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RESOURCES MANAGEMENT***

**EXPOSURE TO INDOOR AIR CONTAMINANTS IN SCHOOL BUILDINGS OF THE
UNIVERSITY OF RWANDA, CASE FOR COLLEGE OF SCIENCE AND TECHNOLOGY
(CST)**



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

By

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Kigali, August 2024

DEDICATION

This work is dedicated to God.

DECLARATION

I, Innocent NZABONIMPA, declare that the material contained within this thesis is entirely my own creation. None of the content in this thesis has been submitted previously for evaluation or the granting of a degree at any other academic institution. I have appropriately credited all sources used in this project.

Signature

Date: 30th August 2024

APPROVAL

I certify that this research project entitled "**EXPOSURE TO INDOOR AIR CONTAMINANTS IN SCHOOL BUILDINGS OF THE UNIVERSITY OF RWANDA, CASE FOR COLLEGE OF SCIENCE AND TECHNOLOGY (CST)**" was done under my supervision and has been submitted for examination with my approval.

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LIST OF ABBREVIATION AND ACRONYMS

1. CFU/m³ - Colony-Forming Units per Cubic Meter
2. DALY - Disability-Adjusted Life-Year
3. DBPs - Disinfection By-Products
4. B ETS - Environmental Tobacco Smoke
5. HVAC - Heating, Ventilation, and Air Conditioning
6. IAQ - Indoor Air Quality
7. NO_x - Nitrogen Oxides
8. OPDs - Outpatient Departments
9. OTs - Operation Theaters
10. PAH - Polycyclic Aromatic Hydrocarbons
11. SBS - Sick Building Syndrome
12. THMs - Trihalomethanes
13. TVOCs - Total Volatile Organic Compounds
14. UFPs - Ultrafine Particles
15. VOCs - Volatile Organic Compounds

LIST OF FIGURES

Figure 1. The size of PM compared to human hair ((United States EPA, 2016a)	7
Figure 2. Pie chart showing the proportion of time spent in outdoor and interior spaces. Information was gathered from the US Environmental Protection Agency (US EPA)	10
Figure 3. University of Rwanda College of Science and technology – CST Nyarugenge campus locational map.	22
Figure 4. Sensor used in Data collection.....	24
Figure 5 Concentrations of PM _{2.5} (particulate matter with a diameter of less than 2.5 micrometers) measured in two different buildings: Einstein and Muhabura.	26
Figure 6: The boxplots show the PM _{2.5} and CO ₂ concentrations during the day and night across the buildings.....	28
Figure 7. Correlation matrix of various factors, such as building occupancy, the number of building flows, and the presence of appliances like printers and computers, in relation to CO ₂ and PM _{2.5} concentrations in the Einstein and Muhabura buildings at CST.	32

Contents

DEDICATION.....	2
DECLARATION.....	i
ACKNOWLEDMENT	iii
LIST OF ABBREVIATION AND ACRONYMS.....	iv
LIST OF FIGURES	v
ABSTRACT.....	viii
CHAPTER ONE	1
1. INTRODUCTION.....	1
1.1. BACK GROUND	4
1.1.1. Construction style to indoor air quality	4
1.1.2. The Significance of indoor air quality	5
1.1.3. Indoor air pollutants	5
1.1.4. Sources of indoor pollutants.....	6
1.1.5. Particulate matter air pollution levels, source and health effects.	6
1.1.8. Carbon dioxide (CO ₂) levels, their sources, and the impact on human health.	9
1.3. PROBLEM STATEMENT	11
1.4. RESEARCH JUSTIFICATION	11
1.9. MAIN OBJECTIVE	12
1.11. SIGNIFICANCE OF STUDY	12
1.12. RESEARCH QUESTION AND HYPOTHESIS OF THIS STUDY.....	12
1.12. 1. Research Questions	12
1.12.2. Hypothesis.....	13
CHAPTER TWO	14
2. LITERATURE REVIEW.....	14
2.1. The concentrations of PM _{2.5} and CO ₂ in indoor environments	14
2.2. Comparative analysis of air pollution levels across various buildings characterized by different environmental conditions and occupancy rates.....	15
2.3. Sources of PM _{2.5} and CO ₂ emissions within the buildings.	16
CHAPTER THREE.....	21
3. MATERIALS AND METHODS.....	21
3.1. SITE DESCRIPTION.....	21
3.2. PM _{2.5} and CO ₂ concentrations measurements from different building and their comparison.	22

3.2.1. Instrumentation and Calibration	22
3.2.2. Data Collection Protocol	23
3.3. Factors that contribute to indoor air pollution within the buildings and their estimated sources	24
4. RESULT	26
4.1. PM2.5 AND CO2 CONCENTRATION PER BUILDING FLOOR	26
4.1.2. CO₂ Concentrations	27
4.2. PM2.5 and CO2 Concentrations by Time of Day	28
4.2.1. PM2.5 Concentrations	28
4.2.2. CO2 Concentrations	29
CHAPTER FIVE	29
5. DISCUSSION	29
5.1. BUILDINGS CONCENTRATIONS	29
5.2. Day and Night	30
5.3. Factors that contribute to indoor air pollution within the buildings and their estimated sources	31
6. CONCLUSION AND RECOMENDATION	33
REFERENCES	35

ABSTRACT

Indoor air pollution is a growing global concern, particularly in office environments where workers spend most of their time. In rapidly developing Rwanda, data on indoor air quality (IAQ) in offices is limited, prompting this observational study at the University of Rwanda, College of Science and Technology (CST), to monitor concentrations of particulate matter (PM_{2.5}) and carbon dioxide (CO₂) across two buildings. The study aimed to provide actionable insights to improve IAQ by measuring pollutant levels, comparing buildings, and identifying sources. Data collected over three working days revealed that PM_{2.5} concentrations, particularly in the Muhabura building, exceeded WHO limits, with higher levels at night due to reduced ventilation. CO₂ levels were elevated, especially in the Einstein building during peak times, indicating ventilation issues. Ground floors in both buildings showed the highest CO₂ concentrations, emphasizing the need for ventilation improvements. The study found that occupancy, equipment uses, and nearby environmental factors like traffic contributed to air pollution. Recommendations include better filtration systems, increased nighttime ventilation, and strategies to mitigate pollutant sources, highlighting the need for targeted interventions to protect occupant health.

Key words: Pollution, indoor, particulate matter, carbon dioxide, ventilation, healthy

CHAPTER ONE

1. INTRODUCTION

The recent World Health Organization (WHO) air quality study, show that 92% of the global population lives in areas where ambient and household air pollution surpasses WHO guideline levels, resulting in seven million deaths annually (Lelieveld et al., 2018). Humans spend the majority of their lives indoors approximately 90%, where the air they breathe often contains higher levels of contamination compared to outdoor air (Ukëhaxhaj et al., 2023). Conversely, premature deaths due to environmental factors are predominantly attributed to air pollution on a global scale, with roughly 90% of such loss of life occurring in low and developing countries (Lelieveld et al., 2018). Children are particularly open to attack to the impacts of air pollutants contrast to adults, primarily due to their immature immune and respiratory systems, lower body mass index, and different breathing patterns (Pillai, 2018) (Mendell & Heath, 2005) (Faustman et al., 2000). Schools are environments characterized by significant levels of activity and a dense population of children, facilitating the introduction and prolonged presence of various pollutants from both indoor and outdoor origins (Vornanen-Winqvist et al., 2020). People are frequently exposed to numerous potentially hazardous pollutants in the surrounding air, notably particulate matter air pollution with a diameter in the aerodynamic range less than 10 μm (PM_{10}) and less than 2.5 μm ($\text{PM}_{2.5}$), Carbon Dioxide (CO_2) and Nitrogen dioxide (NO_2). These air pollutants are of the greatest health concern and pose adverse health risk on human. Studies have shown associations between specific indoor exposures, even at low concentration, and the start or worsening of asthma and respiratory symptoms, particularly among allergic individuals and those previously unsensitized (Kanchongkittiphon et al., 2015). A long side indoor air pollutant, indoor environmental factors like high temperatures, low relative humidity, and ventilation quality significantly impact IAQ and can either cause or contribute to health issues and discomfort in indoor environments (Turunen et al., 2013) (Mendell & Mirer, 2009) (Air et al., 2011) (Torresin et al., 2018) . The primary sources of these pollutants ($\text{PM}_{2.5}$, PM_{10} , CO_2 and NO_2 are predominantly linked to combustion activities, such as traffic, biomass burning, dust and natural sources (Volcanoes eruptions and wild fires). The study underscores that an individual's health is heavily influenced by the air quality in places they frequent, such as their home, workplace, school, and public facilities. Because of the time

they spend in school environments, indoor environmental conditions significantly play a role in children's total exposure to different air pollutants (Lai et al., 2015) (Sheehan et al., 2012) (Jacobs et al., 2013) (Yassin & Pillai, 2019) (Bennett et al., 2019) (Salthammer et al., 2016). Children's school attendance and academic performance are adversely impacted by poor indoor air quality and air pollutants, as well as the heightened risk of both short-term and long-term health issues for students and staff (Taylor & Annesi-maesano, 2013) and comfort levels (Chithra and Nagendra, 2018). Moreover, they decrease teachers' productivity and increase sick leaves (Ervasti et al., 2012) (Chithra & Nagendra, 2018). Consequently, the characterization of various indoor air pollutants and their effects on both measured and perceived IAQ in school settings is a matter of significant public health concern, given the potential long-term adverse consequences of such exposures. However, there is a scarcity of available IAQ data from school buildings concerning the simultaneous characterization of pollutants and the mapping of perceived disadvantages and symptoms. For example, research on indoor air quality (IAQ) in Finnish comprehensive schools has generally concentrated on microbial studies, and none have collected thorough, concurrent data on both perceived and measured IAQ in the Helsinki metropolitan area. (Peitzsch et al., 2012) (Haverinen-Shaughnessy et al., 2012) (Meklin et al., 2005). The increasing presence of pollutants in the air has significantly altered the composition of the atmosphere, posing risks to both humans and other forms of life (Nicholas et al., 2023). These pollutants, including various gases, droplets, and particles, degrade air quality and are believed to be responsible for significant health issues, particularly in urban areas experiencing rising pollution levels (Pai et al., 2022).

