CHARACTERIZING PARTICULATE AIR POLLUTION IN RURAL AREAS OF BANGLADESH USING A NETWORK OF LOW-COST SENSORS

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It is hereby declared that the studies embodied in this thesis are the results of experiments carried out by the author under the supervision of Dr. Provat Kumar Saha, Associate Professor, Department of Civil Engineering, BUET except where specified by reference to other works. Neither the thesis nor any part of it has been submitted elsewhere for any other purposes. (except for publication).

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Dedicated to

My Beloved Father

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ABSTRACT

This study presents a comprehensive study on characterizing fine particulate matter ($PM_{2.5}$) pollution levels across Bangladesh through an utilization of a network of low-cost sensors. Prior to deployment in rural sites, the low-cost sensors were calibrated against a reference $PM_{2.5}$ monitor (Beta Attenuation Monitor, BAM) at DoE continuous air monitoring stations (CAMS). The calibration process involved continuous data collection for one month each during the dry and wet seasons. This rigorous calibration ensured the accuracy and reliability of the collected data. Over a four-month period, comprising two months each in the dry and wet seasons, continuous measurements were collected at 20 rural sites spread across the country. The raw data gathered from these rural deployments were then corrected using calibration models developed from the co-location deployments.

The calibration of the low-cost sensors against the reference monitor showed excellent agreement, with consistent sensor-to-sensor performance throughout the calibration process. The linear calibration models achieved a R^2 of 0.85 - 0.9, and the normalized root mean square error (RMSE) ranged between 10-15%.

The average $PM_{2.5}$ levels measured across the 20 rural sites were remarkably higher, ranging from 49 to 214 µg/m^3, in comparison to the WHO interim target-1 of 35 µg/m^3. Furthermore, a comparison of pollution levels in rural areas with those in Dhaka, one of South Asia's most polluted megacities, revealed that many rural sites exhibited comparable or within 10-20% of Dhaka's pollution levels. This finding suggests that regional pollution is a significant driver of $PM_{2.5}$ pollution across the country, with local urban sources contributing an additional 10-20%. The study also identified a regional spatial gradient in measured pollution levels, with higher concentrations observed in the western and central parts of Bangladesh compared to the eastern region. This spatial gradient is likely due to the influence of transboundary pollution from neighboring Indian states, particularly the Indo-Gangetic Plain (IGP) states. The study's seasonal analysis demonstrated substantial variation in $PM_{2.5}$ levels in rural areas. During the wet season, concentrations ranged from 49 to 98 µg/m^3, while during the dry season, they varied from 55 to 214 µg/m^3. These seasonal fluctuations are likely driven by meteorological factors, seasonal influx of transboundary air pollution, and seasonal sources.

It is evident from the findings of the study that addressing $PM_{2.5}$ pollution across Bangladesh requires a comprehensive, regional air quality management approach. Such an approach should encompass collaboration between various regions to collectively combat air pollution effectively and safeguard public health. While this study is a significant advancement in understanding $PM_{2.5}$ pollution in Bangladesh, to gain deeper insights into long-term pollution dynamics, it is crucial to conduct multi-year continuous measurements in rural locations. Additionally, it is essential to characterize the long-term performance of low-cost sensors to ensure their sustainable and effective application in rural areas.

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LIST OF ABBREVIATION

APCR	Air Pollution Control Rules
AQI	Air Quality Index
BAM	Beta Attenuation Monitor
CAMS	Continuous Air Quality Monitoring Station
CASE	Clean Air and Sustainable Environment
DoE	Department of Environment
GHG	Green House Gas
IGP	Indo-Gangetic Plain
LCS	Low-Cost Sensor
MIST	Military Institute of Science and Technology
NAAQS	National Ambient Air Quality Standard
PA	Purple Air
PM	Particulate Matter
RH	Relative Humidity
RMSE	Root Mean Square Error
SOB	Survey of Bangladesh
USEPA	United States Environment Protection Agency
UV	Ultraviolet
WHO	World Health Organization

Chapter 1

INTRODUCTION

1.1 Background

Poor air quality is the single largest environmental risk factor for human health (Malings et al., 2020). Outdoor air pollution exposure is estimated to have caused about 4.2 million premature deaths worldwide in 2016. Based on the report of the World Bank, air pollution is responsible for about 20% premature death in Bangladesh (World Bank,2023). The majority (about 90%) of the mortality is attributed to fine particulate matter ($PM_{2.5}$; particles of less than 2.5 µm). Numerous air pollution health studies worldwide have repeatedly shown the substantial health effects of exposure to $PM_{2.5}$ (Zimmerman, 2022). Therefore, an improved understanding of sources and spatial distribution of $PM_{2.5}$ exposure is needed to improve the policy to reduce air pollution particularly $PM_{2.5}$ emissions and exposures.

