ASSESSMENT OF $PM_{2.5}$ AND PM_{10} OVER SRI LANKA: SPATIOTEMPORAL TRENDS, POTENTIAL SOURCE REGIONS AND ASSOCIATED HEALTH EFFECTS

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by

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Assessment of $PM_{2.5}$ and PM_{10} over Sri Lanka: Spatiotemporal Trends, Potential Source Regions and Associated Health Effects

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ABSTRACT

Air pollution, specifically the presence of particulate matter ($PM_{2.5}$ and PM_{10}) is a growing concern in many parts of the world, including Sri Lanka because of their ability to cause serious health issues, mortality among the community and negative effects on the nation's economy. This study analyzed the $PM_{2.5}$ and PM_{10} concentrations at 17 locations in Sri Lanka over a two year period (Jan 2021-Dec 2022); impact of meteorological parameters on the PM levels, potential source regions for high PM; and human health risks associated with $PM_{2.5}$ exposure. Jaffna showed the highest annual mean $PM_{2.5}$ (29.9±19.4 μgm^{-3}) and PM_{10} (55.8±37.8 μgm^{-3}) in 2022, while Kurunagala exhibited the highest annual mean $PM_{2.5}$ (21.4±7.8 μgm^{-3}) and PM_{10} (41.1±14.8 μgm^{-3}) concentrations in 2021. The annual average $PM_{2.5}$ and PM_{10} concentrations at all the stations throughout both years were always higher than WHO guidelines ($PM_{2.5}$: 5μgm^{-3}, PM_{10}: 15μgm^{-3}). However, the Sri Lankan Air Quality Standards (SLAQS) ($PM_{2.5}$: 25 μgm^{-3}, PM_{10}: 50 μgm^{-3}) were exceeded only in 2022 for $PM_{2.5}$ at Colombo, Jaffna, Kurunagala, Vavuniya; and Puttalam with annual average $PM_{2.5}$ ~ 25±20 μgm^{-3} and for PM_{10} at Jaffna and Vavuniya with annual average PM_{10} ~ 55±37 μgm^{-3}. No exceedances above SLAQS in 2021 may be attributed to the restricted activity during the lockdown period. Seasonally, the Northeast monsoon season (Dec.-Feb.) experienced highest average $PM_{2.5}$ (54.7 μgm^{-3}) and PM_{10} (104.2 μgm^{-3}) in 2022, which may be attributed to the low rainfall (~ 4.5 mm), moderate temperature (~26 °C), and low wind speed (~24 mph). CBPF was used to find out the potential source regions for high $PM_{2.5}$ and PM_{10} levels. During northeast and southwest monsoon, Colombo, Jaffna and Galle experienced high PM concentrations at 30-50 mph from South and South-East, while Jaffna, Vavuniya, Galle, Kurunagala and Puttalam experienced high PM concentrations at high wind speed of 30-40 mph from East, South-East and South-West. Potential sources in these areas could be motor vehicles (in Colombo, Galle, Kurunagala), biomass burning (at all sites), textile units (in Colombo, Kurunagala,), cement manufacturing plants (in Galle, Puttalam), fuel-based power stations (in Colombo, Jaffna) and coal-fired power plant (in Puttalam). Finally, the health effects of $PM_{2.5}$ exposure were estimated using the AirQ+ software, which evaluated the mortality attributable to acute lower respiratory disease (ALRI) (in children 0-5 years) and mortality in adults aged ≥ 25 years old attributable to lung cancer (LC) and chronic obstructive pulmonary disease (COPD). For 2022, maximum attributable cases were discovered in Jaffna which was 130 for ALRI in children; and 6,621 for LC and 7,945 for COPD in adults. The results of this study may be taken up by the local and national government for appropriate policy intervention and implementation to control air pollution in Sri Lanka.

Key words: Sri Lanka, $PM_{2.5}$, PM_{10}, Human Health Risk, Potential source regions

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LIST OF ABBREVIATION

PM	Particulate Matter
$PM_{2.5}$	Particulate Matter with a diameter of 2.5 µm or less
PM_{10}	Particulate Matter with a diameter of 10 µm or less
WHO	World Health Organization
SLAQS	Sri Lankan Air Quality Standards
ALRI	Acute Lower Respiratory Illness
LC	Lung Cancer
COPD	Chronic Obstructive Pulmonary Disease
ADHD	Attention Deficit Hyperactivity Disorder
NO_X	Nitrogen Oxides
SO_2	Sulfer Dioxide
NBRO	National Building Research Organization
CBPF	Conditional Bivariate Probability Function
GBD	Global Burden of Disease
NEM	North-East Monsoon
SWM	South-West Monsoon
FIM	First Inter-Monsoon
SIM	Second Inter-Monsoon

E	East
N	North
S	South
W	West
NE	North-East
SW	South-West
SE	South-West
NW	North-West

Chapter I

INTRODUCTION

1.1 Background

Air offers the most critical life-support function, sustaining human health and enabling the survival of all ecosystems. Although clean air is considered a fundamental requirement for human health and well-being, rapid industrialization, enhanced energy use, and transportation have all contributed to significant degradation in air quality. Air pollution is a major global issue that has negative consequences for human health, the environment, and the economy. Aside from anthropogenic sources, temporal fluctuation in air pollution can be related to local topography (plain terrain, hilly, or mountainous), weather or meteorological conditions, regional transport, and atmospheric chemistry (Shrestha, 2022). These variables contribute to the complicated character of air pollution, making it especially difficult to control in metropolitan settings. Air pollution is particularly prevalent in cities due to the wide range of sources of pollutants, which include automobiles, factories, bakeries, hotels, diesel generators, and home solid fuel combustion. Furthermore, recent decades of economic expansion and population growth have intensified air pollution, exacerbating its impact on human health and the environment. This has resulted in degradation of air quality, which poses substantial threats to human health and well-being. Furthermore, the lack of suitable air quality monitoring networks and inadequate financial resources in low- and middle-income nations make it difficult to effectively combat air pollution (Nandasena et al., 2010). Recent studies have shown that increasing levels of air pollution have serious consequences for respiratory health. These studies have shown that air pollution, together with climate-related factors such as heat waves and fluctuations in infectious illnesses and allergies, can have a negative impact on respiratory health (Arregocés et al., 2023).

Among the many pollutants, particulate matter (PM) has been identified as a major contributor to air pollution-related health problems, which is responsible for ~8.7 million deaths globally (World Health Organization, 2018). PM pollution is classified according to particle size, with $PM_{2.5}$ (diameter fewer than 2.5 microns) and PM_{10} (diameter less than 10 microns). Worldwide particulate matter pollution is a significant environmental issue that poses numerous health and environmental risks. Air pollution, particularly PM pollution, is a major global issue that endangers both human health and the environment. These pollutants come from a variety of sources, including industrial emissions, automobile exhaust, and agricultural operations. As economic development and population increase continue to exacerbate the worsening of air quality, it is critical to address this issue through the implementation of environmental and ecological hygiene policies. Developing measures and regulations to mitigate and minimize particulate matter pollution is critical for protecting public health, preserving ecosystems, and ensuring a sustainable future for future generations.

PM originates from both natural and man-made sources, contributing to air pollution with serious environmental and health consequences. Natural sources include volcanic eruptions, forestfires, dust storms, and sea spray, which are formed by natural processes like as erosion, combustion, and biological activity. Anthropogenic sources, on the other hand, are primarily human-made and include activities such as industrial processes and power plants, vehicle emissions, building, residential heating and cooking using solid fuels such as coal and wood, agricultural practices such as burning of crop residues (Mukherjee & Agrawal, 2017). These operations emit fine particles into the atmosphere, which often contain hazardous substances such heavy metals, organic compounds, and soot. The combustion of fossil fuels continues to be a major source to anthropogenic PM, emitting both primary particles and precursors that undergo chemical reactions in the atmosphere. The highest amounts of PM emissions are typically found in areas with crowded population centers, heavy industrial activity, and inefficient combustion processes. East Asia, particularly China and India, has some of the highest PM emissions, as increasing industrialization, urbanization, and reliance on coal for energy generation have contributed to serious air pollution challenges. Other locations, such as the Middle East, Central Asia, and Eastern Europe, have high amounts of PM emissions as a result of industrial activity, traffic, and agricultural practices. Furthermore, urban regions around the world frequently experience high levels of PM pollution as a result of traffic congestion, car emissions, construction activities, and other localized pollution sources (Mukherjee & Agrawal, 2017).

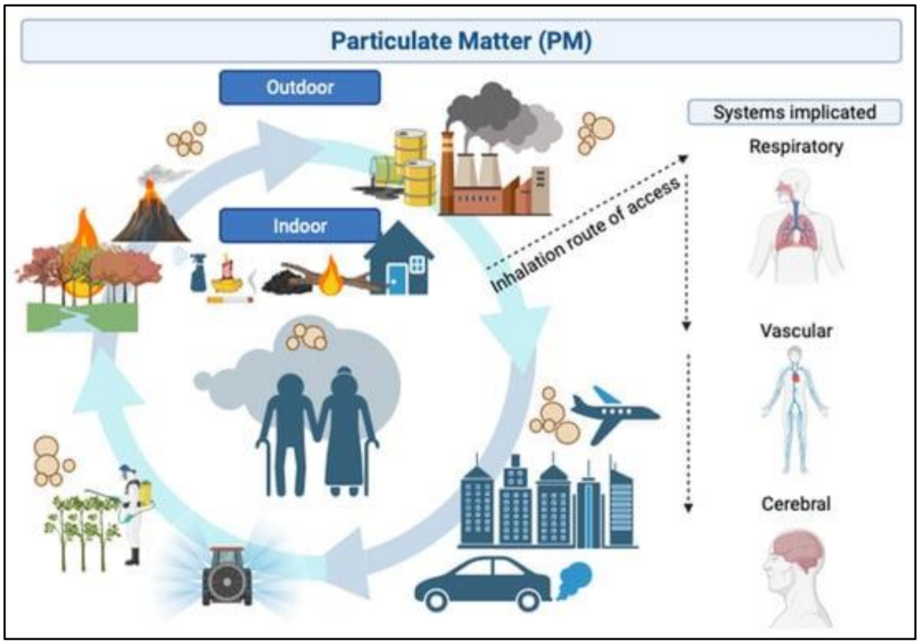

Figure 1.1: Overview of Indoor and Outdoor Air Pollution Sources and Their Impacts to the Human Body (López-Granero et al., 2024)

1.1.1 Environmental Impacts of PM Pollution

The environmental consequences of PM pollution are numerous and far-reaching, influencing ecosystems, climatic patterns, and socioeconomic well-being. These effects are caused by both the physical features of PM particles and the chemicals they contain, which come from a variety of natural and manmade sources. PM pollution has a severe environmental impact by interfering with atmospheric processes and climate dynamics. PM particles can directly soak up or scatter sunlight, altering the Earth's energy balance as well as regional and global climatic trends. Furthermore, PM act as nuclei for cloud formation, influencing cloud characteristics and precipitation patterns. Changes in cloud cover and precipitation can have an impact on ecosystems, agriculture, and water resources, causing alterations in biodiversity and hydrological cycles (Bond et al., 2013). Fine particulate particles, in particular, can scatter and absorb sunlight, resulting in low vision and hazy situations. This phenomenon can have serious consequences for transportation, tourism, and overall well-being of people living in locations with high PM concentrations. On land, PM pollution can contaminate soil and water bodies, reducing the quality of soil, water and aquatic ecosystems. PM deposition can deliver nutrients or contaminants into ecosystems, affecting nutrient cycling, soil composition, and the health of aquatic creatures. Increased PM deposition can also reduce visibility, lessen natural beauty, and disrupt tourism, which can have an economic impact on communities that rely on tourism earnings. Furthermore, PM pollution has a substantial impact on biodiversity and ecosystem health. Fine PM particles can enter plant tissues, influencing photosynthesis, nutrient uptake, and total plant growth. Furthermore, PM pollution can hasten the extinction of sensitive species, alter ecological relationships, and fragment habitats, increasing biodiversity loss and ecosystem deterioration. (Gupta et al., 2023, Shelton et al., 2022)

1.1.2 Health Impacts of PM Pollution

Particulate matter (PM) pollution, which consists of microscopic solid or liquid particles dispersed in the air, causes serious health dangers to both humans and animals. These particles range in size, with tiny particles ($PM_{2.5}$) being especially problematic due to their potential to penetrate deep into the respiratory system. PM pollution has a wide-ranging impact on human health, impacting multiple organ systems and leading to a variety of acute and chronic health disorders. Inhaling PM can cause a variety of respiratory disorders, including airway irritation, asthma exacerbation, bronchitis, and impaired lung function. Fine particulate matter can enter deep into the lungs, producing inflammation, oxidative stress, and tissue damage. PM pollution increases the risk of cardiovascular disorders such as hypertension, heart attacks, strokes, and arrhythmias. Fine PM particles can reach the bloodstream via the lungs and cause systemic inflammation, oxidative stress, and endothelial dysfunction. People with pre-existing cardiovascular problems are particularly exposed to the negative effects of PM pollution (Brook et al., 2010).