Indoor air quality typically refers to the state of the air within and surrounding a building or enclosed space or structure, which can impact the health, comfort, and well-being of users (Paleologos et al., 2021). It's widely recognized that Indoor air pollutants can have detrimental effects on human health. (Zhu et al., 2021). Key factors used to assess indoor air quality include temperature, humidity, air movement within the room, and the concentration of contaminants. Poor indoor air quality can result from pollutants emitted by building materials, equipment used indoors, or activities like cooking and heating. For many years, research on indoor air quality lagged behind studies on outdoor air quality, often overlooked due to perceived lesser severity compared to outdoor pollution (Buonanno et al 2013). In recent years, extensive investigation has been conducted on understanding the health effects of particulate pollution. Numerous epidemiological studies have indicated that PM₁₀ (serves as a strong indicator for various health impacts (Buonanno

et al., 2013) (Schwartz, 1994) (Ackermann-Liebrich et al., 1997) (Vuille et al., 1997). Adverse health effects associated with PM₁₀ exposure include increased mortality, decreased lung function parameters, and an increased prevalence of respiratory symptoms. However, despite these established associations, the biological mechanisms underlying these effects remain incompletely understood. Additionally, it is hypothesized that other properties of particulate matter, such as surface area, particle number quantity, or chemical composition, may also play significant roles in eliciting a biological response. In the absence of other sources like environmental tobacco smoke (ETS) or cooking activities, the levels of carbon dioxide (CO₂) can be used as an indicator for how people perceive the quality of indoor air. Based on a study conducted by (Fehlmann1992), an indoor air concentration of 1000 ppm of carbon dioxide is deemed acceptable for 80% of the people in a room, while a concentration of 1500 ppm meets the needs of 80% of the occupants(Lelieveld et al., 2018).

To maintain a CO₂ concentration of 1000 ppm, it is necessary to supply 6.9-8.3 liters per second of fresh air per person. For a CO₂ concentration of 1500 ppm, an air supply of 3.3 to 4.2 liters per second per person is required. Modern guidelines consider additional sources of pollution beyond occupants themselves, recognizing the building itself as a potential source of pollution (Moreci et al., 2016) Tobacco smoking is also identified as a significant source of pollution.

The available papers have primarily focused on ice arenas, with carbon monoxide (CO), nitrogen dioxide (NO₂), and particulate matter (PM₁₀ and PM_{2.5}) emitted by ice resurfaces (Andrade & Dominski, 2018) (R. O. Salonen et al., 2008)being the most investigated pollutants, as well as indoor swimming pools, where high quantity of disinfection by-products (DBPs) such as trihalomethanes (THMs) have been studied (Dyck et al., 2011) (Gouveia et al., 2019). Additionally, other pollutants like ultrafine particles (UFPs), volatile organic compounds (VOCs), aldehydes (e.g., formaldehyde), ozone (O₃), and bioparticles (fungi and bacteria) could potentially result in health consequences.

Furthermore, critical comfort characteristics like as temperature (T) and relative humidity (RH) might impact material emissions (Xiong et al., 2016) (Zhou et al., 2019) (Huangfu et al., 2019) occupants' impression of indoor air quality (IAQ) should be addressed when considering exposure problems in school buildings. (Berquist et al., 2019). While the general outdoor and indoor sources of these contaminants and the parameters affecting their concentrations are well-known,

knowledge about exposure to these pollutants in different school facilities is currently scattered and limited. In contrast to residential areas and other public spaces there is relatively little published research on air quality and exposure to various pollutants in different indoor facilities like schools and offices (Alves et al., 2013) (Andrade & Dominski, 2018) where an increasing number of people engage in activities such as exercise, work, or study full or part-time (Stathopoulou et al., 2008) (Tolis et al., 2018) . While numerous studies have been conducted on ambient air contaminants (Carlisle & Sharp, 2001; Guo & Fu, 2019; Mullins, 2018; Reche et al., 2020; Strak et al., 2010) limited research exists on exposure to air pollutants in various indoor facilities. Therefore, the objective of this study is to conduct a thorough characterization of air pollution in school buildings at the University of Rwanda. The research will specifically focus on measuring the levels of carbon dioxide (CO₂) and particulate matter (PM_{2.5}) as pollutants. Additionally, occupants' perceptions will be recorded to initially categorize buildings into those with and without perceived indoor air quality (IAQ) issues.

1.1. BACK GROUND

Technology has introduced new solutions and software to streamline tasks, there are still many work environments where employees spend much of their time indoors especially at schools and Universities. This prolonged indoor exposure is significant because air pollution indoors can pose serious health risks, as recognized by numerous studies (EPA, 2009). High levels of indoor air contaminants can have both immediate and long-term health consequences, with the lungs being particularly vulnerable to prolonged exposure. Apart from the potential development of respiratory illnesses, exposure to indoor pollutants can also result in decreased comfort and difficulty focusing. These factors can contribute to inconsistent work performance, longer breaks, reduced attention to customers, shorter work hours, and increased sick leave (Duflo et al., 2020)

1.1.1. Construction style to indoor air quality

Over the past few decades, there have been notable transformations in the way buildings are constructed and managed. These alterations have been influenced by the necessity for improved energy efficiency, primarily because of the rising fuel prices since the oil crisis of the 1970s.(Jones, 1998). Today's homes and workplaces are substantially better insulated than in the past, with ventilation rates as low as 0.2 to 0.3 air exchanges per hour becoming normal(Mittal et al., 2017). In older homes, especially those with open fireplaces, it is common to find higher ventilation rates of more than 1 air exchange per hour. In addition to better insulation, there have been many other

changes in managing indoor environments, such as the growing use of synthetic building materials because of advancements in construction technology (D'Amato et al., 1994). Although these modifications have improved the comfort of buildings, they have also resulted in environments where airborne contaminants are easily generated and can accumulate to much higher levels than those typically found outside (Teichman, 1995). Indoor air pollutants can originate from different sources, such as the materials used in constructing the buildings and the activities carried out within them. These sources can be broadly categorized as those associated with the actions of building occupants and other biological sources, combustion for heating or fuel, and emissions from building materials. Furthermore, infiltration from external sources, such as water, air, or soil, can play a substantial role in the presence of specific contaminants within indoor environments.

1.1.2. The Significance of indoor air quality

While most people are familiar with the negative effects of outdoor air pollution on health, it is important to note that indoor air pollution can also have serious and harmful health consequences, as acknowledged by the U.S. Environmental Protection Agency (EPA). Research on the impact of air pollutants on human well-being has revealed that indoor pollutant concentrations can be up to five times higher than outdoor levels, and in certain instances, surpass outdoor levels by over 100 times. The heightened presence of indoor air pollutants is especially worrisome considering that the majority of people spend approximately 90% of their time indoors (EPA, 2009).

Certain air pollutants persist for extended periods and accumulate in the environment and food chain, posing a threat to both humans and animals through various exposure routes such as inhalation, skin contact, and ingestion. According to the European Environment Agency (EEA), the main contributors to air pollution include the transportation, industrial, energy, power generation, agricultural, household, and waste management sectors (Oliveira et al., 2019). Ensuring good indoor air quality is essential for protecting public health and minimizing the chances of experiencing negative health effects caused by indoor air pollution.

1.1.3. Indoor air pollutants

As per (Elminir, 2005), human activities worldwide generate approximately 3,000 distinct air pollutants. However, only a small subset has undergone extensive investigation. Notable among these are Particulate matter (PM₁₀, PM_{2.5}), ozone (O₃), carbon monoxide (CO), nitrogen oxide (NO₂), sulphur dioxide (SO₂), CO₂, and methane (CH₄). These contaminants are largely responsible for the worsening of indoor air quality. The present research focuses on two pollutants:

small particulate matter with an aerodynamic width of less than 2.5 micrometres ($PM_{2.5}$) and carbon dioxide (CO_2). These pollutants are chosen due to their significant impact on human health, particularly for individuals spending prolonged periods indoors

1.1.4. Sources of indoor pollutants

Indoor air pollution is primarily caused by a combination of factors, such as combustion processes, the materials used in buildings, indoor activities, and the entry of outdoor air pollution. Incomplete combustion of fuels can result in the release of particulate matter, hydrocarbons, and gaseous pollutants such as carbon monoxide, nitrogen oxides, and sulfur dioxide (Sekar et al., 2020). Certain sources of indoor pollution can be traced back to activities like cleaning and maintenance, which require the use of cleaners, disinfectants, air fresheners, mats, and lubricants. Additionally, sources related to individuals, such as tobacco products, office equipment like computers, printers, and copiers, cooking stoves and microwaves, paper products, and dirt, also contribute to indoor pollution. Lastly, the construction materials used in the building process included compressed wood, wall panels, construction adhesives, carpets, tiles, as well as heating, ventilation, and air conditioning systems like boilers, furnaces, generators, and stoves, can also release pollutants (Ukëhaxhaj et al., 2023).

1.1.5. Particulate matter air pollution levels, source and health effects.

$PM_{2.5}$, also known as particulate matter, is typically characterized by its aerodynamic diameter, measured in micrometers (Qiu et al., 2020). PM is a complex combination of solid particles and liquid droplets that are suspended and dispersed in the air. Particles that are smaller than or equal to 10 microns ($\leq PM_{10}$) have the ability to enter the lungs deeply when inhaled. Nevertheless, particles with a diameter of 2.5 microns or smaller ($\leq PM_{2.5}$) are more hazardous to health, as they can penetrate the lung barrier and enter the bloodstream. For instance, these particles are up to 70 times smaller than the width of a single strand of human hair (Kalisa, 2019).

