Etete	December	170.83	15	60

CHAPTER FIVE

DISCUSSION

5.1 Discussion

According to the findings of the study, $PM_{2.5}$ concentrations appear to rise sharply as the year goes on and December approaches. A mix of regional climate impacts, human activity, and meteorological factors are responsible for this seasonal increase. Nigeria experiences the Harmattan season in December, which is marked by dusty and dry north-easterly trade winds that blow over West Africa from the Sahara Desert (Adepoju, 2018). Long-distance transport of tiny dust particles by these winds considerably raises ambient $PM_{2.5}$ levels and lowers air quality (Yarwood *et al*., 2020). Dust advection from the Sahara causes substantial atmospheric aerosol loads throughout the dry season, especially between November and February, according to studies. According to research conducted in Port Harcourt by Oyebande *et al*. (2020), $PM_{2.5}$ levels were substantially higher during the Harmattan season than during the rainy season. These findings are consistent with the higher $PM_{2.5}$ levels in December seen in this study.

In addition to weather-related factors, human activity throughout December also raises $PM_{2.5}$ levels. Increases in open garbage burning, vehicle emissions, industrial activity, and biomass-fueled home cooking are all linked to the holiday season (Olayiwola and Ogunyemi, 2021). During this time, social and economic activity peaks, increasing fuel consumption and, as a result, air pollution (Akinyemi *et al*., 2022). Air quality problems are made worse by these variables, especially in cities with high car traffic and lax enforcement of emission standards (Ideriah *et al*., 2022). Diurnal changes in atmospheric conditions and human activity may be the cause of the considerable difference in $PM_{2.5}$ concentrations between day and night ($p<0.01$). Studies have shown that increased vehicle traffic, industrial emissions, and commercial activity tend to result in greater $PM_{2.5}$ levels during the day (Obioh *et al*., 2019). Particularly in urban areas, morning and evening rush hours see the highest emissions, creating localised pollution hotspots (Afolayan and Oyewole, 2021).

Conversely, nighttime frequently sees a decline in human activity, but climatic conditions such as temperature inversions can retain pollutants close to the ground, inhibiting their dispersion (Zhang *et al*., 2020). Pollutants build up at ground level when a layer of warm air covers colder air at the surface, preventing vertical mixing. This phenomenon is known as a temperature inversion (Guan *et al*., 2020). Nighttime temperature inversions have caused persistently high $PM_{2.5}$ concentrations despite lower emissions in a number of locations, including Nigeria (Ekundayo *et al*., 2021).

Moreover, interior spaces are a contributing factor to nighttime persistent particle pollution. According to a research by Ekundayo *et al*. (2021) on indoor air quality in northern Nigeria, there is a considerable amount of particle pollution in both indoor and outdoor locations. The study found higher $PM_{2.5}$ levels in commercial kitchens, residential buildings, and abattoirs. The health hazards are increased by this extensive exposure, especially for children, the elderly, and those who already have health issues like asthma or chronic obstructive pulmonary disease (COPD) (Pérez *et al*., 2021). The measured $PM_{2.5}$ values in this investigation are startlingly high in comparison to global air quality regulations. The World Health Organization (WHO) advises limiting the annual mean $PM_{2.5}$ concentrations to 5 $\mu g/m^3$ in order to reduce health hazards (WHO, 2021). This threshold is greatly exceeded by the measured averages of 144.3561 $\mu g/m^3$ during the day and 119.1061 $\mu g/m^3$ at night, suggesting a serious public health risk.

Increased incidence of cardiovascular disorders, respiratory infections, and early death have all been related to exposure to elevated $PM_{2.5}$ levels (Zhang *et al*., 2020). Studies conducted in other urban areas, including Lagos, have also revealed air quality levels that are higher than WHO standards, especially in places with a lot of traffic and industrial activity (Ideriah *et al.*, 2022). Similar results have been documented at Port Harcourt, where soot pollution, industrial pollutants, and oil refining operations have harmed the quality of the air (Oyebande *et al.*, 2020). Although not as significantly as in this study, a study conducted in Owo, Nigeria by Akinyemi *et al.* (2022) also revealed that $PM_{2.5}$ concentrations were higher than WHO standards, demonstrating regional differences in air pollution sources and levels.