New research indicates that PM pollution may have detrimental impacts on cognitive performance, mental health, and neurodevelopment. Fine PM particles can cross the blood-brain barrier and collect in the brain, potentially causing neuroinflammation, oxidative stress, and neuronal death. Prenatal exposure to PM pollution has been associated to poor neurodevelopmental outcomes, including reduced cognitive function, behavioral abnormalities, and neurodevelopmental disorders like autism spectrum disorder and attention deficit hyperactivity disorder (ADHD)

(Calderón-Garcidueñas, 2015). PM pollution has been linked to a variety of negative health impacts, including poor birth outcomes like low birth weight and premature birth, as well as an increased vulnerability to infections, allergies, and autoimmune illnesses. Furthermore, exposure to PM pollution may exacerbate existing health inequities, disproportionately affecting underserved groups with inadequate access to healthcare, clean air, and other resources (Kelly & Fussell, 2015).

1.1.3 Importance of the Study

The study of PM emissions (both $PM_{2.5}$ and PM_{10}) and their related health concerns in a country like Sri Lanka is crucial due to many regionally specific variables. Sri Lanka, as same as many other developing countries, confronts considerable issues due to air pollution. PM emissions, particularly $PM_{2.5}$, are a significant contribution to poor air quality in cities such as Colombo. These particles can enter deep into the lungs, causing respiratory disorders like asthma, bronchitis, and lung cancer. Understanding the sources, distribution, and health effects of PM emissions is critical for safeguarding the health and well-being of Sri Lanka's population, particularly sensitive groups such as children, the elderly, and those with pre-existing health disorders. Sri Lanka's population is particularly sensitive to the health impacts of air pollution due to a number of variables, including high population density, rapid urbanization, and poor access to healthcare services. Many citizens live in highly populated urban areas with heavy traffic congestion, industrial activities, and biomass burning, all of which contribute to significant PM emissions. Studying PM emissions and their health hazards helps identify high-exposure locations and susceptible groups, allowing for targeted interventions and public health measures to minimize the burden of air pollution-related diseases.

Air pollution frequently disproportionately impacts marginalized areas and low-income populations, who lack the resources to reduce exposure and seek medical care. In Sri Lanka, research on PM emissions and their health consequences is critical for achieving environmental justice and resolving disparities in air quality and health outcomes. Understanding the social determinants of exposure and susceptibility allows policymakers to design fair policies and treatments that protect all citizens' health, regardless of socioeconomic level or geographic location. Furthermore, reducing PM emissions can improve climate change mitigation. Many of the sources of PM emissions, such as fossil fuel burning and industrial operations, also contribute to greenhouse gas emissions and global warming. By decreasing PM emissions, Sri Lanka can enhance air quality, preserve human health, and lessen the effects of climate change. The study of PM emissions and related health concerns identifies opportunities for synergistic treatments that address many environmental and public health challenges at the same time.

Also, the study of PM emissions yields useful data and evidence that may be used to inform governmental and regulatory initiatives to enhance air quality. Sri Lanka may create and implement air quality standards, emission limits, and pollution control measures using scientific study and monitoring data. Understanding the origins and causes of PM emissions allows policymakers to undertake targeted interventions like car emissions requirements, sustainable energy initiatives, and urban design strategies to minimize pollution and safeguard public health.

1.2 Literature Search

Since PM pollution is a significant environmental and public health concern in worldwide, there are various studies are going on about enhancing the ability to monitor and characterize particulate matter. This section provides a comprehensive analysis of recent research studies focused on spatiotemporal trends of PM pollution, meteorological impacts on PM pollution and associated health risk in the world. Furthermore, since air pollution is a significant environmental and public health concern in developing countries like Sri Lanka, this study serves as a critical case study for getting to know the impacts of air pollution and building effective interventions. Also, the studies based on Sri Lankan PM pollution scenario especially about are analyzed. This research analyzing helps to understand the importance of health risk assessment associated with PM pollution in Sri Lanka. It underlines the necessity of ongoing research into air quality forecasting tools to support policy decisions aimed at reducing air pollution and boosting public health.

A study revealed that the World Health Organization's AirQ+ and the United States Environmental Protection Agency's Benefits Mapping and Analysis Program—Community Edition (BenMAP—CE) are two of the most common techniques for quantifying the economic impact of air pollution-related premature deaths and illnesses, as evidenced by the hundreds of peer-reviewed articles and technical reports that have used these tools over the last two decades across many countries and continents (Sacks et al., 2020). Another study looked at PM_{10} and $PM_{2.5}$ concentrations, associated mortality, and transport mechanisms in Ghaziabad, an industrial city on the Indo-

Gangetic Plain. The greatest daily average PM_{10} and $PM_{2.5}$ values were around 1000µgm^{-3} and 450µgm^{-3}, respectively. A nonparametric Spearman rank correlation analysis of meteorological parameters and PM concentrations found that ventilation coefficients were negatively correlated with PM concentrations during the most polluted seasons (post-monsoon and winter), with rank correlation values of around -0.50. Ghaziabad had approximately 873 deaths per million people due to ambient $PM_{2.5}$ levels, which was approximately 70% higher than Delhi (Gupta et al., 2021). In 2022, there was a study in Thailand which aimed to discover the connection between meteorological data and air pollutants and health impacts of long-term $PM_{2.5}$ exposure on expected life remaining (ELR) and years of life lost (YLL) indices. The study predicts that the maximum and lowest YLL for all age groups will be 24,970.60 in 2017 and 11,484.50 in 2019. The number of deaths from COPD, IHD, and stroke caused by long-term exposure to ambient $PM_{2.5}$ was 125, 27, and 26, respectively. The findings revealed that elderly persons (> 64) had a higher YLL index than those < 64. The greatest and lowest readings for all ages were 307.15 in 2015 and 159 in 2017 (Kliengchuay et al., 2022).

Tariq et al. 2023 attempted to analyze the long-term spatiotemporal trends and associated health impacts of $PM_{2.5}$ concentrations from 2001 - 2019 in Nigeria. Nigeria's lowest $PM_{2.5}$ concentration exceeds the WHO's intermediate target-1 (35µgm^{-3}). During the study period, the mean $PM_{2.5}$ concentration increased by 0.2µgm^{-3} per year from 69µgm^{-3} to 81µgm^{-3}. Health concerns have increased in most mid-northern and southern states. The percentage of locations with ultra-high health risk (UHR) levels of $8 \times 104 - 7.3 \times 106$µgm^{-3} per person developed from 1.5% to 2.8%. Around 91% Nigerian population is exposed to ultra-high-rise area (Tariq et al., 2023). Arregocés et al. 2023 discussed the impact of particulate matter exposure which was evaluated through the updated Global Burden of Disease health risk functions using the AirQ+ model for mortality attributable to acute lower respiratory disease (in children≤4 years), mortality in adults aged>18 years old attributable COPD, IHD, LC, and stroke, and all-cause post-neonatal infant mortality. Long-term exposure to $PM_{2.5}$ is responsible for around 11.6% of ALRI fatalities in children under 4 years old, 16.1% of COPD and 26.6% of IHD deaths among adults. PM exposure was expected to cause 9.1% and 18.9% of LC and stroke cases, respectively, on an annual basis. Particulate matter pollution is directly responsible for approximately 738 fatalities per year. The adult population over the age of 18 has the greatest annual death rate, with a mean of 401 incidents (Arregocés et al., 2023).

Air pollution is becoming a major issue in Sri Lanka, owing mostly to the remarkable growth in the number of motor vehicles and traffic congestion. Regular monitoring of air pollution with automatic air quality stations began in 1997 with two monitoring stations in Colombo. (Ileperuma, 2020) Since then there have been number of air quality studies with limited datasets in different parts of Sri Lanka.

A review on air pollution studies in Sri Lanka was done in 2020 which showed that CO levels are falling while SO_2, NO_2, and O_3 levels continue to rise during 1997 – 2003 period. Pollutant levels are below national requirements, with the exception of PM (PM_{10} and $PM_{2.5}$) which consistently exceed them. This review revealed that Kandy's air quality is worse than that of Colombo due to its geographic position, increasing vehicle population, and traffic congestion. Carcinogenic polyaromatic hydrocarbons found in cooking smoke and vehicle exhaust provide a significant health risk. The concentration of 16 prioritized PAHs (PPAHs) ranged from 57.43 to 1246.12ngm^{-3}, with a mean of 695.94ngm^{-3} in urban heavy traffic areas in Kandy. Air pollution in Kandy is leading to an increase in respiratory disorders, including COPD (Ileperuma, 2020). Another study examined how ambient particulate matter (PM) affected respiratory disease hospitalization in Kandy, Sri Lanka in 2019. This discovered that during the high ambient air pollution period, hospital admissions rose among people over 65 years old, males, and for COPD and pneumonia (Priyankara et al., 2021). Senarathna et al. 2021 discussed about the impact of COVID 19 lockdown on air quality of Colombo and Kandy, Sri Lanka. This study examined the changes in $PM_{2.5}$ and CO levels before and after the COVID-19 lockdown in Sri Lanka. Colombo's "Urban Background" area saw the biggest average decreases in $PM_{2.5}$ and CO levels (52.4% and 46.7%, respectively). In Kandy, the "Urban Background" site exhibited a larger decrease of $PM_{2.5}$ and CO (30.2% and 41.2%, respectively) than the "Primary Residential" site (10% and 9%, respectively) (Jayaratne et al., 2021).

Abayalath et al. 2022 designed a study to conduct chemical analysis and biological impacts of PM_{10} in Kandy, Sri Lanka and findings revealed that Kandy city air may contain carcinogenic and mutagenic chemicals (PAHs, metals and heavy metals), leading to increased health risks and respiratory tract anomalies (Abayalath et al., 2022). In 2022, a study was conducted on $PM_{2.5}$ in Sri Lanka which attempts to understand the distribution of $PM_{2.5}$ in Sri Lanka by examining data acquired by the Beta Attenuation Monitor (BAM) and utilizing low-cost sensors, models, and remote sensing data. According to BAM data, $PM_{2.5}$ levels were "Unhealthy for Sensitive Groups" or "Unhealthy" for at least 50% of the time between November and February, as classified by the US system. This occurs simultaneously with the northeast monsoon, when stable air masses limit pollutant dispersal (Dhammapala, Ranil., Basnayake, Ashani., Premasiri, Sarath., Chathuranga, Lakmal., Mera, 2021). Mampitiya et al. 2024 studied about forecasting PM_{10} levels in Sri Lanka. This study compares the effectiveness of eight cutting-edge machine learning models (ANN, Bi-LSTM, Ensemble, XGBoost, CatBoost, LightGBM, LSTM, and GRU) in predicting particulate matter in two urbanized regions in Sri Lanka (Battaramulla and Kandy). The regression coefficient, Root Mean Squared Error, Mean Squared Error, Mean Absolute Error, Mean Absolute Relative Error, and Nash-Sutcliffe Efficiency were used to determine the optimal model for both cities. The Ensemble model is recommended for further research on PM_{10} in Sri Lanka, where high air pollution levels are an increasing issue (Mampitiya et al., 2024).

In recent years, many initiatives and policies have been implemented to reduce air pollution in Sri Lanka. These measures are intended to minimize emissions from various sources, enhance fuel quality, and encourage sustainable transportation. Evaluating the success of these measures is critical for understanding their impact on air quality and informing future decisions. Several studies have evaluated the effects of actions such as reducing sulfur levels in diesel fuel, implementing a vehicular emission testing (VET) program, improving road surfaces, removing road barriers, and introducing hybrid vehicles (Premasiri et al., 2015). These evaluations provide useful information on the effectiveness of certain measures and aid in the identification of best practices for air pollution control. Future study should focus on rigorously evaluating air quality interventions to assess their long-term influence on Sri Lanka's air pollution levels. This can include monitoring air quality before and after measures are implemented, analyzing changes in pollutant concentrations, and evaluating the health impacts. Policymakers can identify successful tactics and prioritize actions that result in the greatest improvements in air quality by assessing effectiveness of interventions.

1.3 Research Gap

There are several critical research gaps that need to be addressed to further enhance the knowledge among the society and improve the accuracy of both $PM_{2.5}$ and PM_{10} concentration monitoring and implementation of mitigation measures of PM pollution in Sri Lanka.

One noteworthy research gap is a lack of attention on PM-specific studies. While there is a considerable corpus of research on air pollution in Sri Lanka, there are very few studies that focus exclusively on PM. It is critical to close this gap since PM particles pose a greater threat to human health due to their small size and propensity to penetrate deeply into the lungs. Conducting extensive investigations on the sources, spatial temporal patterns, and health effects of PM across Sri Lanka can provide valuable insights for targeted interventions and policies. Understanding the impact of localized elements is another study gap in Sri Lanka's PM pollution investigation. Sri Lanka's metropolitan regions are growing more diversified and complicated, with changes in land use, transportation patterns, and industrial activities. However, there is a need to obtain a better knowledge of the localized elements that cause PM pollution. Further research should look into the effects of local emission sources, meteorological circumstances, and socioeconomic factors on PM concentrations in specific parts of Sri Lanka. This knowledge will help to build targeted actions and policies that successfully address the particular difficulties encountered by different regions of the country.