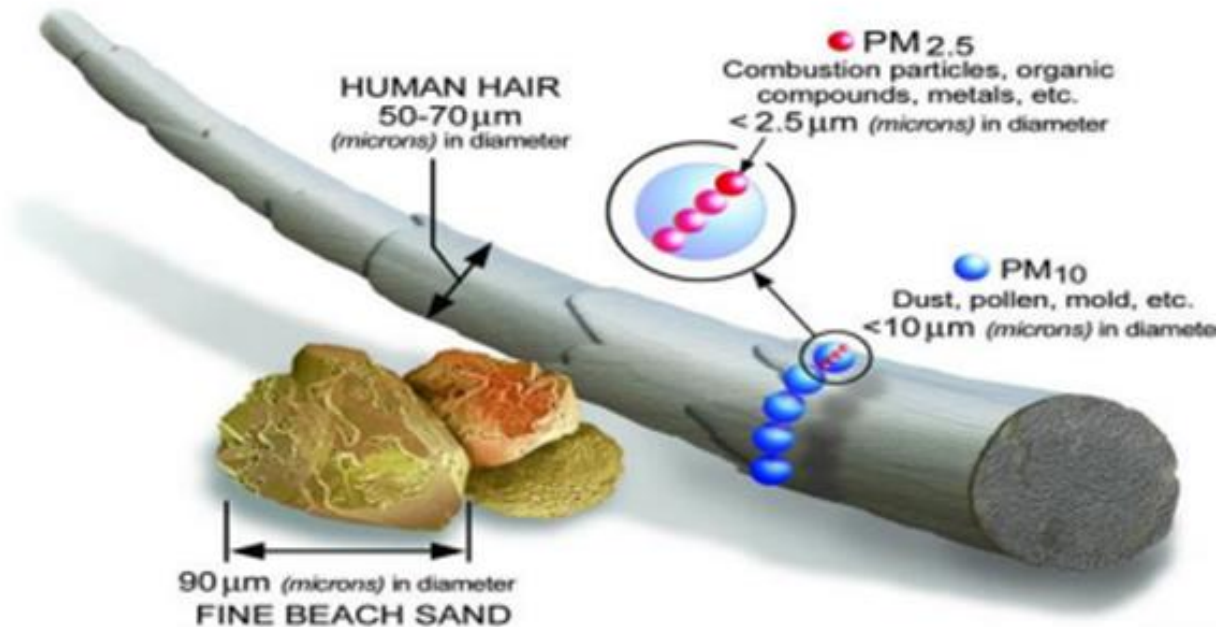


Figure 1. The size of PM compared to human hair ((United States EPA, 2016a)

Particulate matter (PM) can arise from various sources, including construction activities involving on-site machinery and off-site vehicles engaged in construction work. This encompasses emissions from non-road mobile machinery and static machinery. Additionally, the lack of proper management of dust and air pollution during demolition activities can have a substantial negative impact on the health and well-being of individuals who work or live in close proximity to these sites. Implementing effective management practices is essential to protect the well-being and quality of life of individuals impacted (Araújo et al., 2014). The emissions from these activities notably affect the indoor air quality in the surrounding vicinity (Araújo et al., 2014). In summary, PM can originate directly from emissions as well as chemical conversions of precursor gases released by power plants, vehicles, wood burning, forest fires, agricultural fires, and natural sources such as dust, volcanoes, and vegetation. It's important to recognize that the sources of PM are diverse, and the concentrations of PM can vary depending on size, season, and geographical location.

PM_{2.5} comes from a wide range of sources, including both human activities and natural occurrences. Natural sources of particulate matter include emissions resulting from volcanic eruptions (Pm et al., 2017). These pollutants can be released directly into the atmosphere as primary air pollutants or form secondary air pollutants by undergoing chemical reactions within the atmosphere (Oliveira et al., 2019). Indoor PM_{2.5} concentrations are influenced by a blend of indoor and outdoor sources. According to Cedeño Laurent et al., 2021, P M_{2.5} indoors originates from various sources, including the stirring up of settled dust, indoor smoking, cooking activities, and the secondary generation from cleaning products. However, in office buildings, many of these indoor sources are less common compared to other types of buildings.

Particulate matter of small size, specifically PM_{2.5}, is an air pollutant capable of leading to negative health consequences (Park et al., 2020). The negative impact of PM_{2.5} on human health manifests in various chronic ailments, including cancer, asthma, cardiovascular diseases, and neurological alterations associated with dementia (Di et al., 2017; Koenig, 2000; Tuckett-Jones & Reade, 2017) indicated that a rise of 10 µg/m³ in PM_{2.5} levels is linked to a 6–13% elevation in the long-term risk of cardiopulmonary mortality and a 7.3% increase in overall mortality. In the present day, particulate matter pollution emerges as a significant pollutant posing numerous challenges (Klinmalee & Srimongkol, 2009). It impacts humans and other living organisms. Multiple research studies have been conducted on this topic, indicating that approximately 28% of illnesses and fatalities in developing countries can be attributed to indoor air particulate matter. Furthermore, worldwide, it is estimated that 6.4 million individuals lose their lives due to PM_{2.5}-related air pollution (Araújo et al., 2014).

The harmful effects of PMs are influenced by factors such as their size, composition, source, solubility, and capability to generate reactive oxygen products (Xing et al., 2016) (Xing et al., 2016). Due to their small aerodynamic diameter and larger surface area, PM_{2.5} particles exhibit reactivity and can carry toxic chemicals attached to them. Their size allows them to bypass filtration by nose hairs and enter the lungs directly, causing harm to the respiratory system (Paleologos et al., 2021). Based on the aforementioned explanation of the size and affinity of PM_{2.5}, researchers have revealed that there is a connection between exposure to atmospheric PM_{2.5} and various respiratory health issues. These include a decrease in lung capacity, and a greater

likelihood of developing respiratory conditions like shortness of breath, asthma, rhinitis, sinusitis, and chronic obstructive pulmonary diseases. Additionally, prolonged exposure to PM_{2.5} has been associated with a higher likelihood of developing lung cancer. (Habre et al., 2014; Oliveira et al., 2019) (Habre et al., 2014; Oliveira et al., 2019). Through epidemiological investigations, studies have discovered a strong association between fine particle pollutants and both respiratory illness and death (Habre et al., 2014; Oliveira et al., 2019). In countries belonging to the European Union, the pollution caused by PM_{2.5} particles reduced the average lifespan by approximately 8.6 months (Orru et al., 2010).

1.1.8. Carbon dioxide (CO₂) levels, their sources, and the impact on human health.

Carbon dioxide (CO₂) is an invisible, scentless, and non-toxic gas generated through the combustion of carbon and the breathing process of living beings (Satish et al., 2012) it can also be defined as colorless, odorless gas (Satish et al., 2012). It is acknowledged as a greenhouse gas because of its capacity to retain heat within the earth's atmosphere. Carbon dioxide is not classified as an atmospheric contaminant since it occurs naturally in the atmosphere (Günel, 2016). However, this chemical can be an indoor pollutant when its concentration exceeds the normal levels found in ambient air (Kodali et al., 2020). CO₂ is primarily produced by human respiration (Qiu et al., 2020) and combustion processes, such as burning fossil fuels for heating or cooking. In enclosed spaces with inadequate ventilation, CO₂ levels can rise, leading to potential health hazards (Lowther et al., 2021). High levels of CO₂ can cause drowsiness, headaches, poor concentration, and even impaired decision-making abilities. Prolonged exposure to elevated CO₂ concentrations may also result in more severe symptoms, including respiratory issues and increased heart rate (Gall et al., 2016) and impact the well-being and satisfaction of the people inside the building (Al-Awadi, 2018). To maintain a healthy indoor environment, it is crucial to ensure proper ventilation and adequate air exchange to prevent excessive CO₂ buildup and promote a comfortable and safe living or working environment. Humans continuously release carbon dioxide (CO₂) as a result of metabolic processes, and in environments where no fuel is being burned, these emissions constitute the primary source of indoor CO₂ concentrations (WHO Guidelines for Air Quality., 1998) Furthermore, CO₂ is the major by-product of combustion from gas, kerosene, and wood or coal-fuelled appliances, which can act as substantial producers of CO₂ when in use (Moriske et al.,

1996). Indoor CO₂ levels typically range from 700 to 2000 parts per million (ppm) but can surpass 3000 ppm during the use of unvented appliances (Jones, 2002) . Although CO₂ acts as a simple asphyxiant and can irritate the respiratory system, exposure to extremely high concentrations (above 30,000 ppm) is necessary before significant health issues are likely (Maroni et al., 1995) Moderate levels of CO₂ can induce feelings of stuffiness and discomfort, with slight effects on respiration observed at levels exceeding 15,000 ppm. Exposures surpassing 30,000 ppm can result in headaches, dizziness, and nausea, as well as impacting perception of motion (Schwarzberg, 1993). This impact may be due to CO₂'s capacity to alter the activity of cells in the visual brain.

1.1.9. Patterns of indoor time utilization

People spend much of their time in various types of buildings due to their daily activities, such as residences, workplaces, schools, offices, cars, and restaurants (figure 3 illustrates the percentage proportion). Various studies on the urban population have revealed that people allocate over 90% of their daily lives in indoor settings. Research revealed that adults in North America allocate an average of 87% of their time indoor settings, 6% in driving, and 7% in outdoor environments (Klepeis et al., 2001). The quality of the air within indoor spaces plays a crucial role in determining the health and overall well-being of individuals. Several research investigations have shown correlations between better interior conditions and enhanced human health (Mujan et al., 2019).

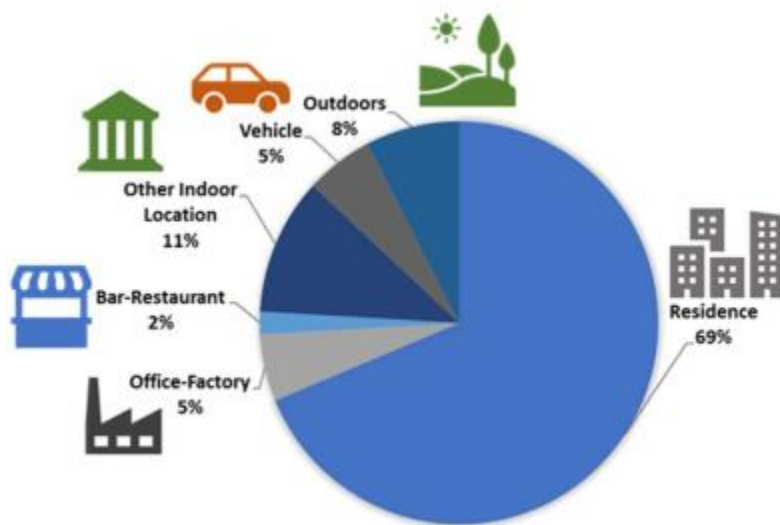


Figure 2. Pie chart showing the proportion of time spent in outdoor and interior spaces. Information was gathered from the US Environmental Protection Agency (US EPA)

(Mannan & Al-Ghamdi, 2021).

1.3. PROBLEM STATEMENT

Despite outdoor air pollution being a major public concern, indoor air quality poses significant health risks, particularly as people spend about 90% of their time indoors. Studies have shown that indoor environments often contain higher concentrations of pollutants, such as volatile organic compounds (VOCs), particulate matter (PM), mold, and radon, which contribute substantially to the global disease burden. Inadequate indoor air quality can lead to health issues, reduced cognitive function, and increased absenteeism in schools, as seen in studies from China, Portugal, and Washington State. Unfortunately, indoor air pollution in developing countries remains under-researched, including in educational buildings in Rwanda. Therefore, it's crucial to assess the air quality in these spaces and implement preventive measures if necessary to protect occupants' health.