The influence of localised pollution sources is shown by the notable variations in $PM_{2.5}$ concentrations across sample locations, especially along the Ugbowo-Sapele road route ($p<0.05$). High $PM_{2.5}$ concentrations are typically seen in industrial zones, high traffic areas, and locations with a lot of open burning. Due to outdated car fleets, inadequate maintenance procedures, and insufficient emission control regulations, transportation in Nigeria is a major source of air pollution (Onakpoya *et al.*, 2021). According to a research by Ideriah *et al.* (2023), a combination of industrial discharges and traffic congestion causes major roadways and industrial zones in Nigeria to consistently have high pollution levels. Similarly, research from Lagos shows that a significant factor in the declining quality of the air is excessive traffic (Afolayan and Oyewole, 2021). The issue is made worse by industrial pollutants from companies and power plants, especially in cities where regulations are not strictly enforced (Aliyu *et al.*, 2018). Particulate pollution comes from a variety of sources, including domestic activities, industry, and transportation. One of the main causes of $PM_{2.5}$ pollution both indoors and outdoors is the extensive use of biomass fuels (wood, charcoal, and kerosene) for cooking (Ekundayo *et al.*, 2021). According to research, indoor $PM_{2.5}$ levels in homes using biomass fuels frequently surpass outside concentrations, endangering the health of women and children who spend a lot of time indoors (Aliyu *et al.*, 2018).

5.2 Conclusion

According to this study, $PM_{2.5}$ concentrations in Benin City fluctuate significantly over time, with daytime levels continuously being greater than nocturnal levels. Intense human activities including traffic jams and industrial pollutants, as well as Harmattan winds that transport Saharan dust, are responsible for the December spike. According to WHO recommendations, the measured $PM_{2.5}$ levels are much higher, suggesting severe air pollution and increased risks of cardiovascular and respiratory illnesses. The stark disparity in pollution levels between sites points to industrial activity and traffic congestion as key causes. The results show how urgently specific initiatives, such as more stringent pollution laws and better urban design, are needed. Public health will continue to be at risk due to exposure to increased $PM_{2.5}$ levels if quick action is not taken, especially for vulnerable groups. Evidence-based policies are essential, as these findings demonstrate. Based on these findings, air pollution in Benin City must be addressed using evidence-based policy.

5.3 Recommendations

The following recommendations are made based on the findings of the study:

1. Establishing and expanding air quality monitoring networks would allow the government to track PM2.5 levels in real time and issue early warnings for areas with high pollution.
2. PM2.5 emissions should be decreased by regulatory bodies enforcing industrial pollution controls and automobile emission requirements.

3. To reduce air pollution both indoors and outdoors, households and businesses should be encouraged to switch from biomass fuels to cleaner energy sources including solar, electricity, and LPG.
4. Green spaces, tree planting, and better ventilation are all things that city planners should include in metropolitan areas to help absorb airborne contaminants and enhance air quality.
5. Public health campaigns should be launched by NGOs and government agencies to educate the public about the dangers of $PM_{2.5}$ exposures and to promote lifestyle changes that reduce pollution.
6. To reduce $PM_{2.5}$ emissions, authorities should enact and enforce laws that limit open burning, control traffic, and promote public transit usage.

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APPENDIX

STATISTICAL ANALYSES

Comparison of day and night concentrations

	Means	df	t	p-value
Day	144.3561	526	8.2432	1.346E-15**
Night	119.1061			

* significant at 0.05; ** significant at 0.01

Comparison of PM2.5 concentrations by month (ANOVA)

	df	Sum of squares	Mean square	F	p
Factor	2	182155	91078	272.3	2E-16**
Residuals	261	87300	334		

* significant at 0.05; ** significant at 0.01

Comparison of PM2.5 concentrations by month (Tukey test)

Location	Difference	Lower limit	Upper limit	p (adjusted)
November-December	-34.33676	-40.91051	-27.76302	0

October-December	-62.82873	-69.18530	-56.47215	0
October-November	-28.49196	-35.09903	-21.88490	0

* significant at 0.05; ** significant at 0.01

Comparison of PM2.5 concentrations by location (ANOVA)

	df	Sum of squares	Mean square	F	p
Factor	2	9598	4799	4.82	0.0088**
Residuals	261	259857	996		

* significant at 0.05; ** significant at 0.01

Comparison of PM2.5 concentrations by location (Tukey test)

Location	Difference	Lower limit	Upper limit	p (adjusted)
Sapele road-Etete	-6.811005	-18.181055	4.559044	0.336
Ugbowo-Etete	7.626495	-3.743555	18.996544	0.256
Ugbowo-Sapele Road	14.437500	3.471250	25.403750	0.006**

* significant at 0.05; ** significant at 0.01