In addition, there is a study void in understanding the long-term health implications of $PM_{2.5}$ exposure in Sri Lanka. Longitudinal studies that track individuals over time are required to examine the cumulative health effects, latency periods, and potential recovery following PM pollution reduction. Understanding the long-term consequences is critical for developing effective therapies and assessing their efficacy in lowering the burden of PM-related health problems. The current study on PM in Sri Lanka is mostly concerned with air quality monitoring data and meteorological elements. However, additional integration of multidimensional data is required to acquire a thorough knowledge of the sources and complexities of $PM_{2.5}$ pollution. Incorporating socioeconomic indicators, transportation patterns, and land use data into the research can provide useful insights into the underlying causes of $PM_{2.5}$ pollution in Sri Lanka. This integration of multidimensional data will allow for the creation of more accurate and tailored forecasting models. There is a study vacuum in measuring the effectiveness of Sri Lanka's air pollution-reduction laws and legislation.

While policies exist, their impact and effectiveness must be evaluated, and hurdles to implementation must be recognized. Future research should assess the effectiveness of policy interventions including as emission controls, traffic management methods, and public awareness campaigns. These studies will shed light on the success of these policies and support evidence-based decision-making for future air pollution reduction activities. Future studies that address these research gaps can help to provide a more comprehensive picture of PM pollution in Sri Lanka. This, in turn, will facilitate evidence-based decision-making and interventions aimed at minimizing the negative consequences of PM pollution in Sri Lanka.

1.4 Objectives

So far, there has been no comprehensive air quality study in Sri Lanka which explores the PM at multiple locations throughout the country over a complete year. Thus, it is still unclear: i) how the PM is varying spatially throughout Sri Lanka; ii) the possible source regions contributing to the PM; and iii) the mortality associated with high PM experienced in Sri Lanka. To bridge this gap, we undertook a two year-long study of analyzing ambient $PM_{2.5}$ and PM_{10} at 17 locations in Sri Lanka, with an overall objective of understanding the local sources of pollutions, impact of meteorological factors on the spatial-temporal variability of PM; and to estimate the associated human health risks. The specific objectives of the present work were:

1. To understand the spatial and temporal variation in $PM_{2.5}$ and PM_{10} concentration at 17 locations over a two year period in Sri Lanka;
2. To understand the dominant local sources contributing to high $PM_{2.5}$ and PM_{10} throughout Sri Lanka;
3. To estimate the mortality due to acute lower respiratory disease (ALRI) in children aged 0-4 years, chronic obstructive pulmonary disease (COPD) and lung cancer in adults aged >25 years.

Chapter II

METHODOLOGY

2.1 Study Area

The Palk Strait divides Sri Lanka, an island in the Indian Ocean, from peninsular India which is located between latitude 5°55′ and 9°51′ N and longitude 79°41′ and 81°53′ E, respectively. Its maximum length and width are 268 miles (432 km) and 139 miles (224 km), respectively. The total area is approximately 65,610 km^2, with a coastline that stretches for about 1,340 km. The core highland, the plains, and the coastal belt can be separated into three different zones based on their distinctive elevations. Mountainous with heights over 2.5 km, the centre region of the island's southern half is mountainous. The central highlands' main areas are home to numerous intricate topographical features such ridges, peaks, plateaus, basins, valleys, and escarpments (Department of Meteorology, 2019).

Sri Lanka, a South Asian island nation, is home to a diverse and vibrant population of almost 22 million people (Wikipedia, 2024). The country is rather densely inhabited, particularly in major regions like as Colombo, the capital, and Kandy. Sri Lanka is undergoing increasing urbanization. Colombo, as the main city and commercial hub, is under severe population pressure, resulting in a variety of environmental issues, including air pollution. The growing number of automobiles, especially in metropolitan areas, is a major cause of air pollution. Traffic congestion in places like Colombo increases pollutant emissions such as NOx and PM. Industrial zones, particularly those surrounding Colombo and other major cities, contribute heavily to air pollution. Pollutants emitted by factories and power plants include SO_2, NOx, and PM. The fossil fuels utilizing in industry contributes significantly to greenhouse gas and other pollutant emissions. The reliance on thermal power plants, which use coal and oil, contributes to air pollution. Although Sri Lanka is investing in renewable energy, thermal electricity remains a substantial contributor. Burning agricultural leftovers is prevalent in rural areas, resulting in substantial amounts of smoke and particulate pollution. Poor waste management methods, such as open burning of rubbish, are common and contribute to air pollution. This is a typical practice in both urban and rural regions, producing a wide range of contaminants, including dioxins and furans.

The climate in Sri Lanka is tropical, with four distinct monsoon seasons. The southwest monsoon brings rainfall from May to September, primarily affecting the western, southern, and central regions, while the northeast monsoon occurs in December and February, affecting the northern and eastern parts of the country. During First inter-monsoon which is from March to April, the majority of the island receives between 100 and 250 mm of rainfall, with the Northern Jaffna Peninsula being the noticeable exception while Second Inter-monsoon season, October-November, has the most evenly distributed rainfall over Sri Lanka. Almost the entire island receives more than 400 mm of rain during this season, with the southwestern slopes receiving heavier rainfall in the range of 750 mm to 1200 mm. Particularly during the monsoon season, topographical features (such as ridges, peaks, plateaus, basins, valleys, and escarpments) have a significant effect on the spatial patterns of winds, seasonal rainfall, temperature, relative humidity, and other climatic aspects (Department of Meteorology, 2019).

This study focused on PM concentrations (both $PM_{2.5}$ and PM_{10}) based on data collected from 17 Air Quality Monitoring Stations in all over Sri Lanka (Fig 2). Monitoring stations such as Colombo (CMB), Kalutara (KAL), Galle (GAL), Trincomalee (TRI), Mullativue (MUL), Jaffna (JFN), Puttalam (PUT) are situated in coastal area of Sri Lanka. Other stations such as Vavuniya (VVY), Anuradhapura (ANU), Polonnaruwa (POL), Kurunagala (KUR), Kandy (KAN), Kegalle (KEG), Nuwaraeliya (NUW), Badulla (BAD), Rathnapura (RAT) and Embilipitiya (EMB) are located in the middle of the country.

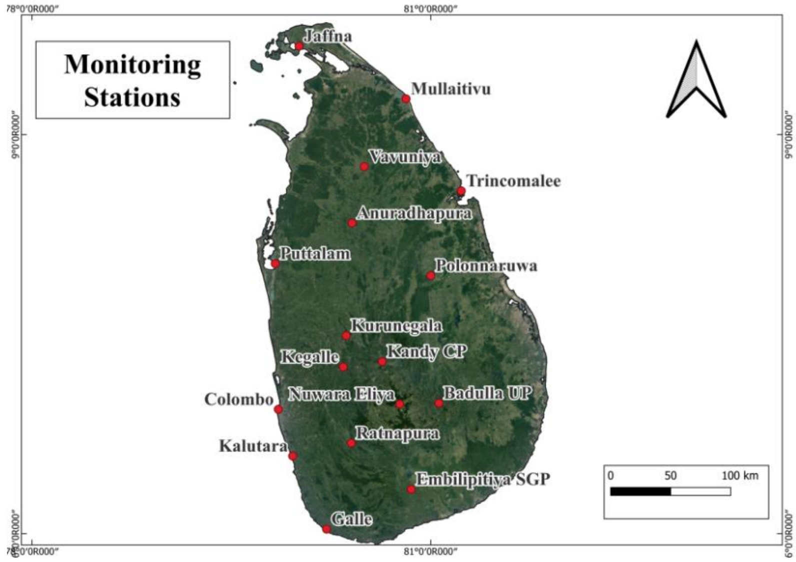

Figure 2.1: PM Monitoring Stations in Sri Lanka

2.2 Data Collection

2.2.1 Air Quality Data

24-hour average $PM_{2.5}$ and PM_{10} data for all the 17 locations over two year period (January 2021 – December 2022) were taken from National Building Research Organization (NBRO) (https://nbro.gov.lk/index.php?lang=en) which is a government organization in Sri Lanka. There are some blank days for monitoring PM concentrations due to the power failures and other unavoidable situations. For data screening, any negative values or when $PM_{2.5}/PM_{10}$ was more than 1was not considered. Also, if continuously more than 75% of data in a month was missing; monthly average value was not calculated.

2.2.2 Meteorological Data

CSV file of 24 hours daily mean values of meteorological parameters such as rainfall, mean temperature, wind speed and wind direction are freely available at https://www.kaggle.com/datasets/rasulmah/sri-lanka-weather-dataset?resource=download. It contained the information of 11 stations and for the remaining few stations, the information of the adjacent stations was considered for this study.

2.2.3 Population Data

Mid-year Population data for health risk assessment in different monitoring stations is calculated based on the Census of Population and Housing 2012 (Census and Statistics Department Sri Lanka, 2012).

2.3 Statistical Analysis

This study's statistical analysis was performed using R software (version 4.3.1). QGIS (version 3.32.1) was used to map the study area and compare annual mean PM concentrations. K-mean clustering was utilized to group the annual average PM concentrations with their associated monitoring sites.

2.4 CBPF Analysis

A Conditional Bivariate Probability Function (CBPF) analysis was used to investigate the effect of local emissions on measured PM concentrations at 17 monitoring stations. The CBPF figure includes wind speed as a third variable shown on the radial axis. This provides additional information about the kind of sources being recognized by providing essential dispersion characteristic information. CBPF is beneficial for understanding the amount to which sources have an impact, as it can provide a more full picture of how sites are influenced by a variety of sources. For example, if it is demonstrated that a significant point source can be detected considerably further away from its position than previously assumed, such information is useful in proving this. Isolating specific source types may also be advantageous in some cases, such as with thermal power plants (Uria-Tellaetxe & Carslaw, 2014). CBPF is accessible as part of the openair software package. The openair software is publicly downloadable as R package. R runs on Microsoft Windows, Linux, and Apple Mac systems. Openair does not require any additional hardware beyond a typical desktop PC.

2.5 AirQ +

The WHO Regional Office for Europe created AirQ+, a software tool for estimating the health burden and impact of air pollution. AirQ+ offers approaches for evaluating the effects of short- and long-term exposure to ambient air pollution. The major techniques rely on evidence from epidemiological cohort studies that reveal a link between average long-term air pollution concentration levels and mortality risks in exposed populations. An epidemiologist or an expert in air pollution effect assessment should always be consulted before using AirQ+. This software includes manuals with different levels of competence to help users with their analyses.

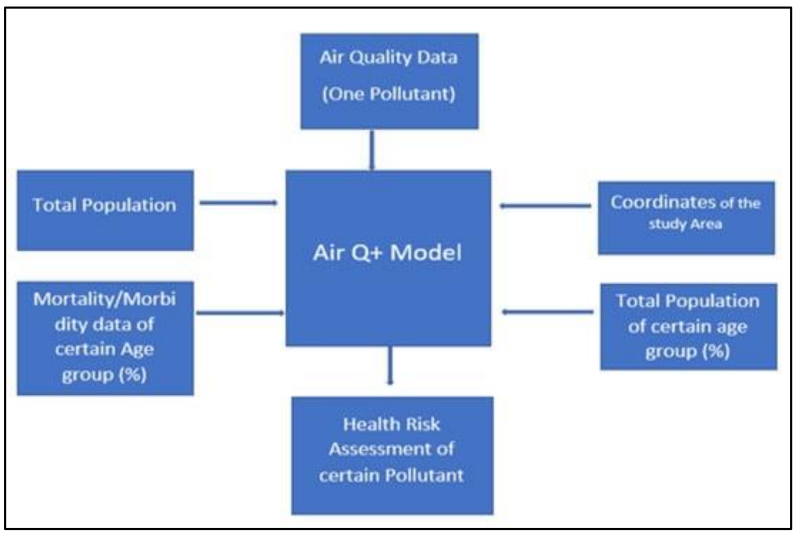

Figure 2.2: Input Data Required for AirQ+ Software (Nasir et al., 2022)

The AirQ+ software is intended to measure the health impact of air pollution on human health over time and in specific locations. The AirQ+ model bases all of its computations on concentration-response curves and methods derived from epidemiological studies. The AirQ+ computes the attributable proportion of cases, the number of attributable cases, the number of attributable cases per 100,000 people in the at-risk population, and the proportion of cases per category of air pollutant concentration based on baseline health outcomes, a cut-off value for consideration, and relative risk values. The following data are required for evaluating the short- and long-term effects: air quality data (frequency of days with specified pollutant concentration values), population at risk data, and health data such as baseline incidence of health outcomes, desired concentration cut-off values, and relative risk values if they differ from the default values provided by WHO.

For this study, to evaluate the associated health risks the software required the following factors: (i) annual $PM_{2.5}$ averages for the years 2021 and 2022 in 17 monitoring stations; (ii) the WHO's recommended cutoff values for annual $PM_{2.5}$ concentrations of 25 µg m^{-3} [GBD 2020 (integrated function 2019 – WHO 2021 Interim target-2)] ; and (iii) Information about the population at risk, including the total number of adults and children over the age of 25 and under 4 years (taken from the Census of Population and Housing 2012).