1.4. RESEARCH JUSTIFICATION

In the past, indoor air quality issues were more obvious than they are today, yet health concerns related to poor indoor air remain significant. Although many buildings show no visible signs of poor air quality, various illnesses are now being linked to non-industrial indoor air pollution. In fact, deficiencies in indoor air quality are among the most common environmental health concerns faced by doctors. Factors like air volume, pollutant production rates, and air exchange with the outdoors influence indoor pollutant levels, but accurately measuring human exposure remains difficult due to individual behavior and activity patterns. Rwanda, with a population of 13.2 million, is undergoing rapid urbanization, yet lacks sufficient air quality data and established standards. In 2006, WHO estimated that 3,000 deaths in Rwanda were attributable to air pollution, with Kigali's PM_{2.5} levels in 2014 reaching 185 µg/m³, far exceeding WHO's limit of 10 µg/m³. Recent research by Subramanian et al. (2020) at the University of Rwanda found high carbon monoxide levels, likely due to traffic around the campus. Other studies in Ndera sector reported higher hospital visits for respiratory illnesses in areas with elevated pollution levels. Poor indoor air quality in schools affects students and staff, leading to illness, absenteeism, reduced focus, and fatigue, which can negatively impact academic performance.

1.9. MAIN OBJECTIVE

The primary goal of this thesis is to examine the differences in the levels of particulate matter (PM_{2.5}) and carbon dioxide (CO₂) in various floors of the University of Rwanda

1.10. SPECIFIC OBJECTIVES

1. To measure the concentrations of PM_{2.5} and CO₂ within the CST buildings.
2. To compare air pollution levels from different floor level in buildings characterized by different environmental conditions and occupancy rates.
3. To identify the sources of PM_{2.5} and CO₂ emissions within the CST buildings.

1.11. SIGNIFICANCE OF STUDY

The findings of this research offer a glimpse into the prevailing indoor air quality conditions in a University of Rwanda setting. Considering that individuals tend to spend more time indoors than outdoors, and it is generally recommended for them to stay indoors when outdoor air quality is hazardous, with the common perception that indoor spaces are generally safer than outdoor ones. The outcomes of this study furnish data that can help determine the tolerance level for indoor pollution for the university office buildings.

The outcomes of this study will provide valuable information for university facilities managers aiming to maintain a healthy environment for both staff and students in university buildings. This study will also serve as an informative resource for University management and various stakeholders at the University of Rwanda, shedding light on the overall air quality within the institution. Furthermore, it will enable university management and other personnel to gain a better understanding of the exposure risks their staff face and the associated health risks. Additionally, this research will contribute to decision-making processes based on the air pollution indices observed across different areas within the university. Moreover, the findings of this study can be used to develop air quality management initiatives for indoor environments.

1.12. RESEARCH QUESTION AND HYPOTHESIS OF THIS STUDY

1.12. 1. Research Questions

1. What are the concentrations of PM_{2.5} and CO₂ within CST buildings, and how do they compare to the recommended indoor air quality standards?

2. How do air pollution levels (PM_{2.5} and CO₂) differ between various floor levels in buildings characterized by distinct environmental conditions and occupancy rates?
3. What are the primary sources of PM_{2.5} and CO₂ emissions within CST buildings?

1.12.2. Hypothesis

1. The concentrations of PM_{2.5} and CO₂ within CST buildings are hypothesized to exceed recommended indoor air quality standards. Poor ventilation, building materials, and human activity may contribute to elevated levels, potentially posing health risks to occupants.
2. Air pollution levels are expected to vary across different floors, influenced by factors such as airflow patterns, floor usage, and the number of occupants. Buildings with higher occupancy rates and limited ventilation may have higher concentrations of pollutants.
3. Indoor sources like human activities, cooking, and external environmental factors such as traffic are presumed to significantly contribute to PM_{2.5} and CO₂ emissions.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. The concentrations of PM_{2.5} and CO₂ in indoor environments

In 2024, Benjamin Jones conducted crucial research on the health effects of residential indoor air pollution, employing a health-centered methodology to quantify and assess the chronic harm caused by these pollutants using the disability-adjusted life year (DALY) measure. The study sought to better understand the long-term health impacts of airborne pollutants in houses and to identify the most harmful ones. Using epidemiological and toxicological information, the study examined population morbidity and death to calculate harm intensities, which indicate chronic harm per unit of pollutant concentration. The study assessed the uncertainty in the concentrations of 45 commonly observed indoor air pollutants and predicted chronic harm using these concentrations and related harm intensities. The study found PM_{2.5}, PM_{10-2.5}, NO₂, formaldehyde, radon, O₃, and CO₂ as the most damaging indoor pollutants, accounting for more than 99% of the overall median damage of 2200 DALYs per 100,000 person-years. The study revealed that chronic damage caused by all airborne pollutants in residential settings comprises 7% of the entire global burden of all illnesses, highlighting the considerable health effect of indoor air pollution (Morantes et al., 2024).

Junker did a thorough investigation on indoor air quality at three concerts and one ice hockey game at three different venues in 1999. The study measured gas phase components CO₂, CO, and NO—as well as particulate indicators, such as particle mass distributions (0.05-9 μm), particle number distributions (0.75-10 μm), and particle-bound polycyclic aromatic hydrocarbons (PAH). Junker did a thorough investigation on indoor air quality at three concerts and one ice hockey game at three different venues in 1999. The study measured gas phase components—CO₂, CO, and NO—as well as particulate indicators, such as particle mass distributions (0.05-9 μm), particle number distributions (0.75-10 μm), and particle-bound polycyclic aromatic hydrocarbons (PAH). The findings revealed that ventilation rates fell short of the threshold necessary for smoking areas to be regarded acceptable by 80% of occupants. The average PM₉ mass concentrations varied from 318 to 2000 μg/m³ throughout the incidents. Particle concentrations in the 0.4 μm size range were detected at 203-696 μg/m³, primarily due to ambient tobacco smoke (ETS). Particle counts in the 0.75 μm range varied from 2x10⁴ to 1.9x10⁵ particles per litre, while PAH concentrations ranged

from 336 to 990 ng/m³. For gaseous components, average event concentrations ranged from 1110 to 1700 ppm for CO₂, 2-3.1 ppm for CO, and 237 ppb for NO_x. Event-to-baseline concentration ratios for gaseous components varied from 1.1 to 4.3, whereas particle indicators demonstrated substantially higher ratios, ranging from 0.7 to 140 (Junker et al., 2000).

In January 2009, Dimitrios Kotzias conducted a thorough investigation on exposure to numerous air pollutants in public buildings, schools and kindergartens (Kotzias et al., 2009). The study examined nearly 1000 samples from 182 working contexts, such as offices, schools, and waiting halls in public buildings, as well as 103 private houses and 148 samples from adult volunteers. The study concentrated on volatile organic compounds (VOCs) and carbonyls (CARBs), with sampling campaigns carried out twice at each location throughout distinct seasons to investigate potential climate-related changes in indoor, outdoor, and personal exposure concentrations. Indoor air pollution levels were found to be greater than outside levels for the selected chemical families. Personal exposure concentrations were found to be greater or comparable to indoor values, but substantially higher than outdoor levels. Notably, indoor concentrations in residences frequently outperformed those in public buildings and schools, indicating that powerful indoor sources dominated personal exposures. The study found that for some substances, such as benzene and formaldehyde, median or mean average, and 95th percentile individuals' exposures and indoor concentrations were much higher than health guidelines. This implies that relying exclusively on outdoor concentration measurements would greatly understate the long-term health concerns associated with human exposure to these contaminants (Kotzias et al., 2009).

2.2. Comparative analysis of air pollution levels across various buildings characterized by different environmental conditions and occupancy rates.

In 2020, Camilla Vornanen conducted a study to present data on both perceived and measured indoor air quality (IAQ) in six comprehensive school buildings in Finland. The study aimed to identify differences in IAQ between schools with reported IAQ complaints ('problematic schools') and those without such complaints ('comparison schools'). The first classification was confirmed using an indoor temperature survey and a newly constructed online questionnaire completed by 186 instructors and 1268 pupils from the six schools. IAQ measurements of physical parameters, gaseous pollutants, particulate matter, and bioaerosols were taken in four problematic school

buildings (26 classrooms) and two comparative school buildings (12 classrooms). The study discovered that detecting elevated concentrations of airborne cultivable microbes and pathogenic, toxic, and micro parasitic *Trichoderma* strains via air sampling, exhaust air filters, and classroom settled dust was the most effective method for distinguishing problematic schools from comparison schools. Other IAQ measures revealed no significant differences between the two groups, as concentrations were often quite low. The data indicate that tenant concerns may be connected to unresolved moisture or mould issues. The study suggested that future research should specifically target ventilation pressure condition investigations and the cultivation of dust from exhaust and supply air filters (Vornanen-Winqvist et al., 2020).

In 2022, Ahmad Hassan carried out an extensive study to analyze and compare the microbial load, composition, and prevalence of fungal and bacterial species across different hospital sites with varying ventilation systems, disinfection frequencies, and occupancy levels. The research involved sixteen sampling locations within two public hospital buildings, including outpatient departments (OPDs), surgical wards, operation theaters (OTs), emergency departments, waiting rooms, burn units, intensive care units, nursing units, and medical laboratories. The study found that the highest bacterial (829–4980 CFU/m³) and fungal (90–920 CFU/m³) levels were in OPDs and wards, respectively, while the lowest concentrations were in the OTs of both hospitals. Overall, sites with central or mechanical heating, ventilation, and air conditioning (HVAC) systems, more frequent cleaning, and lower occupancy densities showed reduced contamination levels. The study identified *Staphylococcus* spp. (53%), *Micrococcus* spp. (30%), and *Bacillus* spp. (11%) as the most common bacterial species, and *Aspergillus* spp. (67%) and *Penicillium* spp. (28%) as the dominant fungal genera.

2.3. Sources of PM_{2.5} and CO₂ emissions within the buildings.

Heid Salonen undertook a thorough assessment to evaluate human exposure to key indoor air pollutants, the variables that influence their levels, and techniques for reducing dangerous exposure in indoor sports facilities. The study identified several primary contaminants of concern, including particulate matter in indoor climbing, golf, and horse-riding facilities; carbon dioxide and particulate matter in fitness centres, gymnasiums, and sports halls; *Staphylococci* on gymnasium surfaces; nitrogen dioxide and carbon monoxide in ice hockey arenas; carbon monoxide, nitrogen oxides, and particulate matter in motor sports arenas; and disinfection by

products in indoor chlorinated swimming pools. To reduce human exposure, the study recommended several strategies, including adequate mechanical ventilation with filters, effective cleaning practices, limiting the number of occupants in fitness centres and gymnasiums, using electric rather than engine-powered resurfaces in ice hockey arenas, carefully regulating chlorine and temperature levels in indoor swimming pools, ensuring proper pool ventilation, and practicing good personal hygiene. Given the vast number of vulnerable persons in these facilities, as well as the elevated respiratory rates and airflow velocities of active people, the study highlighted the need of maintaining rigorous air quality requirements in indoor sports areas (H. Salonen et al., 2020).

Jones in 1999 did a detailed analysis on the influence of indoor air quality on health and its sources (Jones, 2002). The analysis discusses how current building designs, aiming at increasing energy efficiency, have resulted in more airtight houses and workplaces than previous constructions. Furthermore, as construction technology has advanced, the use of synthetic building materials has risen, resulting in interior conditions where toxins may accumulate to much higher levels than those found outside. The research investigates the link between indoor air pollution and health, finding a variety of indoor contaminants and their sources.

The study's key findings encompass the adverse health effects resulting from exposure to combustion byproducts from heating, cooking, and tobacco smoking, as well as the symptoms linked to pollutants released by building materials. Volatile organic compounds (VOCs), which come from paints, varnishes, solvents, and preservatives, are emphasized as particularly important. The review also addresses the risk of exposure to asbestos in deteriorating buildings, which can lead to chronic respiratory diseases like mesothelioma.

Furthermore, the health effects of inhaled biological particles, which are abundant in indoor environments, are considered, including their role in causing illness through immune responses, infections, and direct toxicity. The review underscores the importance of radon, a radioactive gas that originates outdoors but poses serious health risks indoors, along with its decay products.

The occurrence of sick building syndrome (SBS), where individuals in specific buildings experience a variety of vague and subjective health issues, is also examined. SBS is often linked

to poor indoor air quality, providing insight into the challenges faced by investigators in establishing causality.

The review concludes that there is a substantial lack of knowledge regarding the health risks associated with indoor air pollution compared to outdoor air contamination. In order to rectify this disparity, the review emphasizes the need for sufficient financial resources and a firm dedication to taking action from both the public and private sectors. It underscores that addressing the challenges and uncertainties associated with indoor air quality will be a substantial undertaking, requiring a collective effort to enhance our comprehension and control of indoor air pollution (Jones, 2002).

In 2022, Yu Liu carried out a comprehensive study on a systematic literature review concerning indoor levels of PM_{2.5} and personal exposure. Particulate matter with an aerodynamic diameter less than 2.5 μm (PM_{2.5}) is currently a significant air pollutant that has been garnering public attention. Research has shown that both short-term and long-term exposure to fine particulate matter (PM_{2.5}) can have harmful effects on health. Considering that individuals in most parts of the world spend a significant amount of time indoors, it is crucial to thoroughly examine personal exposure to PM_{2.5} within the home environment. The purpose of this review was to examine and summarize research studies on personal exposure to indoor particles with a diameter of 2.5 micrometers or less from the years 2000 to 2021. Factors from both outdoor and indoor environments that can affect indoor PM_{2.5} levels were explained. The exposure studies were confirmed to be accurate in relation to an individual's activity pattern and the exposure models used. It was discovered that numerous studies on personal exposure to indoor PM_{2.5} are influenced by factors such as the concentration level, duration of exposure, and individual differences. Various personal exposure models, such as the microenvironment model, mathematical model, stochastic model, and other simulation models, were examined to understand particle deposition in different regions of the human airway. The study suggested that additional research combining indoor air quality measurements and computer simulations of particle concentration should be conducted to better understand the impact on human respiratory health and develop effective protection strategies. Exposure in buildings located in urban areas (Liu et al., 2022).

In 2020, Iradukunda Elisephan carried out research to evaluate the effects of industrial activities on air pollution at the Cimerwa cement factory, which is one of Rwanda's largest industries, and

its neighboring regions. The research employed portable air quality sensors (pocket-sized PM_{2.5} sensors) to measure the concentration levels of PM_{2.5} and PM₁₀. Furthermore, a survey was conducted to examine the occurrence and possible origins of pollution within the area. The survey findings revealed that dust, noise pollution, and particulate matter were the primary pollutants, with industrial activities and vehicle emissions being the main contributors. The sampling activities indicated that the average concentration levels of PM_{2.5} varied from 28.0 to 32.0 µg/m³ during morning hours and from 46.0 to 50.0 µg/m³ during evening hours. For PM₁₀, the average concentration levels were between 51.0 and 55.0 µg/m³ in the morning and between 69.0 and 73.0 µg/m³ in the evening. These findings indicate significant variations in particulate matter concentrations throughout the day, highlighting the substantial impact of the cement factory's operations on local air quality.

(Elisephane & Ishigaki, 2020) .

2.4. Factors contributing to indoor air pollution in the buildings.

Building materials and furnishings are primary sources of indoor air pollutants, particularly volatile organic compounds (VOCs). (Jones, 1999) highlights that modern construction materials such as synthetic paints, varnishes, and adhesives release VOCs, which can lead to health problems including respiratory issues and headaches. These materials continue to off-gas VOCs over time, exacerbating indoor air pollution (Jones, 2002). Combustion processes within buildings, such as cooking, heating, and smoking, contribute significantly to indoor air pollution. A study by Salonen (2020) found that particulate matter (PM) and nitrogen dioxide (NO₂) levels are elevated in environments where combustion occurs regularly, such as homes with gas stoves and fireplaces (Al-Radhi et al., 2023). Occupant activities, including cooking, cleaning, and smoking, introduce various pollutants into the indoor environment. Kotzias (2009) identified that activities such as frying foods increase PM_{2.5} and PM₁₀ levels, while smoking elevates levels of nicotine and other harmful chemicals (Senerat et al., 2021a). Environmental tobacco smoke is a significant source of indoor air pollution. Junker (1999) reported that ETS contributes to high levels of PM and VOCs, which can persist in the indoor environment even after smoking has ceased, impacting non-smokers through secondhand exposure (Heide et al., 2023). Biological contaminants such as mold, bacteria, and dust mites are prevalent in indoor environments and contribute to poor IAQ. Vornanen (2020) demonstrated that moisture problems and inadequate ventilation in buildings lead

to the proliferation of mold, which can release spores and mycotoxins into the air, causing allergic reactions and respiratory illnesses (Hong et al., 2023).

Outdoor air pollution can infiltrate buildings through ventilation systems and openings, contributing to indoor pollution levels. Iradukunda (2020) showed that proximity to industrial activities and heavy traffic increases indoor concentrations of pollutants such as PM_{2.5} and NO₂ (By, 2018). Inadequate or poorly maintained ventilation systems can exacerbate indoor air pollution by failing to remove contaminants effectively. Elisephan (2020) noted that buildings with inadequate ventilation had higher concentrations of indoor pollutants, emphasizing the need for proper ventilation design and maintenance (Charvát et al., 2020). Household products such as cleaning agents, personal care products, and air fresheners release various pollutants into the indoor environment. Research by Jones (1999) pointed out that these products emit VOCs and other chemicals, contributing to indoor air quality degradation (Vardoulakis et al., 2020). Modern building designs that emphasize energy efficiency often result in airtight structures that limit natural ventilation. This can lead to the accumulation of indoor pollutants, as highlighted by Salonen (2020), who found that airtight buildings tend to have higher levels of indoor pollutants due to limited air exchange. The overall cleanliness of the indoor environment significantly impacts IAQ. Kotzias (2009) emphasized that regular cleaning and maintenance can reduce the levels of dust, biological contaminants, and chemical residues, thereby improving indoor air quality (Senerat et al., 2021b).

In conclusion, a multitude of factors contribute to indoor air pollution in buildings, ranging from building materials and occupant activities to inadequate ventilation and outdoor pollution infiltration. Addressing these factors through improved building design, effective ventilation, and regular maintenance is essential for enhancing indoor air quality and protecting occupant health.

CHAPTER THREE

3. MATERIALS AND METHODS.

This chapter aimed to provide a comprehensive roadmap of procedures utilized in the study. This chapter meticulously details the materials utilized, including and equipment, ensuring that the study can be accurately replicated and validated by other researchers. It also outlines the methodologies implemented, encompassing both established protocols and novel approaches tailored to address the research objectives. In this chapter, the selection and preparation of materials will be discussed first, highlighting the sources, purity, and any preparatory steps necessary to ensure consistency and reliability. Moreover, this chapter will cover the analytical techniques employed to collect and interpret data, including descriptions of instrumentation, calibration methods, and statistical analyses. Special attention will be given to any innovative methodologies developed during the research, underscoring their significance and potential impact on the field.

3.1. SITE DESCRIPTION

The University of Rwanda's College of Science and Technology (CST) serves as an exemplary setting for this research, renowned for its commitment to fostering scientific innovation and technological advancement. Situated in Kigali, the capital city of Rwanda, CST is strategically located in a region characterized by rapid urban development and a vibrant academic atmosphere. The college is specifically housed within the Nyarugenge campus, which is positioned at approximately 1.9441° S latitude and 30.0619° E longitude (**Figure 3**).

The data collection for this study was conducted within two prominent buildings on the CST campus: MUHABURA and EINSTEIN, these buildings were selected for their relevance to the study, providing a representative sample of the diverse academic and administrative environments within the college. The campus is easily accessible via major transportation routes, ensuring convenient access for students, faculty, and visiting researchers. The geographical coordinates, 1.9441° S latitude and 30.0619° E longitude, place CST within a region that benefits from a moderate climate and stable socio-economic conditions, further enhancing its suitability as a research site. Data collection within MUHABURA and EINSTEIN was meticulously planned and executed to ensure the reliability and validity of the research findings. Each building's unique

characteristics were taken into account, with specific methodologies tailored to their respective environments.