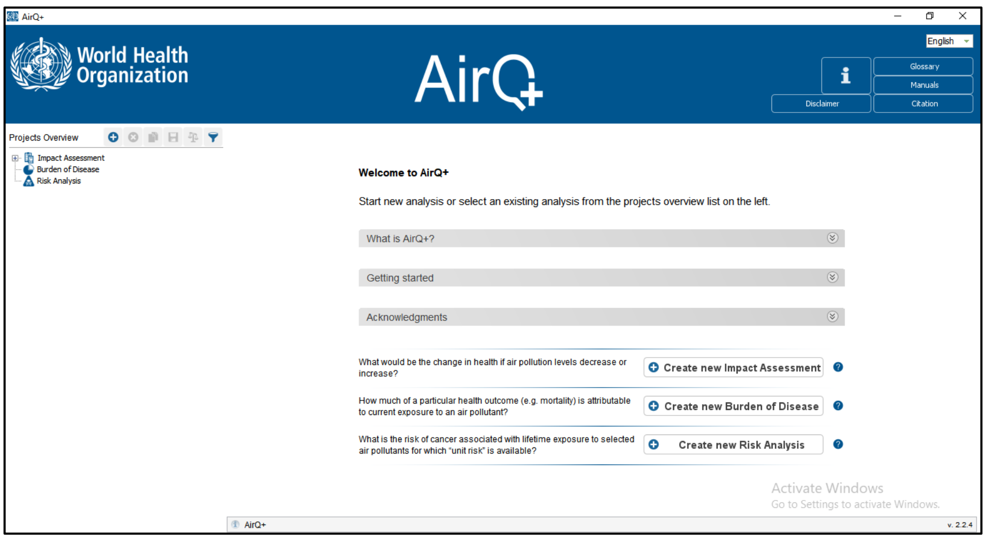

Figure 2.3: Welcome Window of AirQ+

Chapter III

RESULTS AND DISCUSSION

This section presents the findings and analysis of the study on air pollution in Sri Lanka, focusing on the seasonal trends of PM ($PM_{2.5}$ and PM_{10}) levels over 17 monitoring stations during two-year study period, distribution of PM over the time, the relationship with meteorological parameters, and health risks associated with $PM_{2.5}$ concentrations. This segment reveals valuable insights into the dynamics of air pollution in Sri Lanka and its implications for public health. The chapter begins with the annual statistical summary of both $PM_{2.5}$ and PM_{10} concentrations, which provides important insights into the distribution of PM levels in different monitoring stations in Sri Lanka during 2021 and 2022. Following that, the variation of 24-hr and monthly mean PM levels were analyzed over the study period. The chapter then analyzes the seasonal trend in PM levels in Sri Lanka, which is impacted by meteorological circumstances, human activity, and spatial variability. After seasonal variations, meteorological parameters such as rainfall, temperature, and wind speed have been analyzed to explain further the reason for seasonal variation of PM. Then CBPF plots were designed to discover the potential source regions in different monitoring stations and finally health risk assessment was done using the calculations from AirQ+ software tool.

3.1 Annual Statistical Summary of $PM_{2.5}$ and PM_{10} concentrations

24 hour mean $PM_{2.5}$ and PM_{10} data were obtained from 1st January 2021 to 31st December 2022 from 17 stations placed in all over Sri Lanka. Considering the annual

average PM values, these 17 stations were clustered into different groups using K-mean clustering method. This clustering indicated proper behavior of PM values across the country throughout the study time period. The statistical summary of $PM_{2.5}$ and PM_{10} throughout the 2 year period for all the stations is presented in Table 3.1 and Table 3.2 respectively.

Fig. 3.1 revealed that in 2021, $PM_{2.5}$ values varied below 25µgm^{-3}, the standard $PM_{2.5}$ level in Sri Lanka. With reference to the Table 1, annual maximum average of $PM_{2.5}$ was measured in Kurunegala which is 21.4±7.8 µgm^{-3}. According to Fig. 3.1, in 2022, highest annual mean concentration was in Jaffna (29.9±19.4 µgm^{-3}) and minimum value was in Nuwara Eliya (12.2±5.2µgm^{-3}). As reported by Table 3.1, the annual mean $PM_{2.5}$ levels in the stations such as Colombo, Jaffna, Kurunegala, Vavuniya and Puttalama had exceeded SLAQ guidelines in 2022.

Table 3.1: Descriptive Statistics of $PM_{2.5}$ at 17 Stations in 2021 and 2022. N Stands for the Number of Available Data per Year and Min (Minimum), Max (Maximum), Median, Mean, Q1 (first quartile), Q3, and SD (Standard Deviation) Values were Mentioned in µgm^{-3}.

Station	2021								2022							
	N	Min	Max	Median	Mean	Q1	Q3	SD	N	Min	Max	Median	Mean	Q1	Q3	SD
CMB	352	6	76.6	16	19	12	22.2	10.1	360	3.9	87	23	25.04	12	35	14.6
JFN	360	6	58	16	17.8	12	21	8.8	360	5	139	26	29.9	15	42	19.4
ANR	360	6	52	14	14.8	10	17.7	6.7	268	4	55	14.8	18.2	10	23.3	11.1
KUR	360	7	53	21	21.4	16	25.4	7.8	331	7	102	25	26.1	18	33	12.1
VVY	360	6	51	15.9	17.4	12	19.1	8.5	301	6	88	22	25.8	17	31	13.7
KAN	360	6	44	18	19.6	12	26	9	360	5.7	75	21	22.7	14.3	30	10.6
KEG	360	6	53	19.9	20.2	14	24	8.3	339	7	90.6	23	23.8	15	29	11.9
GAL	360	5	38	15	16.9	11.3	22	7.2	303	5	63	20.9	21.2	15	27	9
NUW	360	3	28	8	8.7	6	10	3.8	337	4	33	11	12.2	9	15	5.2
RAT	360	5	43	14.5	16.3	12	19	6.9	358	4	56	20	20.4	13	26	10
EMB	360	7	43.7	16	16.6	12	19	6.4	350	4.3	57	20	19.9	12	26	9.2
PUT	360	7	53	18	18.8	14	22	7.4	347	5	83	26	26.7	15	34.5	14
TRI	360	4	50	14	15.5	11	17	6.8	349	4	81	16	18.8	10	25	12
POL	360	3.2	36	11	12.2	9	14	5	344	4	90	17	19.1	10	25	10.9
BAD	236	5	35	14.6	15.3	11	19	5.6	329	5	68.8	21	24.1	12	33	14.6

MUL	359	-	-	-	-	-	-	-	343	4	79	17	20.8	9	29.5	14.5
KAL	272	-	-	-	-	-	-	-	358	2.8	53	18	19.3	12	25	9.6
SLAQS = 25μgm^{-3} (Chandrasiri, 2021) **WHO Guidelines = 5μgm^{-3}** (World Health Organization, 2021)																

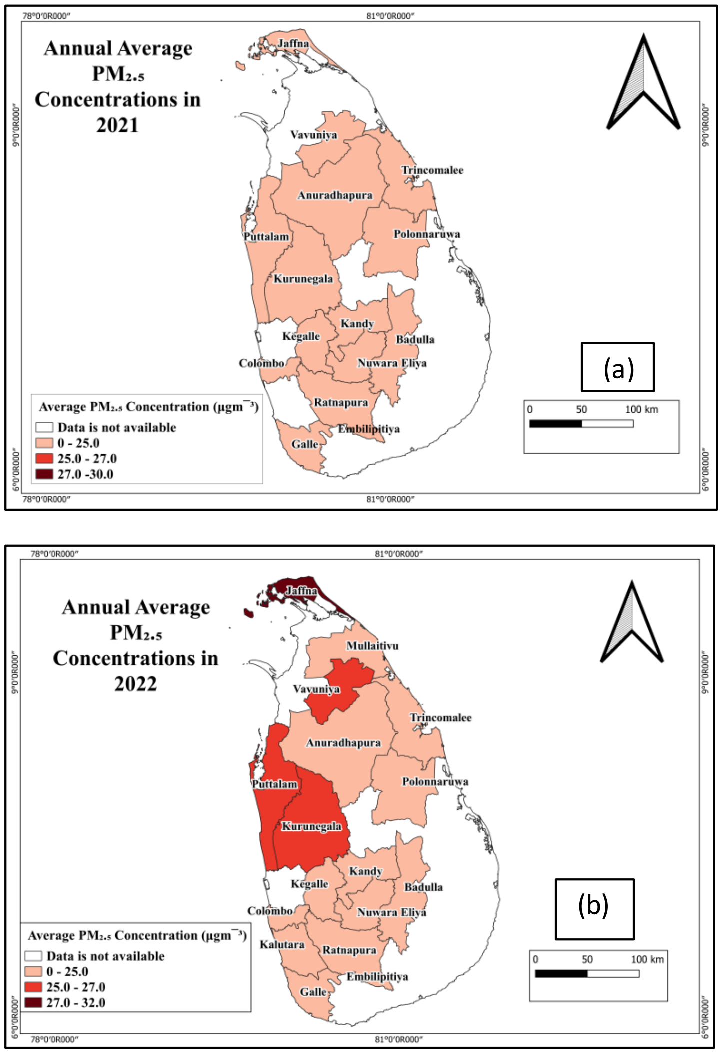

Figure 3.1: Annual Average $PM_{2.5}$ Concentrations in 2021(a) and 2022 (b)

Comparing average mean concentrations in both years there was an increase of PM_{10} levels in 2022 than in 2021(Table 3.2). None of stations did not exceed SLAQS which was 50μgm^{-3} in 2021 while Jaffna (55.8±37.8μgm^{-3}) and Vavuniya (54.3±31.0μgm^{-3}) stations showed the annual average PM_{10} levels higher than SLAQS in 2022. As same as $PM_{2.5}$

concentrations, Nuwaraeliya had the minimum average PM_{10} levels during both study years. (15.3±7.4µgm^{-3} and 20.1±10.2µgm^{-3} respectively) (Table 3.2, Fig 3.2)

Table 3.2: Descriptive Statistics of PM_{10} in 17 Stations in 2021 and 2022. N Stands for the Number of Available Data per Year and Min (Minimum), Max (Maximum), Median, Mean, Q1 (first quartile), Q3, and SD (Standard Deviation) Values were Mentioned in µgm^{-3}.

Station	2021								2022							
	N	Min	Max	Median	Mean	Q1	Q3	SD	N	Min	Max	Median	Mean	Q1	Q3	SD
CMB	352	10.2	106.4	32	35.9	23	42.9	17.7	360	6.5	152	33.9	40.5	19.3	56.4	26.6
JFN	360	9	110	29	32.9	21.4	41.1	16.7	360	7.1	264.1	50.7	55.8	26	77.5	37.8
ANR	359	5	93.6	24	26	17.3	31	12.5	285	9	110	26	32	18	39.6	19.3
KUR	360	12	103	40.9	41.1	31.4	50.2	14.8	330	12	161	46	46.5	30.2	57.9	22.4
VVY	360	11	95.9	29	31.9	22	36.5	15.2	301	11	152	45.9	54.3	30	80	31
KAN	360	11	81	33.9	35.3	22	45.8	16.1	353	9.4	142.5	34.7	38.1	22	49.4	21.3
KEG	360	0	104	37.4	37.3	27.7	46	14.7	339	12	156	41.8	43.5	23	56	23.8
GAL	360	9	96.2	28.4	30.7	21	37.4	14	281	12	117	35.1	38.6	25	49	18.1
NUW	360	4	44.8	13.3	15.3	10	18	7.4	337	6	55	18	20.1	13	23.8	10.2
RAT	359	9	80.8	25.6	29	20.4	34.2	12.9	358	7	111	32	35.1	21	45	19.1
EMB	360	12	74.3	29.8	30.6	23	36	10.9	350	6.9	12	32	34.2	20.7	45.6	17.1
PUT	360	13	92.8	33.7	34.8	25.4	42	12.6	347	8	154	44.1	48.9	25.9	68.8	27.3
TRI	236	9	103	23.2	27.3	19	31.3	14	349	6	153.9	28	34.4	16	49	23.2
POL	359	9.8	56	20.8	22.5	16.9	26	8.3	356	5	153	30.7	34.2	18	44.1	20.5
BAD	236	9	57.6	24	26.1	19	31	9.7	329	7.1	123.5	36.7	43.7	20.6	56.4	27.8
MUL	--	-	-	-	-	-	-	-	343	7	145	28	37.2	15	55.5	27.9
KAL	-	-	-	-	-	-	-	--	355	8	100.7	31	34.6	21	44	16.8
SLAQS = 50µgm^{-3} (Chandrasiri, 2021) **WHO Guidelines = 15µgm^{-3}** (World Health Organization, 2021)																