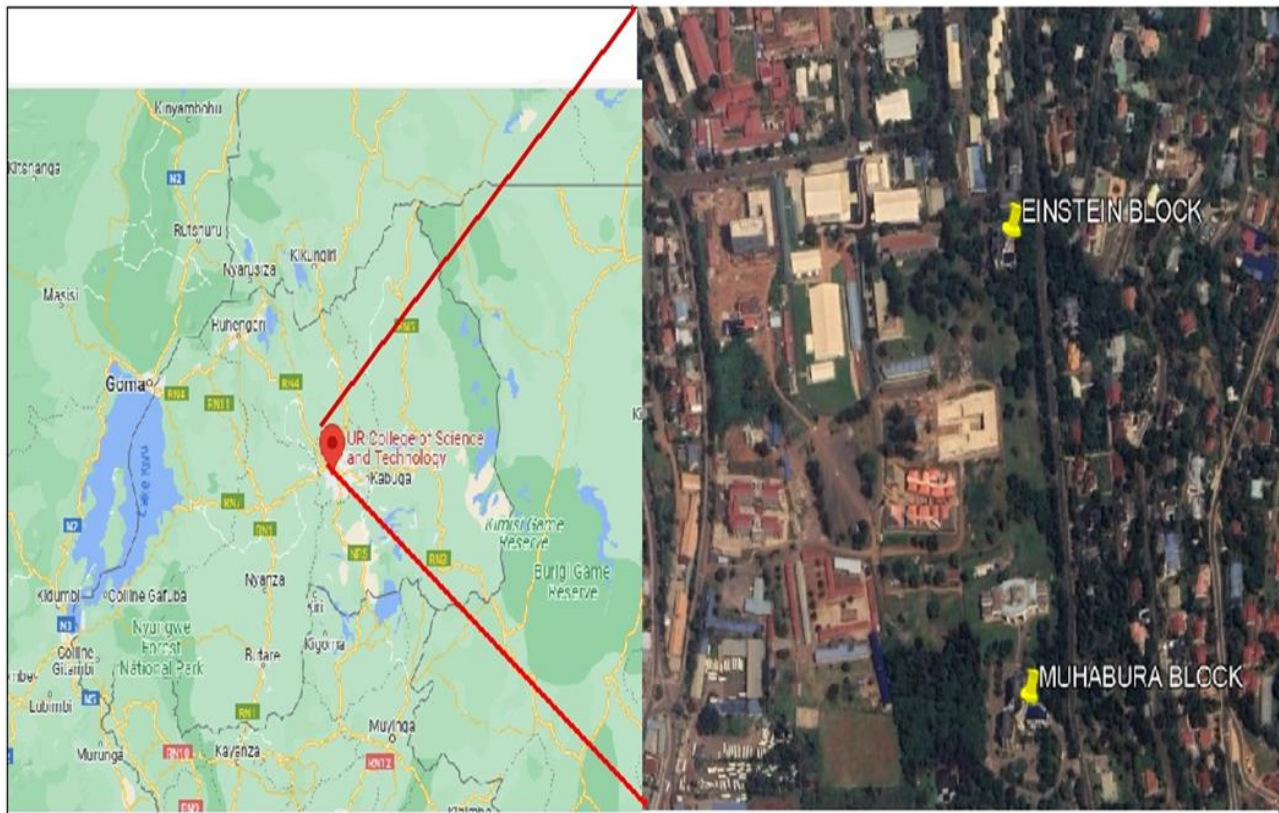


Figure 3. University of Rwanda College of Science and technology – CST Nyarugenge campus locational map.

3.2. PM_{2.5} and CO₂ concentrations measurements from different building and their comparison.

In this study to investigate indoor air pollution at the University of Rwanda, a comprehensive data collection method was employed, involving continuous monitoring of PM_{2.5} (particulate matter with a diameter of 2.5 micrometers or smaller) and CO₂ (carbon dioxide) levels in two distinct buildings: MUHABURA and EINSTEIN. These measurements are crucial for evaluating indoor air quality and assessing potential health impacts.

3.2.1. Instrumentation and Calibration

Indoor air quality meters were strategically installed in one room on each floor of both buildings to ensure a representative assessment of indoor air quality. These sensors were selected for their ability to monitor multiple parameters, including PM_{2.5} and CO₂ concentrations. Prior to deployment, each sensor underwent a rigorous calibration process to ensure accuracy and

reliability of the data. Calibration involved the use of reference standards to adjust the sensors, ensuring they provided accurate readings across all measured parameters.

3.2.2. Data Collection Protocol

Data collection spanned three consecutive working days to capture variations in indoor air quality related to occupancy patterns and daily activities. The sensor Qingping Air Monitoring manufactured by Qingping Technology (Beijing) Co., Ltd was configured to record measurements at regular intervals, providing a detailed temporal profile of indoor air pollution. The data collected included:

- PM2.5 Concentrations: Measured in micrograms per cubic meter ($\mu\text{g}/\text{m}^3$), these readings indicate the level of fine particulate matter present in the indoor environment.
- CO2 Levels: Measured in parts per million (ppm), CO2 concentrations provide an indication of ventilation efficiency and indoor occupancy.

Floor/Building	Muhabura	Einstein
Ground floor	03/08/2023 09:00:00 to 08/08/2023 09:30:00	28/08/2023 10:45:00 to 31/08/2023 10:30:00
Floor I	10/07/2023 1:15:00 to 13/07/2023 09:00:00	10/08/2023 10:15:00 to 15/08/2023 09:00:00
Floor II	13/07/2023 10:15:00 to 18/07/2023 10:00:00	15/08/2023 9:15:00 to 18/08/2023 09:15:00
Floor IV	31/07/2023 09:15:00 to 03/08/2023 08:45:00	18/08/2023 9:30:00 to 23/08/2023 10:00:00

And the recorded data were automatically compiled into Excel sheets, which were then exported via email for further analysis. This automated process minimized the potential for data loss or recording errors, ensuring a robust dataset for subsequent analysis. The data were cleaned to remove any anomalies or outliers that could distort the analysis, followed by statistical evaluations to identify patterns and trends in indoor air quality.

The selection of PM_{2.5} and CO₂ as key contaminants was based on their significant impact on indoor air quality and potential health effects. PM_{2.5} particles can penetrate deep into the respiratory system, causing various health issues, while elevated CO₂ levels can indicate poor ventilation and lead to discomfort or cognitive impairments.

By using this meticulous methodology, the study aimed to provide a comprehensive understanding of indoor air quality within the University of Rwanda's College of Science and Technology, contributing valuable insights into the environmental conditions that affect students and staff. This information is crucial for developing strategies to improve air quality and enhance the overall well-being of the campus community.



Figure 4. *Qingping Air Monitor Qingping Technology (Beijing) Co., Ltd. Sensor used in Data collection*

3.3. Factors that contribute to indoor air pollution within the buildings and their estimated sources.

To investigate the factors that contribute to variations in indoor air quality (IAQ) within the MUHABURA and EINSTEIN blocks at the University of Rwanda's College of Science and Technology, a multifaceted approach was adopted, combining quantitative air quality measurements with qualitative data from personal interviews. The study employed continuous monitoring of PM_{2.5} and CO₂ levels using indoor air quality meters strategically installed in one room on each floor (Floor I, Floor II, Floor IV and Ground Floor) of both buildings. These sensors, calibrated before use, recorded humidity, temperature, TVOCs, PM_{2.5}, and CO₂ concentrations at regular intervals over three consecutive working days. This method ensured a comprehensive dataset capturing daily variations in IAQ.

Similar methodologies have been utilized in previous studies. For instance, measured IAQ in office buildings using continuous monitoring to assess the impact of building occupancy and ventilation on pollutant levels(Mandin et al., 2017) . Additionally, Nunes et al. (2021) conducted a similar study in school environments, focusing on PM2.5 and CO₂ concentrations to evaluate IAQ during different times of the day. In conjunction with the quantitative measurements, an interview strategy was employed to gather detailed contextual information about the rooms under study. Each room in the MUHABURA and EINSTEIN buildings was visited, and comprehensive interviews were conducted with students and staff members. The main questions focused on:

Table 1: Building occupancy

FLOOR	ROOM	MUHABURA OCCUPANCY			EINSTEIN OCCUPANCY		Appliances
		OCCUPANCY	DOOR	Appliances	ROOM	OCCUPANCY	
GROUND	0R05	4	1	4	0R11	3	8
FLOOR I	P105	3	1	1	1R13	1	3
FLOOR II	P202	3	1	2	2R02	0	2
FLOOR IV	4R04	2	1	3	4R04	3	3

- Frequency of room occupancy and the number of users.
- Number and types of electrical appliances in the room, and their weekly usage estimates.
- Duration of lamp usage per day and the number of lamps.
- Days when the room is not in use, to facilitate a baseline analysis.

This approach is consistent with the methodologies used by Lee et al. (2019), who incorporated interviews to understand occupant behavior and its impact on IAQ in residential buildings(Wilson et al., 2014). Similarly, Dutta et al. (2020) utilized occupant surveys in their study of IAQ in commercial buildings to correlate human activity patterns with pollutant levels (Mannan & Al-Ghamdi, 2021). To evaluate and estimate potential sources of indoor pollution, the surrounding environmental activities of the College of Science and Technology were observed. Factors such as nearby traffic, construction activities, and vegetation were noted for their potential influence on indoor humidity, temperature, and pollutant levels. This aspect of the study draws on the work of Chithra and Shiva Nagendra (2018), who highlighted the importance of considering outdoor environmental factors in IAQ assessments within educational institutions(Enitan et al., 2017). By

integrating these diverse methodologies, the study aims to provide a holistic understanding of the factors influencing IAQ in the MUHABURA and EINSTEIN blocks. The combination of quantitative sensor data with qualitative interview insights and environmental observations offers a robust framework for evaluating how various factors contribute to alterations in indoor air quality, particularly focusing on PM_{2.5} and CO₂ levels.

CHAPTER FOUR

4. RESULT

4.1. PM_{2.5} AND CO₂ CONCENTRATION PER BUILDING FLOOR.

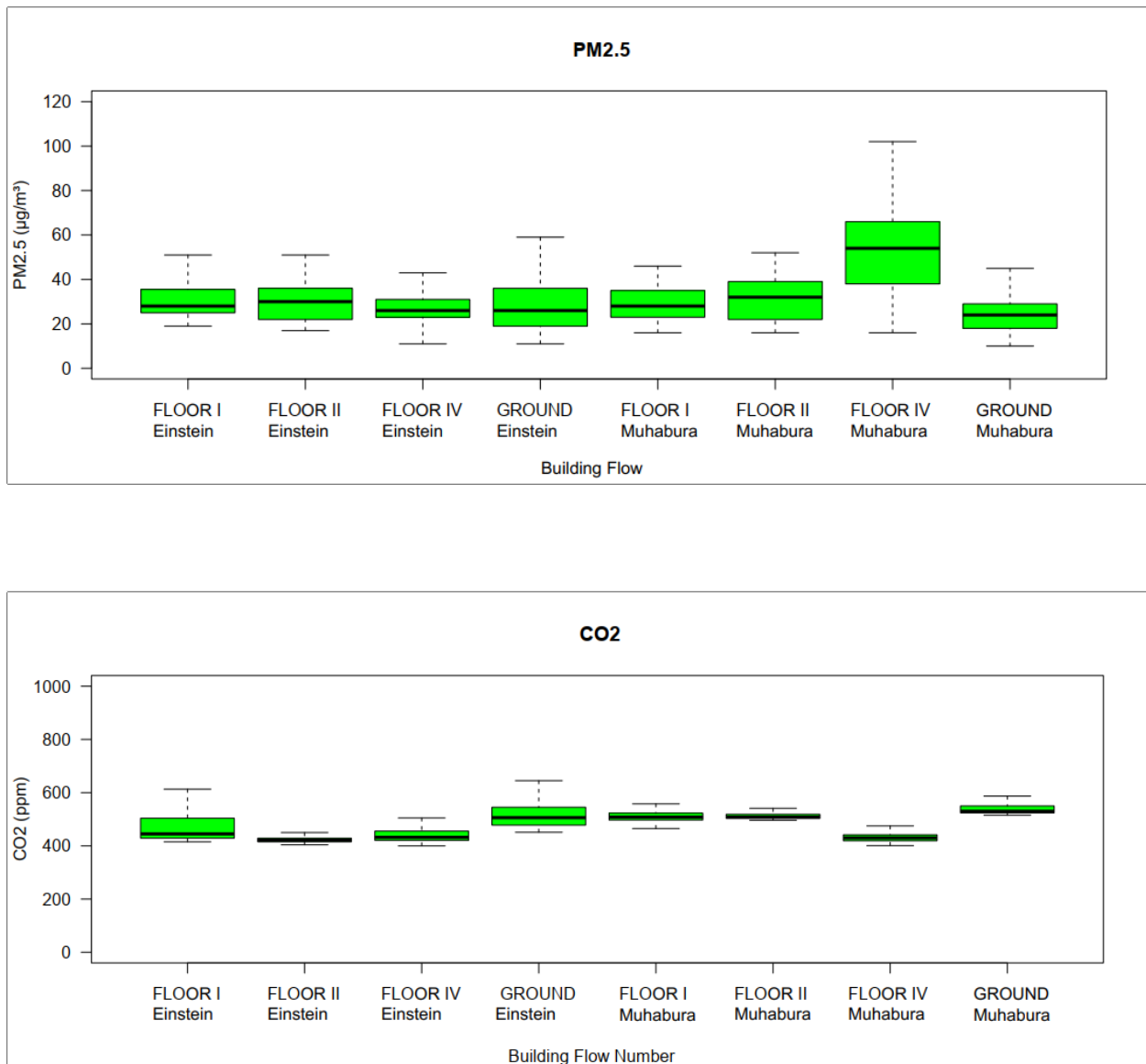


Figure 5 Concentrations of PM_{2.5} (particulate matter with a diameter of less than 2.5 micrometers) measured in two different buildings: Einstein and Muhabura.

4.1.1. PM_{2.5} Concentrations

The PM_{2.5} concentrations across different floors in both Einstein and Muhabura buildings are presented in the first boxplot. The key observations include:

4.1.1.1. Einstein Building:

Flow I: The median PM_{2.5} concentration is around 30 µg/m³, with a range from approximately 20 to 45 µg/m³. Flow II: Similar to Flow I, with a slightly lower median around 28 µg/m³ and a narrower range. Flow IV: Shows a comparable distribution to Flows I and II, with a median near 30 µg/m³. Ground Floor: Slightly lower median concentration around 25 µg/m³, but with a similar range to the other floors.

4.1.1.2. Muhabura Building:

Flow I: Lower median concentration around 25 µg/m³ compared to Einstein, with a range from about 15 to 35 µg/m³. Flow II: Shows a slightly lower median compared to Flow I, with a narrower range. Flow IV: Higher variability with a median concentration near 40 µg/m³, ranging up to approximately 80 µg/m³. Ground Floor: The lowest median concentration around 20 µg/m³, with a narrower distribution.

4.1.2. CO₂ Concentrations

The CO₂ concentrations across different floors in both buildings are presented in the second boxplot. The observations are as follows:

4.1.2.1 Einstein Building:

Flow I: Higher median CO₂ concentration around 600 ppm, with a range extending from approximately 400 to 800 ppm. Flow II: Significantly lower median around 250 ppm, with a narrower range. Flow IV: Comparable to Flow II, with a median near 250 ppm and some outliers extending above 500 ppm. Ground Floor: Median concentration around 300 ppm, with a similar range to Flow II and Flow IV.

4.1.2.2. Muhabura Building:

Flow I: Lower median concentration around 300 ppm, with a range from approximately 200 to 400 ppm. Flow II: Slightly higher median compared to Flow I, but still within a similar range. Flow IV: Higher variability with a median concentration near 350 ppm and outliers extending up to 700 ppm. Ground Floor: The highest median concentration around 400 ppm, with a significant number of outliers extending up to 1000 ppm.

Table 2 : PM_{2.5} And CO₂ Concentration per floor.

School name	Pollutants	Floor 1 (Mean ± SD)	Floor 2 (Mean ± SD)	Floor 4 (Mean ± SD)
MUHABURA	PM2.5 (µg/m ³)	27 ± 3	24 ± 3	41 ± 4
	CO2 (ppm)	300 ± 7	320 ± 13	348 ± 15
Einstein	PM2.5 (µg/m ³)	31 ± 2	28 ± 4	32 ± 2
	CO2 (ppm)	550 ± 12	310 ± 9	340 ± 11

4.2. PM_{2.5} and CO₂ Concentrations by Time of Day

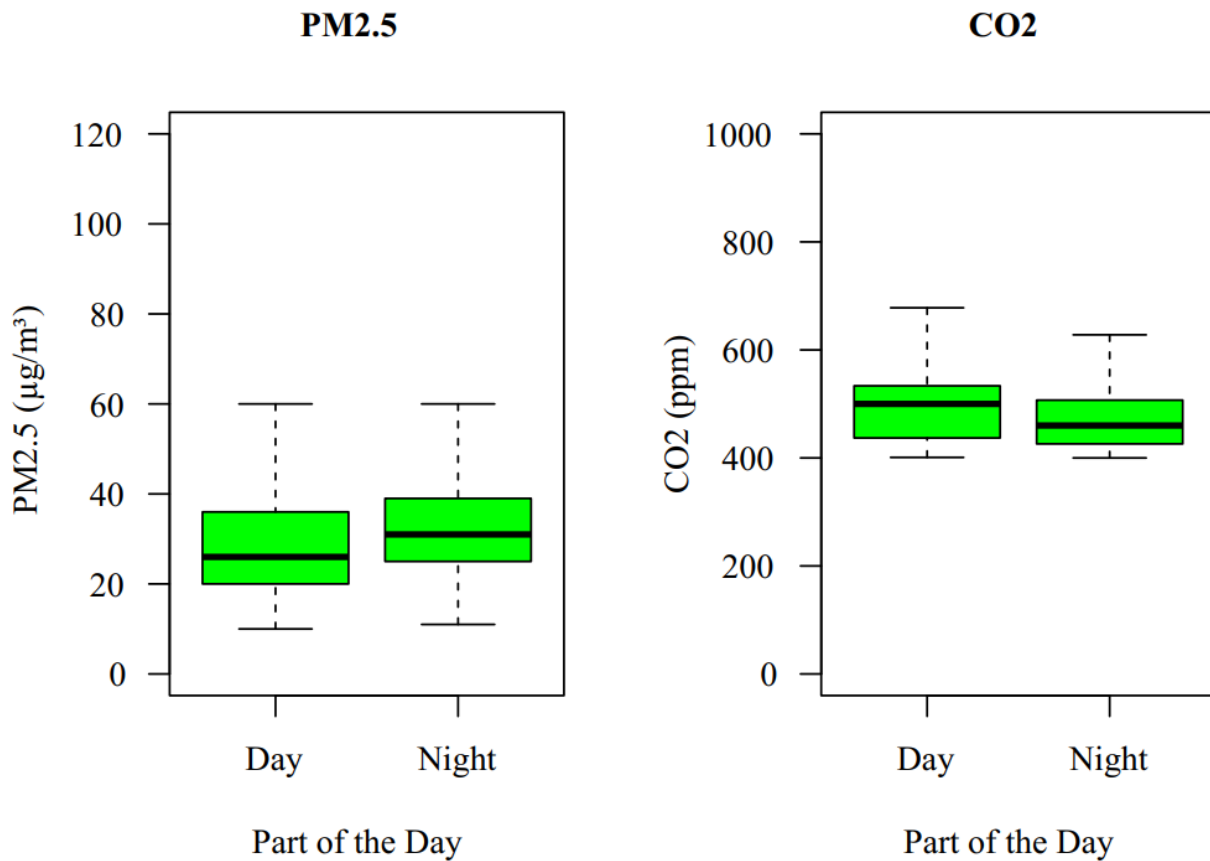


Figure 6: The boxplots show the PM_{2.5} and CO₂ concentrations during the day and night across the buildings.

4.2.1. PM_{2.5} Concentrations

Day: The median PM_{2.5} concentration during the day is around 30 µg/m³, with a range from approximately 10 to 60 µg/m³. There are several outliers extending up to 100 µg/m³, indicating

occasional spikes in particulate matter levels during the day. **Night:** The median concentration is slightly lower at around $25 \mu\text{g}/\text{m}^3$. The range is similar to the day, with outliers also reaching up to $100 \mu\text{g}/\text{m}^3$. However, the distribution appears to be slightly more concentrated around the median compared to the day.

4.2.2. CO₂ Concentrations

Day: The median CO₂ concentration during the day is around 500 ppm, with a range extending from approximately 300 to 700 ppm. Numerous outliers reach up to 800 ppm, indicating higher variability and occasional periods of poor air quality during the day.

Night: The median CO₂ concentration at night is lower, around 450 ppm. The range is narrower compared to the day, with fewer outliers, suggesting more stable and generally lower CO₂ levels at night.

CHAPTER FIVE

5. DISCUSSION

5.1. BUILDINGS CONCENTRATIONS

5.1.1. PM_{2.5}

The results indicate a noticeable difference in PM_{2.5} concentrations between the floors within each building and also between the two buildings. In the Einstein building, the PM_{2.5} concentrations are relatively consistent across the floors, with medians around $30 \mu\text{g}/\text{m}^3$. This consistency suggests that the air quality control measures in place may be uniformly effective across different floors. In contrast, the Muhabura building shows greater variability, particularly on Flow IV, where the median concentration reaches about $40 \mu\text{g}/\text{m}^3$. This higher variability could indicate differences in ventilation efficiency or sources of particulate matter specific to that floor.

The lower concentrations observed on the ground floors of both buildings suggest that ground-level air quality might be better managed or less impacted by indoor sources of PM_{2.5}. However, the higher concentrations in the upper floors of Muhabura require further investigation to identify specific contributing factors such as building materials, occupant activities, or ventilation issues.

5.1.2. CO₂ Concentrations

The CO₂ concentration data reveals significant disparities both within and between the two buildings. The Einstein building shows a notably higher median CO₂ concentration on Flow I, around 600 ppm, which is considerably higher than the other floors. This suggests potential issues

with ventilation or a higher occupancy level on Flow I. The other floors exhibit lower and more consistent CO₂ levels, indicating better air exchange rates or lower occupancy. The Muhabura building demonstrates a progressive increase in CO₂ concentration from Flow I to the Ground floor. The ground floor's median concentration around 400 ppm, with outliers reaching up to 1000 ppm, points to significant ventilation challenges. The presence of numerous outliers suggests episodic conditions of poor air quality, potentially due to crowded conditions or insufficient air exchange rates. The comparison between the two buildings highlights the need for targeted interventions to improve indoor air quality. The Einstein building generally maintains more consistent air quality across floors, whereas the Muhabura building shows significant variability, particularly with higher PM_{2.5} and CO₂ concentrations on specific floors. This variability in Muhabura could be attributed to differences in building design, ventilation systems, or occupancy patterns. These measures can help in maintaining healthier indoor air quality and ensuring the well-being of building occupants.