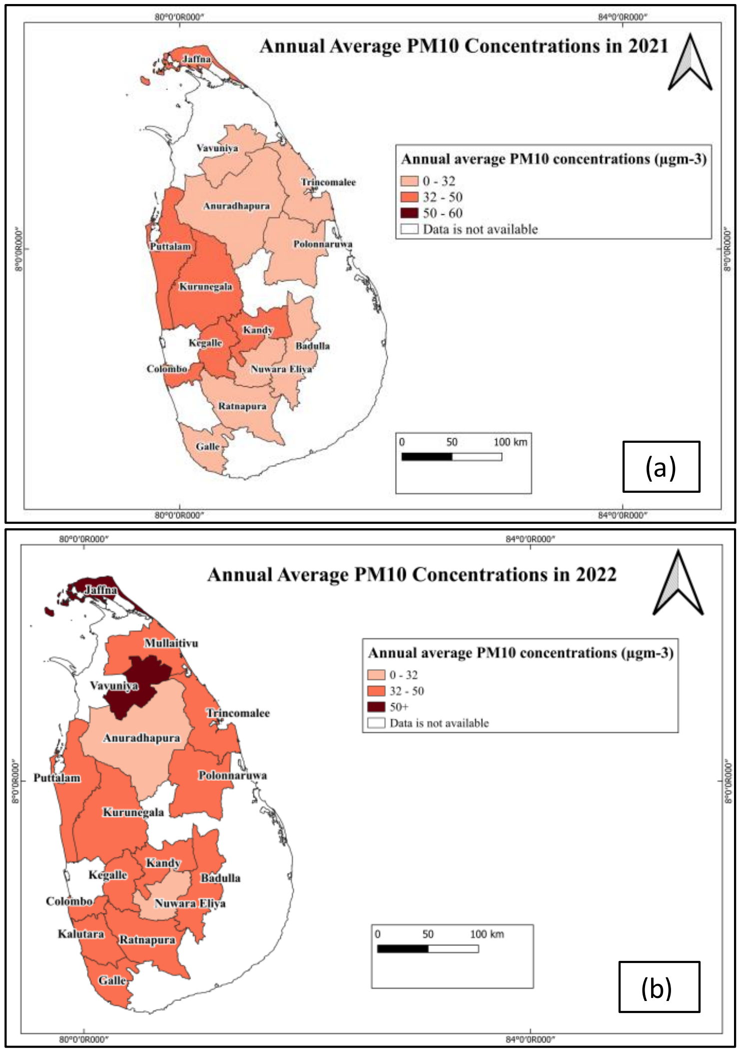

Figure 3.2: Annual Average PM_{10} Concentrations in 2021 (a) and 2022 (b)

3.2 Monthly and Daily variation of PM Concentrations

According to the geographical location, monitoring stations such as Colombo, Kalutara, Galle, Trincomalee, Mullativue, Jaffna and Puttalam were located in the coastal area around Sri Lanka and remain locations such as Vavuniya, Anuradhapura, Polonnaruwa, Kurunegala, Kandy, Kegalle, Nuwaraeliya, Badulla, Rathnapura and Embilipitiya were located inside the country. Vavuniya, Anuradhapura, Polonnaruwa and Kurunagala were lying within the dry zone of Sri Lanka while experienced relatively low rainfall compared to the wetter region of the country. The terrain in these places was mostly flat or moderately rolling, with large plains and some minor hills. Kandy, Kegalle, Nuwaraeliya and Badulla were categorized by steep and hilly topography, with heights ranging from mild hills to tall peaks and have colder temperatures than Sri Lanka's lowlands since they were higher up. Both Ratnapura and Embilipitiya were located near important river systems, such as the Kalu Ganga (Black River) and its tributaries. While not as mountainous as other parts of Sri Lanka, these two had hilly topography with undulating landscapes and occasional tiny hills.

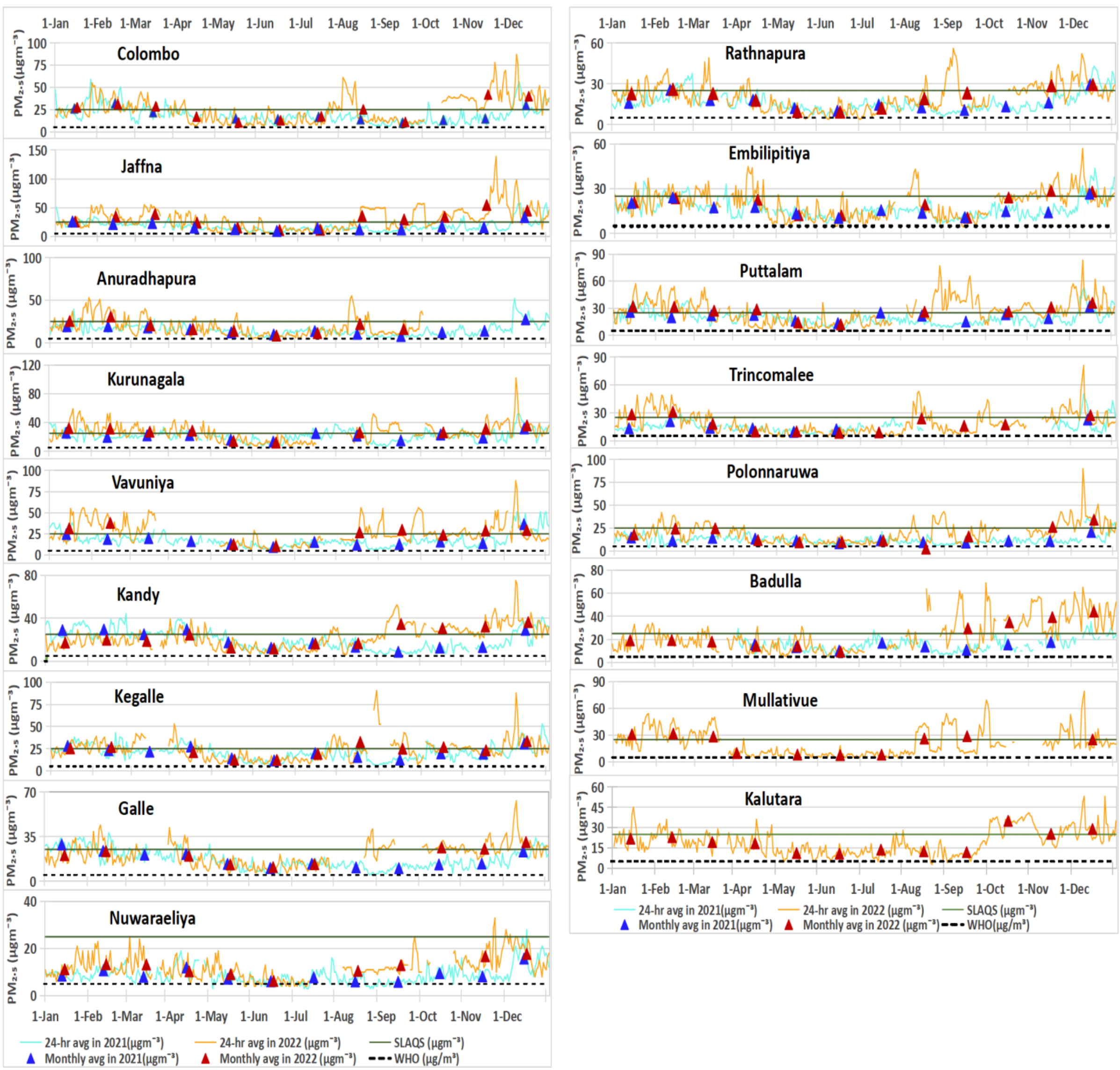

Figure 3.3: 24-hour Daily and Monthly Average $PM_{2.5}$ Concentration Variations at Different Monitoring Stations

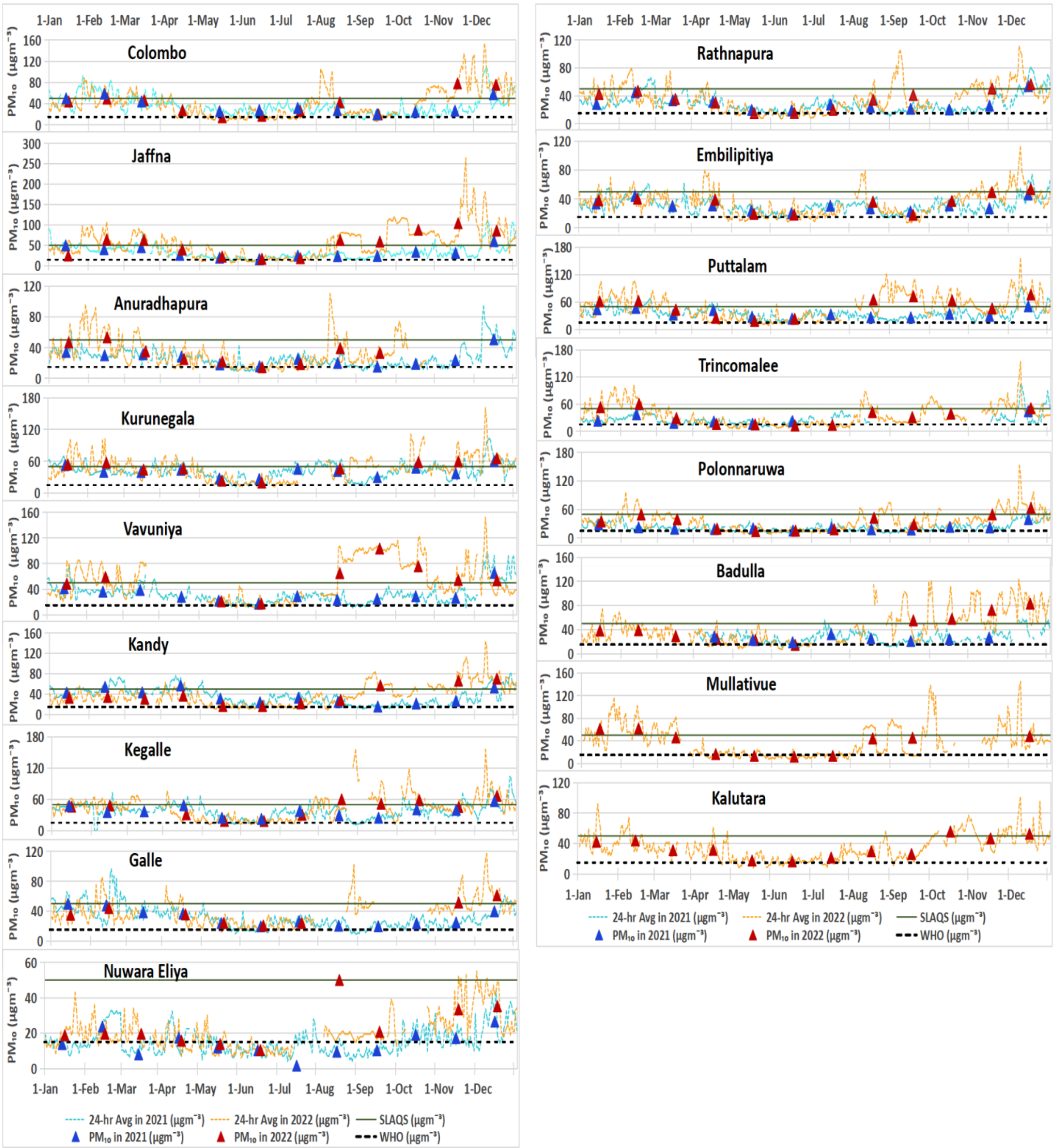

Figure 3.4: 24-hour Daily and Monthly Average PM_{10} Concentration Variations at Different Monitoring Stations

Fig. 3.3 and 3.4 indicated that variation of 24-hour and monthly average PM concentrations at 17 locations over 2 year period compared to the SLAQS and WHO guidelines. Colombo, Sri Lanka's capital city served as the country's economic, cultural, and political hub and was located on the island's western coast. During first three months of both years daily $PM_{2.5}$ concentrations (Fig. 3.3) were varying above the SLAQS (25µgm^{-3}) and in April pollutant level decreased. From April to November 2021, $PM_{2.5}$ concentration was fluctuating near the standard condition. But, in 2022, pollutant level had a growth from mid-July to mid-August and again from October to December. PM_{10} variation (Fig 3.4) of Colombo in 2021 and 2022 displayed higher values than permissible limit (50µgm^{-3}) in February, March, August, November and December. December 2022, Colombo experienced the highest PM_{10} concentrations.

Jaffna, situated at the northern tip of Sri Lanka, showed a rise of $PM_{2.5}$ and PM_{10} levels in 2022 than in 2021. PM levels crossed the SLAQS during February, March, August, October, November and December in both years. May, June and July included lowest PM concentrations. Anuradhapura, located in the North Central Province of Sri Lanka which was renowned for its magnificent archaeological sites. There PM levels were differing within the standard value except in December, 2021 and both $PM_{2.5}$ and PM_{10} concentrations were exceeding the safe limit during February and March in 2022. (PM data in Nov and Dec, 2022 is not available) Meanwhile Kurunagala, which was located in North Central province of Sri Lanka, exhibited a growth of $PM_{2.5}$ levels throughout the study period except May, June, and July. Furthermore, PM_{10} levels in both years showed increased concentrations during Jan, Feb, Oct, Nov and Dec.