5.2. Day and Night

5.2.1. PM_{2.5} Concentrations

The results indicate a marginal difference in PM_{2.5} concentrations between day and night (**See Figure 6**).

During the day, higher human activity such as occupancy, movement, and possibly outdoor pollution infiltrating indoors might contribute to the slightly elevated PM_{2.5} levels and the observed outliers. At night, the slightly lower median concentration and tighter distribution suggest reduced activity and possibly more effective indoor air filtration or reduced outdoor pollution influence. The presence of significant outliers in both day and night suggests episodic events that spike PM_{2.5} levels, which could be due to specific activities like cleaning, cooking, or external pollution sources. These spikes highlight the need for continuous monitoring and potential targeted interventions during identified peak activity periods.

5.2.2. CO₂ Concentrations

The CO₂ concentration data reveals more distinct differences between day and night (**See Figure 6**). During the day, higher CO₂ levels can be attributed to increased occupancy and reduced ventilation efficiency relative to the number of occupants, leading to the higher median and more

outliers. At night, the lower median and fewer outliers suggest lower occupancy and reduced CO₂ generation, allowing the ventilation systems to maintain better air quality.

The day-time outliers, which extend significantly above the median, could indicate periods of high occupancy or inadequate ventilation, suggesting the need for improved ventilation strategies or better management of indoor air quality during peak times. The comparison between day and night air quality within the buildings highlights the dynamic nature of indoor air quality and the impact of human activity: PM_{2.5} The relatively small difference between day and night indicates that indoor sources of PM_{2.5} might be consistently present, though slightly more pronounced during the day due to higher activity levels. CO₂: The more pronounced difference suggests that occupancy and activity significantly impact CO₂ levels, with night-time conditions being more favorable for maintaining lower CO₂ concentrations.

5.3. Factors that contribute to indoor air pollution within the buildings and their estimated sources.

Figure 9 presents the correlation matrix of various factors, such as building occupancy, the number of building flows, and the presence of appliances like printers and computers, in relation to CO₂ and PM_{2.5} concentrations in the Einstein and Muhabura buildings at CST. The study revealed that only occupancy and the number of building flows have a significant effect on these concentrations. Specifically, the number of building flows was found to be significantly negatively correlated with CO₂ concentrations, with p-values less than 0.055, indicating that an increase in the number of flows corresponds to a decrease in CO₂ levels. However, the number of building flows did not show a significant correlation with PM_{2.5} concentrations. On the other hand, occupancy was positively correlated with PM_{2.5} concentrations, also with p-values less than 0.055, suggesting that higher occupancy leads to higher PM_{2.5} levels. Occupancy did not show a significant correlation with CO₂ concentrations. These findings highlight the importance of considering both building flow management and occupancy levels when addressing indoor air quality issues in terms of CO₂ and PM_{2.5} concentrations.

The University of Rwanda - College of Science and Technology, located in Kigali, Rwanda, is situated in an urban environment that can significantly contribute to air pollution levels, particularly concerning PM_{2.5} and CO₂. Kigali is a bustling city with a growing population and increasing vehicular traffic, both of which are primary sources of CO₂ emissions due to fossil fuel combustion. Additionally, the city has various industrial activities, including manufacturing and

construction, which release particulate matter (PM_{2.5}) into the air. The topography of Kigali, characterized by numerous hills and valleys, can also exacerbate pollution levels by trapping pollutants in lower areas, leading to higher concentrations. Furthermore, biomass burning for cooking and heating in residential areas adds to the PM_{2.5} levels. These factors collectively contribute to the air quality challenges faced by the University of Rwanda's College of Science and Technology, impacting both CO₂ and PM_{2.5} levels in the campus environment.

For further reading, refer to the Kigali State of the Environment Report 2021 by the Rwanda Environment Management Authority (REMA), which provides detailed insights into the environmental issues affecting Kigali, including air pollution. Rwanda Environment Management Authority. (2021). *Kigali State of the Environment Report 2021*. Retrieved from REMA Report.

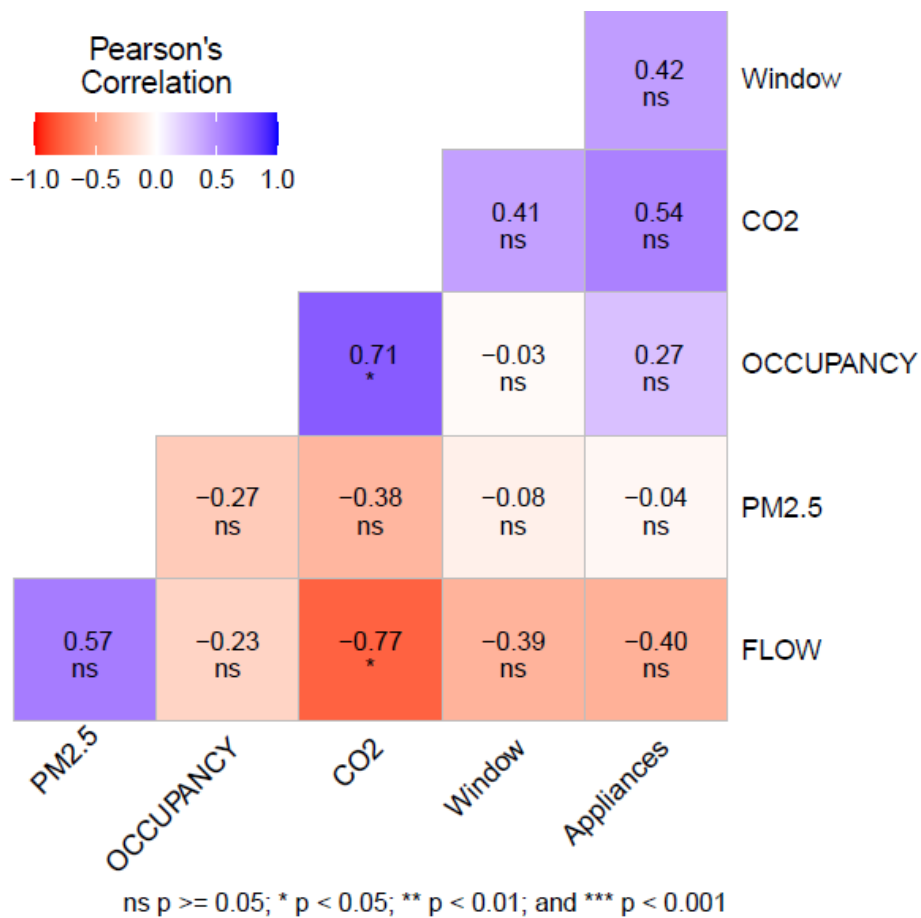


Figure 7. Correlation matrix of various factors, such as building occupancy, the number of building flows, and the presence of appliances like printers and computers, in relation to CO₂ and PM_{2.5} concentrations in the Einstein and Muhabura buildings at CST.

CHAPTER SIX

6. CONCLUSION AND RECOMENDATION

Improving indoor air quality is crucial for the health and well-being of individuals utilizing facilities at the University of Rwanda, College of Science and Technology (CST). This thesis has provided a comprehensive assessment of indoor air pollution, focusing on PM_{2.5} and CO₂ concentrations within CST buildings. The study has highlighted the significant variations in indoor air quality across different buildings and times of day, emphasizing the need for targeted interventions. The findings revealed that PM_{2.5} concentrations are higher at day compared to night time, with notable variability between the MUHABURA and EINSTEIN buildings. These variations are likely due to differences in ventilation efficiency, building usage patterns, and indoor activities. The higher PM_{2.5} levels at day suggest that reduced ventilation during these times contributes to the accumulation of particulate matter. This highlights the need for improved ventilation systems that operate effectively throughout the day and night.

CO₂ concentrations also varied significantly, with the Einstein building showing slightly lower overall levels compared to the Muhabura building. This difference is attributed to higher occupancy rates and less efficient ventilation in the Muhabura building. The findings underscore the importance of effective ventilation systems in maintaining acceptable CO₂ levels and ensuring a healthy indoor environment. The high CO₂ levels observed, particularly during peak usage times and at day, indicate the need for immediate assessment and improvement of ventilation systems.

The study identified several factors contributing to indoor air pollution, including building occupancy, the number of building flows, and the presence of electrical appliances. Higher occupancy was positively correlated with PM_{2.5} concentrations, suggesting that increased human activity leads to higher particulate matter levels. The number of building flows was negatively correlated with CO₂ concentrations, indicating that better ventilation management can help reduce CO₂ levels. These findings emphasize the need for a holistic approach to managing indoor air quality, considering both building design and occupancy patterns.

Environmental factors such as nearby traffic, construction activities, and vegetation also influence indoor air quality. The rapid urbanization and increasing vehicular traffic in Kigali contribute to higher outdoor pollution levels, which can infiltrate indoor environments. This underscores the importance of considering external environmental factors when developing strategies to improve

indoor air quality. Based on the findings, several recommendations can be made to enhance indoor air quality at CST. Implementing better filtration systems and increasing ventilation, especially during day times, can help reduce PM_{2.5} and CO₂ levels. Identifying and mitigating sources of indoor pollution, such as reducing the use of harmful cleaning substances and personal care products, is also crucial. Additionally, continuous monitoring of indoor air quality is essential to identify trends and inform targeted interventions.

The study's methodology, combining quantitative measurements with qualitative data from interviews, provides a robust framework for assessing indoor air quality. This approach can be applied to other buildings within the university and beyond, offering valuable insights into the factors influencing indoor air pollution and effective strategies for mitigation. In conclusion, this thesis has made significant contributions to understanding and improving indoor air quality at the University of Rwanda, College of Science and Technology. The findings highlight the need for targeted interventions to address variations in PM_{2.5} and CO₂ levels, driven by differences in ventilation, occupancy patterns, and environmental factors. By implementing the recommended measures, CST can create a healthier indoor environment, enhancing the well-being of students, staff, and visitors. The insights gained from this study can serve as a foundation for future research and initiatives aimed at improving indoor air quality in educational institutions and other indoor environments.

This study has several limitations that must be acknowledged. Firstly, the scope is restricted to school buildings at the University of Rwanda, which may limit the generalizability of the findings to other educational institutions with different environmental conditions and building designs. This was due lack of enough sensors to record pollutants in all buildings at the same time.

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