Vavuniya, located in the Northern Province of Sri Lanka, situated at the crossroads of the island's northern and central regions. Even though in 2021, Vavuniya faced an increase PM amount during Jan and Dec months, Jan-Mar and Sep- Dec periods exceeded the standard PM limits in 2022. Kandy was nestled amidst the hills of Sri Lanka's central highlands. This station illustrated elevated $PM_{2.5}$ concentrations in Jan-March period during the study period. May-Sep period had pollutant level within SLAQ guidelines. During Sep-Nov in 2021, $PM_{2.5}$ concentrations were less and pollutant level was varying above the standard level in the same period of 2022. But there was an increase in PM_{10} concentrations only in mid-August and Dec in both years. $PM_{2.5}$ concentrations at Kegalle which was a city neighboring to Kandy was exceeding the permissible level during Jan-April and then it started to begin differ in between the standard value until Aug. In 2021 from Aug to Nov it remained same and again in December pollutant level rose. But in 2022, most of the time between Sep-Dec months showed the higher $PM_{2.5}$ values than 25µgm^{-3}. According to the PM_{10} variation, from Apr to Nov Kegalle had pollutant level less than permissible limit and only in Dec it exceeded the limit.

Galle, located in down south of the island showed maximum $PM_{2.5}$ concentrations during Jan, Feb and Dec in both years and in 2022, from Sep to Nov it also had monitored increased $PM_{2.5}$ values. According to the PM_{10} levels, maximum values had been indicated during the months like Feb, Sep, Nov and in Dec. From May to Aug both pollutant concentrations were under the safe limit. Nuwaraeliya was a hill station surrounded by central highlands of Sri Lanka and having a cold climate comparing to other stations. This station was facing lower PM_{10} levels throughout the whole study period except 4 days during Nov and Dec in 2022. $PM_{2.5}$ in 2021 was differing as same as PM_{10} and pollutant level increased during Dec only. But in 2022, there could be seen an increasing of $PM_{2.5}$ levels during Feb, March, Oct, Nov and Dec. In 2021, Rathnapura was experiencing elevated PM concentrations during Feb and Dec. But in 2022, both pollutant levels exceeded the permissible limits during Jan-March, a sudden increase in Sep and again Nov-Dec. Embilipitiya was located approximately 169km southeast of Colombo, was experiencing increased $PM_{2.5}$ concentrations in Jan-Apr and Oct-Dec periods. On the other hand, there was a peak of $PM_{2.5}$ in August 2022. PM_{10} concentrations decreased during 2021 except some days in March and Dec. But in 2022, Jan, Feb, Apr, Nov and Dec had higher concentrations than 50µgm^{-3}.

Puttalam was located in northwestern region. There was an increase of PM levels from Jan-Feb and then less PM levels during Mar-Nov and again an increase in Dec, 2021. PM levels were growing during Jan-Mar, Sep-Dec and PM levels remained closer to SLAQ guidelines in Apr-Aug. Trincomalee which was on northeast coast of the island monitored PM levels more than standard limits during Feb and Dec in both years. Jan, Feb, Aug, Oct, Nov and Dec 2022 had their maximum PM levels. Polonnaruwa, situated in north central province, was experiencing PM concentrations below the safe level in 2021. In 2022, this stations detected PM levels more than USEPA guidelines during Jan-March and Aug-Dec. Badulla was also a hilly region having a cold and dry climate throughout the year than other stations. Here, Jan-March 24 hour daily PM concentrations in 2021 were not available and after analyzing remaining data, both pollutant levels were not exceeding the safe limit except $PM_{2.5}$ in December. Likewise in 2022, while peak $PM_{2.5}$ amounts observed in Jan-Mar and Aug-Dec, elevated PM_{10} values were reported from Aug-Dec only. PM data of Mullativue and Kalutara in 2021 were not available in the dataset. In Mullativue, PM concentrations were exceeding the permissible limits during Jan-March and Aug-Dec, while having lesser pollutant levels from April to July in 2022. Considering Kalutara's PM data variation in 2022, Jan, Feb, Oct-Dec months were experiencing peak PM levels.

Studying the behavior of 24-hr and monthly mean $PM_{2.5}$ and PM_{10} levels represents that maximum pollutant levels were occurring during Jan, Feb, Nov and Dec while minimum pollutant amount were monitored from April to July during the study period at all locations. Further, all monitoring stations experienced PM levels higher than WHO guidelines during both years.

3.3 Seasonal PM Variation

Boxplots were prepared for the data from various locations in Sri Lanka to illustrate the pollutant dispersion patterns during North-East Monsoon, First Inter-Monsoon, South-West Monsoon and Second Inter-Monsoon seasons in 2021 and 2022 (Fig 3.5). Boxplots for Mullativue and Kalutara in 2021 were not available since data were missing.

According to seasonal fluctuations in PM concentrations at various monitoring stations between 2021 and 2022, highest pollutant concentrations were detected during the Northeast monsoon, which lasted from December to February. The NEM brought moderate rainfall to Sri Lanka's north and east regions. PM levels in these places varied, but cooler temperatures and less precipitation than in the SWM could lead to higher pollution levels, particularly from heating and cooking. Pollution dispersal might be limited during the NEM season because to wind patterns and lower atmospheric mixing heights. This could result in increased concentrations of PM in specific areas, particularly in metropolitan areas such as Colombo, Kurunagala, Kandy and Galle where pollution sources such as car emissions and industrial activity were common. Additionally, lower temperatures during the NEM season could cause temperature inversions, in which a layer of warmer air retains pollutants near to the ground. This phenomenon increased the PM levels, resulting in poorer air quality. Furthermore, NEM can potentially carry transboundary pollutants from other locations. According to research, during this time, air masses might transport pollution from the Indian subcontinent, resulting to higher PM levels in Sri Lanka (Shelton et al., 2022).

Fig. 3.5 indicated less PM concentrations during FIM season and the reason for that could be described by analyzing various climatic factors. The FIM period (March to April) was characterized by transitional weather, with NEM winds tapering off and the SWM not yet underway. The FIM season was characterized by thunderstorms and convectional rains, which could temporarily decrease PM levels by washing pollutants out of the atmosphere. However, the FIM season also included periods of dry and very calm weather, which could lead to spikes in PM concentrations, especially in urban and industrial regions. During these dry spells, the absence of wind lead to poor dispersion of pollutants, resulting in localized increases in PM levels. Furthermore, human activities such as increased vehicle use, construction work, and biomass burning for agricultural purposes could all contribute to elevated PM levels at this time. During the FIM season, crop wastes and other biomass were commonly burned in rural and agricultural areas like Jaffna, Anuradhapura, Vavuniya, and Polonnaruwa, caused an increase in PM pollution. Weather patterns that alternate between wet and dry conditions offered a dynamic setting for PM pollution and dispersion. Overall, the FIM season's impact on PM pollution in Sri Lanka was a complicated interaction of climatic circumstances and human activity that causes changes in air quality. Studies have proven that monitoring and controlling PM pollution during this period is critical for public health, particularly in metropolitan areas where pollution sources are concentrated (Alahacoon & Edirisinghe, 2021) .

The least PM pollution occurred during SWM season which is from May to September (Fig. 3.5). During the SWM, strong winds from the Indian Ocean brought moist air to Sri Lanka's southwestern region, resulting in increased rainfall and humidity. These conditions often contributed to lower PM concentrations because rain tends to wipe off airborne particles. Monsoon winds also helped to disperse contaminants by increasing air mixing and transportation away from source sites. The SWM season often improves air quality in Sri Lanka as a result of greater precipitation, higher wind-driven dispersion, and the entrance of cleaner ocean air (Shelton et al., 2022).

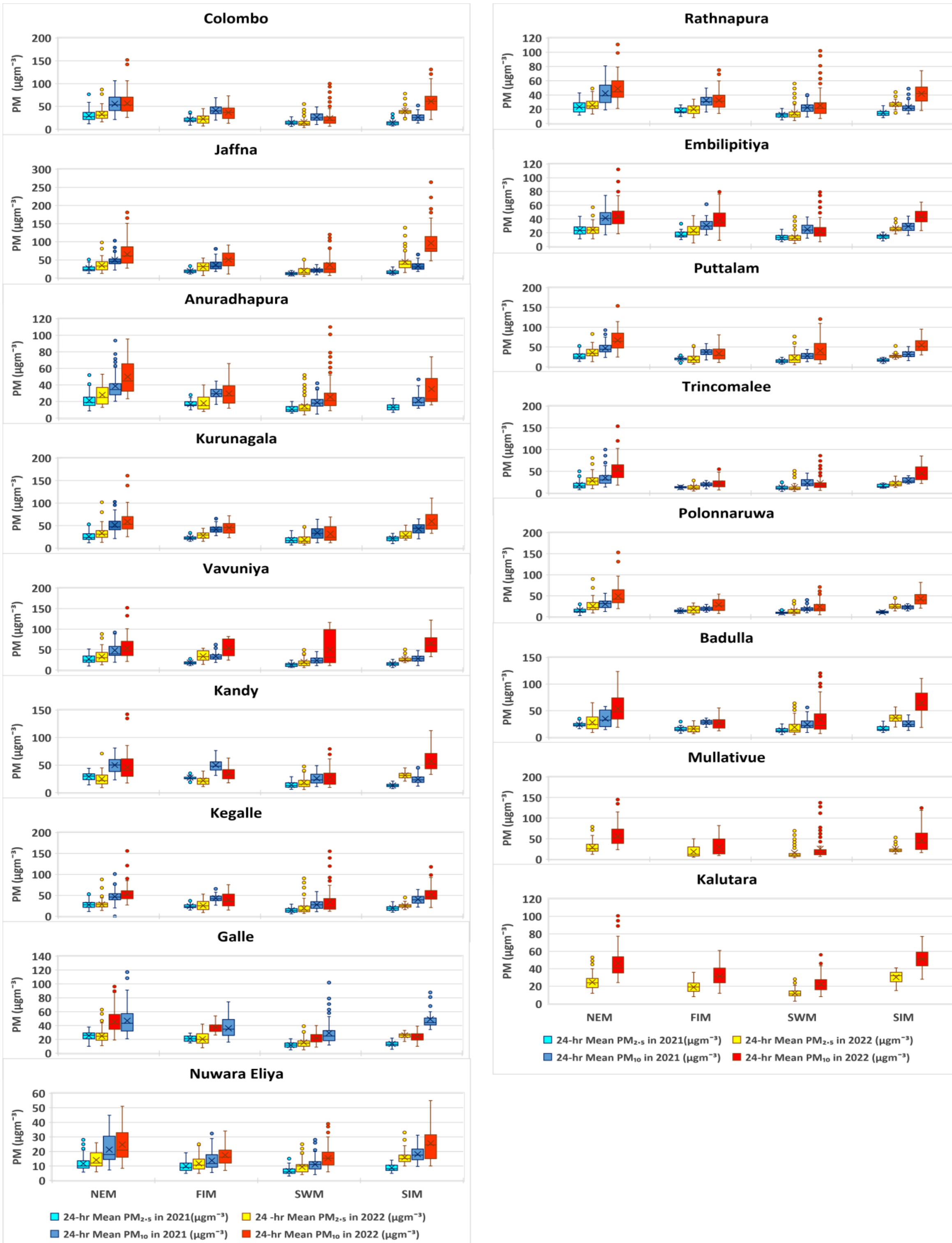
Colombo
Jaffna
Anuradhapura
Kurunagala
Vavuniya
Kandy
Kegalle
Galle
Nuwara Eliya
Rathnapura
Embilipitiya
Puttalam
Trincomalee
Polonnaruwa
Badulla
Mullativue
Kalutara
PM (μgm^{-3})
NEM
FIM
SWM
SIM
24-hr Mean $PM_{2.5}$ in 2021(μgm^{-3})
24 -hr Mean $PM_{2.5}$ in 2022 (μgm^{-3})
24-hr Mean PM_{10} in 2021 (μgm^{-3})
24-hr Mean PM_{10} in 2022 (μgm^{-3})

Figure 3.5: Seasonal Variation of PM Concentrations in 4 Main Seasons (NEM – Northeast monsoon (Dec-Feb), FIM – First inter-monsoon (Mar-Apr), SWM – Southwest monsoon (May-Sep) and SIM – Second inter-monsoon (Oct-Nov))

SIM, like the FIM, includes both rainy and dry days. While rain helped to reduce PM levels, dry spells and human activities such as building and vehicular traffic can cause temporary spikes in pollution. The increased rainfalls during the SIM lead in the elimination of airborne particulates by wet deposition. Rain effectively removed contaminants from the environment, providing a temporary improvement in air quality. This cleansing effect was most visible in metropolitan settings, where pollutant concentrations are typically higher due to automobile and industrial emissions. Furthermore, the atmospheric conditions throughout this season were marked by comparatively calm winds in comparison to the greater monsoonal seasons. This leads to less efficient dispersion of pollutants, perhaps leading in greater PM concentrations in certain locations on days with little rainfall. However, frequent rain showers typically reduced this effect by continuously eliminating pollutants from the air (Rohan Gunasekara, 2020).

3.4 Effects of Meteorological Parameters

Through this study the reason for the behavior of PM was analyzed by using meteorological variables such as rainfall, temperature and wind speed (Fig. 3.6). Since dataset provided data for only 11 stations, Kandy station's data for Kegalle, Trincomalee's data for Mullativue and Vavuniya, Rathnaputa's data for Embilipitiya and Puttalam's data for Anuradhapura and Polonnaruwa had been used because of their geographical similarities.

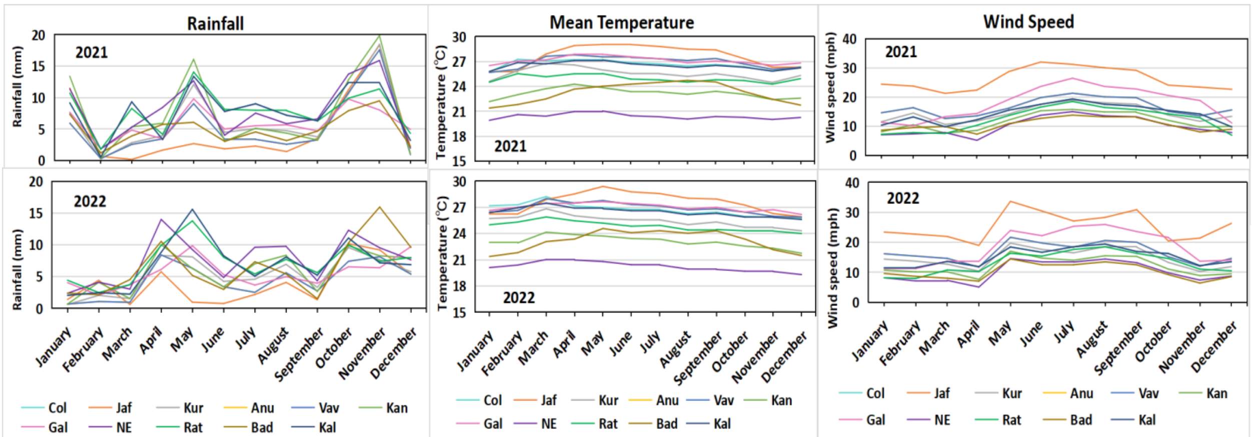

Figure 3.6: Monthly Averages of Meteorological Parameters in Different Monitoring Stations (Col – Colombo, Jaf – Jaffna, Kur – Kurunagala, Anu – Anuradhapura, Vav – Vavuniya, Kan – Kandy, Gal – Galle, NE – Nuwaraeliya, Rat – Rathnapura, Bad – Badulla, and Kal – Kalutara)

In 2021, while Jan, May, Oct and Nov months were experiencing a maximum rainfall, Feb and Dec months were showing a minimum rainfall. Likewise, in 2022, April, May and Nov had the highest and Jan, Feb and March had the lowest rainfall. The monitoring station which was experiencing the lowest rainfall during both years was Jaffna. Monthly average rainfall was fluctuating between 0-20 mm during 2021, while rainfall was varying between 0-15mm in 2022 (Fig 12).

Monthly average temperature at all the monitoring stations was lying between 18 - 30ºC during the study period. Both beginning and end of the year had marked less mean temperature than mid-year. During both years Kandy, Kegalle, Badulla and Nuwaraeliya had cold weather while Jaffna is marking the highest temperature from March to October. Highest monthly average temperature in both years was monitored in Jaffna during June month which were 29.5ºC in 2021 and 29.3ºC in 2022.

On the other hand, wind speed variation differed as a same pattern throughout the study period except Jaffna which was a reduction of wind speed from Jan to April, a climb from Apr to July, and again decrease from July to Dec. But Jaffna in 2022 exhibited a difference of the pattern which was, while April and Oct months were experiencing lowest wind speed, May and Sep had the maximum wind speed. Jaffna marked the highest wind speeds during both years. When analyzing these meteorological parameters with PM variation it could be explained that these parameters caused to the dispersion of pollutant through the air and resulting highest PM concentrations in Jaffna in both 2021 and 2022. Furthermore, increased wind speed could be a reason for the transboundary air pollution and travelling pollutant into the country.

This study found that the combination of rainfall, temperature, and wind speed causes large seasonal fluctuations in PM levels. For example, the SWM's copious rains and strong winds often resulted in the lowest PM concentrations during the study period, but the FIM period was drier and calmer, resulting in higher PM levels. The effect of various climatic conditions on PM dispersion varies geographically. Urban areas with higher emissions were more affected by weather changes than rural areas. Coastal districts benefited from sea breezes, which improved pollutant dispersion, whereas inland places may have higher pollution levels due to limited ventilation. To summarize, meteorological parameters such as rainfall, temperature, and wind speed have a considerable impact on the dispersion and concentration of particulate matter in Sri Lanka. Understanding these linkages is critical for successful air quality management and reducing the health consequences of air pollution across seasons and locations.

3.5 Role of Local Wind Speed and Wind Direction

Seasonal CBPF plots for the nine monitoring stations for $PM_{2.5}$ (Fig.3.7) and PM_{10} (Fig.3.8) were created using the PM concentrations above 75th percentile for northeast monsoon, southwest monsoon and second inter-monsoon seasons. The fourth season (first inter-monsoon) showed the PM concentrations lower than SLAQS in both years, thus was not considered. Also, the meteorological data for only 9 monitoring stations was available for both years, thus only those nine stations were considered for this analysis. The 75^{th} percentile was chosen as this will assist in understanding the role of emission sources toward high PM concentration at the stations.

During northeast monsoon, the high $PM_{2.5}$ concentration (Fig.3.7) at Kurunagala, Kandy, Nuwara Eliya, Rathnapura and Puttalam, occurred at low wind speed (10-20 mph) from SE and SW, indicating the potential sources to be closed to the monitoring site and within the city. Potential sources in these areas could be motor vehicles (in Kandy, Kurunagala), biomass burning (in all sites), textile units (in Kandy, Kurunagala, Rathnapura), cement manufacturing plants (in Puttalam) and coal fired power plant (in Puttalam). For other stations Colombo, Jaffna, Vavuniya, and Galle the high $PM_{2.5}$ concentration was experienced at high wind speed (25-50 mph) from E, SE, SW indicated cross boundary pollution or stack emissions rather than the non-buoyant ground-level sources. Likewise, the high PM_{10} concentration (Fig.14) at Kurunagala, Kandy, Nuwara Eliya, Rathnapura and Puttalam, occurred at low wind speed (10-20 mph) from S, SE and SW. For remaining stations high PM_{10} concentrations occurred at 25-50 mph high wind speed from N, E, SE and SW.

During the southwest monsoon season, Kurunagala, Vavuniya, Kandy, and Nuwara Eliya experienced the high $PM_{2.5}$ concentrations at low wind speed (10-20 mph) from SW, SE and NE while other stations (Colombo, Jaffna, Galle and Rathnapura) occurred high $PM_{2.5}$ at 25-50 mph high wind speed. Conversely, Puttalam had high $PM_{2.5}$ concentrations both at high wind speed (30 mph) from SW and low ws (10 mph) from SE which means not only there were some ground-level emissions close to the monitoring stations, but also some stack emissions such as coal fired power plants were happening. High PM_{10} concentrations in Kurunagala, Kandy and Nuwara Eliya occurred at 10-25 mph low wind speed from SW and N. Likewise, Colombo, Jaffna, Vavuniya, Galle, Rathnapura and Puttalam stations exhibited high PM_{10} at high wind speed (25-50 mph) from S, SW and NW. During this season Kandy had high PM concentrations at lowest wind speed and this illustrated the influence of ground-based sources like vehicular emission, biomass burning and local dust emanating from the construction sites or unpaved roads.

During second inter-monsoon, the high $PM_{2.5}$ concentrations at Colombo, Kurunagala, Kandy, Nuwara Eliya, Rathnapura and Puttalam occurred at 10-20 mph low wind speed from E, NE, SE and SW. Meanwhile, remaining 3 monitoring stations (Jaffna, Vavuniya and Galle) experienced high $PM_{2.5}$ at 25-35 mph high wind speeds from E, NE, SE and SW directions. In contrast, Colombo, Kandy, Nuwara Eliya and Rathnapura exhibited high PM_{10} concentrations at low wind speed (10-20 mph) from E and NE. Kurunagala, Vavuniya and Puttalam experienced high wind speed 25-40 mph from SW which indicated the influence of stack emissions in these areas.

Overall, CBPF maps showed that the sources affecting the nine sites varied in wind speed and direction. The CBPF provides a good image of local source directions, but it may not accurately depict episodic episodes related to transboundary pollution.

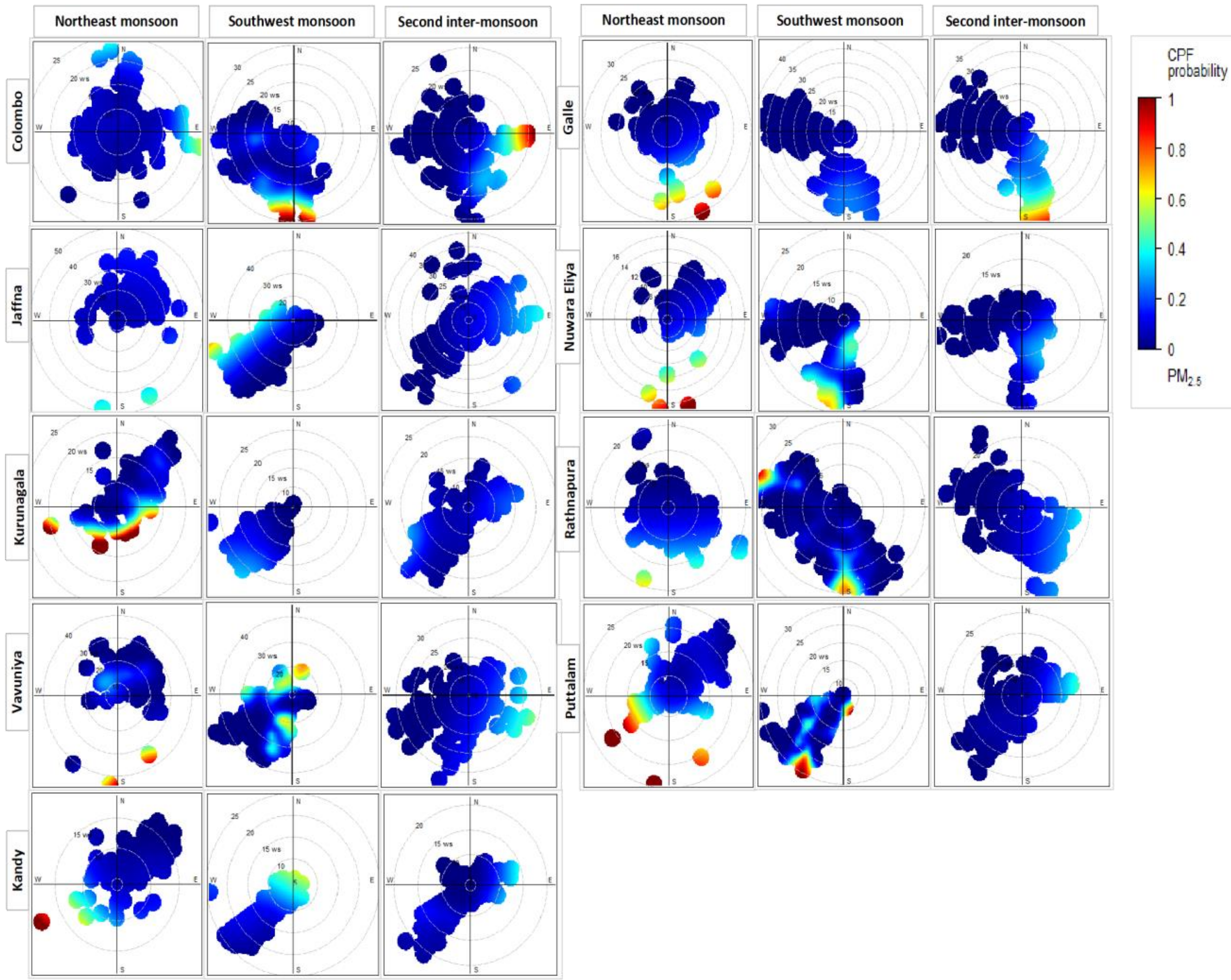

Figure 3.7: $PM_{2.5}$ CBPF Plots at the 9 Monitoring Stations for Three Seasons

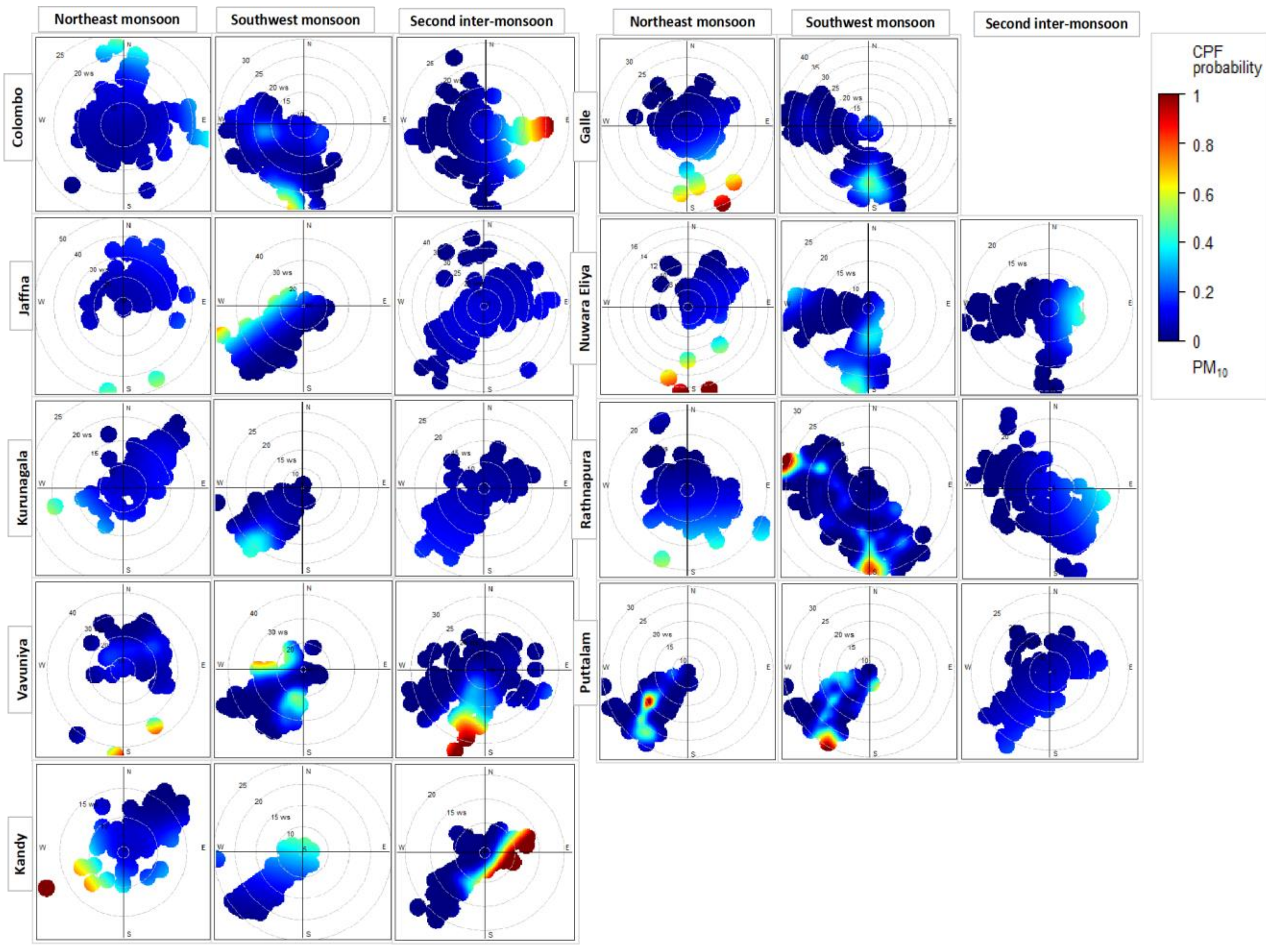

Figure 3.8: PM_{10} CBPF Plots at the 9 Monitoring Stations for Three Seasons

3.6 Long-term Health Risk Assessment

Health risk assessment of PM pollution is critical for protecting human health and informing environmental policy. Particularly tiny particles like $PM_{2.5}$ can penetrate deep into the lungs and even enter the bloodstream, causing a variety of negative health impacts including respiratory and cardiovascular disease, worsened asthma, and early mortality. Assessing the health hazards associated with PM pollution enables scientists and policymakers to better understand the level of exposure and its possible effects on various population groups, particularly vulnerable persons like children, the elderly, and those with pre-existing health disorders. This assessment serves as the foundation for developing air quality standards, guiding regulatory measures, and implementing effective mitigation techniques to minimize pollution and safeguard community health. Furthermore, it allows public health professionals to communicate dangers to the public and advocate for healthier, cleaner settings, resulting in a higher quality of life and lower medical expenditures.

AirQ software is utilized to evaluate the estimated number of attributable cases and attributable proportion of mortality due to lung cancer (LC) and chronic obstructive pulmonary disease (COPD) in adults (>25 years) and acute lower respiratory disease (ALRI) in children (0 – 5 years) for the districts which cross the safe limit of annual mean $PM_{2.5}$. Population data of each and every district were taken from the Census of Population and Housing 2012. (Census and Statistics Department Sri Lanka, 2012) Since, none of station is not exceeding permissible limit of $PM_{2.5}$ in 2021 and only Colombo, Jaffna, Kurunagala, Vavuniya and Puttalam are exceeding the SLAQ standards in 2022, health risk assessment has been done only for those 5 stations. After running the model for 5 different districts with different population data, Jaffna has marked the highest estimated attributable proportions for LC, COPD (in adults) and ALRI (in children) (3.01%, 3.62% and 2.8% respectively). The summary of associated health risk assessment was presented in Table 3.3 and Fig 3.9.

Table 3.3: Health Risk Assessment for Different Stations in 2022

Station	**Population**	**Mortality due to lung cancer LC for adults (25+ years)**			**Mortality due to chronic obstructive pulmonary disease (COPD) for adults (25+ years)**			**Mortality due to acute lower respiratory infection (ALRI) (0 - 5 years)**		
		Estimated attributable Proportion (%)	**Estimated No. of attributable cases**	**Estimated no. of attributable cases per 100,000 population at risk**	**Estimated attributable Proportion (%)**	**Estimated No. of attributable cases**	**Estimated no. of attributable cases per 100,000 population at risk**	**Estimated attributable Proportion (%)**	**Estimated No. of attributable cases**	**Estimated no. of attributable cases per 100,000 population at risk**
Colombo	2,478,000	0.03	229	15.63	0.03	268	18.28	0.02	4	2.04
Jaffna	629,000	3.01	6,621	1,781.06	3.62	7,945	2,137.35	2.8	130	240.92
Kurunagala	1,742,000	0.72	4,386	426.07	0.84	5,130	498.32	0.65	84	55.75
Vavuniya	195,000	0.53	359	311.08	0.61	419	363.42	0.47	7	40.63
Puttalam	850,000	1.1	3,272	651.43	1.3	3,845	765.37	1	63	85.73

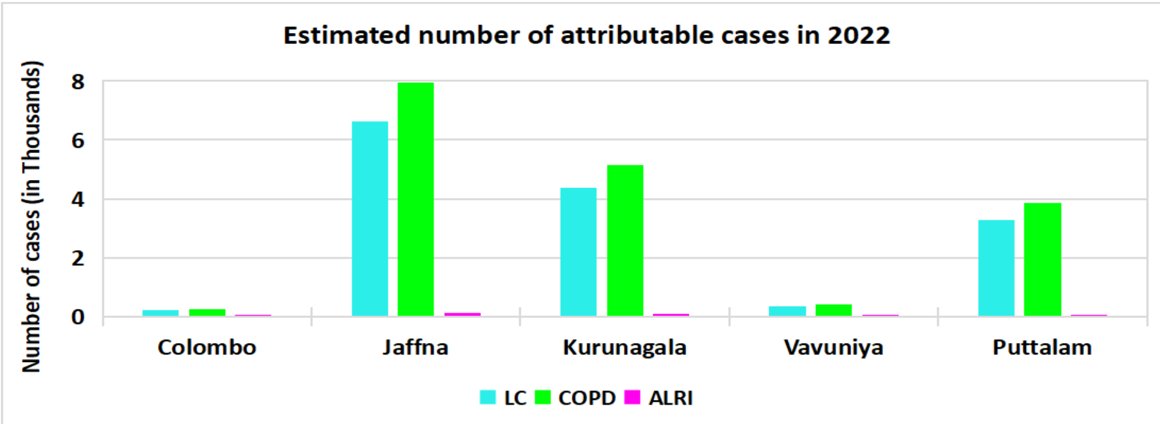

Figure 3. 9: Estimated No of Attributable Cases of Mortality Due to LC, COPD (in adults 25+ years) and ALRI (in children < 5years) in Different Monitoring Stations

Chapter IV

CONCLUSION

PM (both $PM_{2.5}$ and PM_{10}) concentrations in Sri Lanka across 17 monitoring stations over two-year period (Jan 2021 – Dec 2022), impact of meteorological parameters on the PM levels, potential source regions and human health risks associated with $PM_{2.5}$ exposure were analyzed through this study. Both daily and monthly PM level variations analyzing provided a clear picture of behavior of pollutants throughout the year which was PM started at relatively high level in Jan and gradually decreases up to mid-year and again increased at the end of the year. Seasonal PM trends revealed that the northeast monsoon (Dec-Feb) experienced the highest PM levels while first inter-monsoon experienced the lowest PM levels and these seasonal variations were caused by the meteorological parameters that helped for pollutant dispersion over the country (high rainfall and winds peed during FIM while low rainfall and low wind speed during NEM). There was substantial influence from regional sources such as vehicular emission, biomass burning, local dust from construction sites or unpaved roads, industrial emissions (textile units, rubber production, and cement production) and coal-fired and fuel-based power plants during northeast, southwest and second inter-monsoon seasons. CBPF plots revealed that high PM concentrations occurred at high wind speed indicated cross boundary pollution or stack emissions rather than the non-buoyant ground-level sources while high PM amount experienced at low wind speed was because of the potential sources to be close to the monitoring station. Based on the mortality evaluation, the maximum number of attributable cases to air pollution via LC, COPD (in adults 25+ years) and ALRI (in children 0-5 years) were 6,6217,945 and 130 in Jaffna in 2022.

The authors recommend having at least one monitoring station per district and having hourly data available instead of the 24-hour average to get a clearer picture of high PM concentration via diurnal analysis. Furthermore, this study revealed that long-term continuous measurements of air contaminants and meteorological parameters in major Sri Lankan cities are crucial for discovering regional variations. As a solution, improved modeling approaches to characterizing pollutant transit and distribution for local air quality management are advocated. Additionally, source apportionment and trajectory analysis are necessary to identify potential sources and attribute them to specific regions. Comprehensive investigations are necessary to understand the negative influence on human health and conduct proper risk analysis in future studies. The results from this study may serve as a platform for further researches, eventually leading to environmental policy, health plan review, and population welfare plans.

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1.

APPENDICES

Appendix 1: Proof of registration for ICSTCE 2024

DTU

2K22ENE06 Thrividya Rathnayake <rathnayakemudiyanselag_2k22ene06@dtu.ac.in>

Thanks for your registration and requesting information of CST 6065- Reg.

2 messages

ICST Civil 2023 <icstce@dypvp.edu.in> Fri, May 24, 2024 at 5:32 PM
To: 2K22ENE06 Thrividya Rathnayake <rathnayakemudiyanselag_2k22ene06@dtu.ac.in>

Dear author,
Greetings !!!
I am writing this mail to thank you for choosing 2024 Second International Conference on Sustainable Technologies in Civil and Environmental Engineering (ICSTCE 2024) as a platform to present your ongoing research work. I hereby acknowledge that we have received the final documents (Registration fee, Camera Ready Paper and Registration form) for your manuscript which has been accepted for ICSTCE 2024, which will be held at Dr. D.Y. Patil Institute of Technology, Pimpri, Pune, Maharashtra, India during 06 - 07, June 2024.

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Details for ID card and certificates

I would like to request you to provide the following details to prepare ID card and certificates for all the authors of your paper. Please note that the ID cards will be provided only to the authors who attend the conference. Certificates will be provided to all the authors of the registered paper. Please send the following details pertaining to your paper to this (icstce@dypvp.edu.in) mail id not later than 30, May 2024.

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4 of 98

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Dear author,

Greetings!!!!
The review and selection process for your paper ID CST 6065 entitled "Assessment of PM10 in Colombo, Sri Lanka and Its Potential Source Regions" has been completed. **Based on the recommendations from the reviewer(s) assigned for your paper, I am pleased to inform you that your paper has been ACCEPTED by the Technical Program Committee (TPC)** for 2024 International Conference on Sustainable Technologies in Civil and Environmental Engineering (ICSTCE 2024), which will be held at Dr. D.Y. Patil Institute of Technology, Pimpri, Pune, Maharashtra, India during 06 - 07, June 2024.

Publications
Proceedings of ICSTCE 2024 will be published in E3S Web of Conferences (Open Access proceedings in Environment, Energy and Earth Sciences) which in **indexed** in Scopus, Web of Science – Conference Proceedings Citation Index, Ei Compendex, IET Inspec, Technology Collection (ProQuest), Chemical Abstracts Service (CAS) and major indexing databases. E3S Web of Conferences (eISSN: 2267-1242) is an Open Access publication series dedicated to archiving conference proceedings in all areas related to Environment, Energy and Earth Sciences. The journal covers the technological and scientific aspects as well as social and economic matters. Major disciplines include: soil sciences, hydrology, oceanography, climatology, geology, geography, energy engineering (production, distribution and storage), renewable energy, sustainable development, natural resources management, environmental health.

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