While air quality monitoring is a key component of improving air quality management. Bangladesh's current air quality monitoring coverage is not adequate to get an idea on the nationwide air quality. Department of Environment (DoE) of Bangladesh has established 16 (sixteen) continuous air monitoring stations (CAMS) in eleven major cities of Bangladesh. Bangladesh's current monitoring program (DoE CAMS) is mostly urban based. Most of Bangladesh's existing academic research on air pollution is also urban-focused (Gupta et al., 2020). These studies reported that vehicle emissions, construction works, industrial emissions and brick kiln are the major causes of poor air quality in Bangladesh. Air quality monitoring in rural areas is always overlooked (Hossen et al., 2018). However, numerous studies have shown that regional secondary particulate formation, transboundary, and long-range transported pollutants are important drivers of $PM_{2.5}$ exposures (Malings et al., 2020). Furthermore, substantial household uses of solid fuels in rural Bangladesh are a dominant source of $PM_{2.5}$ (Majra et al, 2011).

Present air quality monitoring approach in Bangladesh measured pollutant concentrations at a limited number of locations using a reference grade instrument. The cost of this traditional air quality monitoring approach is very expensive. The recent advent of low-cost air sensors opens the door of monitoring air quality at an affordable cost (Malings et al., 2020). Low-cost sensors provide an affordable, compact, and easily transportable approach to supplement air quality networks in regions where reference-grade instruments are not accessible (Ashley et al., 2021). To address these gaps, this study aims to characterize the fine particulate air pollution ($PM_{2.5}$) in selected rural areas of Bangladesh by establishing a network of low-cost sensors.

1.2 Objectives of the Study

The study aims to achieve the following major objectives:

i. Evaluate the performance of low-cost sensors for measuring particulate air pollution ($PM_{2.5}$) in Bangladesh.

ii. Characterize fine particulate matter ($PM_{2.5}$) concentrations in rural areas across Bangladesh by establishing a 20-node network of low-cost sensors and collecting continuous data in multiple seasons.

1.3 Outcomes of the Study

The study provides following outcomes and benefits:

i. Performance evaluation of low-cost $PM_{2.5}$ sensors provides valuable insights into their utility for air quality monitoring in Bangladesh.

ii. Deployment of sensors in rural areas offers a spatial and temporal pattern of $PM_{2.5}$ exposures, providing essential data for understanding pollution levels in rural settings.

iii. The data obtained from the sensor network will provide guidance for regulatory agencies in effectively implementing pollution control strategies.

1.4 Organization of the Thesis

The thesis has been organized into five chapters as follows:

Chapter 1 provides the background and objectives of the research.

Chapter 2 presents a review of relevant past research.

Chapter 3 outlines the research methodology employed in the study.

Chapter 4 presents the results of the study.

Chapter 5 presents conclusions and provides recommendations for future studies.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Air pollution was the fourth-leading risk factor for premature mortality globally in 2019, causing an estimated 6.67 million deaths (HEI 2020). Air pollution is one of the important global concerns at the present time. It is considered as the major environmental risk to health (WHO,2021). Air pollution is directly related to human health. Air pollution can cause heart-related diseases, lung cancer and respiratory related diseases. Children and old aged people are the most vulnerable group for this air pollution. Ambient (outdoor) air pollution is mostly specified by the air pollution terminology, and it has created major health concerns for human society. Ambient (outdoor) air pollution in both cities and rural areas was estimated to cause 4.2 million premature deaths worldwide per year in 2016; this mortality is due to exposure to fine particulate matter of 2.5 microns or less in diameter ($PM_{2.5}$), which cause cardiovascular and respiratory diseases, and cancers (WHO,2021). Air pollution mostly occurred due to human activities for their own sustenance, livelihood, and future development. Apart from the human activities environmental condition, weather effect, and ambient temperature play vital role in decreasing the air quality. Particulate matter (PM) is one of the prime indicators of air pollution and it is the most dominant factor for determining air quality. The major components of PM are sulfate, nitrates, ammonia, sodium chloride, black carbon, mineral dust, and water. It consists of a complex mixture of solid and liquid particles of organic and inorganic substances suspended in the air (Rahman et al., 2005). There are many methods to identify PM but in the recent past measurement with low-cost sensors (LCS) became very popular. Low-cost sensors have the potential to greatly alter how, where, and when air pollution monitoring is done (Giordano et al., 2021). Low-cost PM monitors, which are based on optical particle counting technology, have emerged as a cost-efficient solution where indicative yet dense monitoring is required to provide real-time information to citizens and stakeholders (Stavroulas et al., 2021). Urban air quality is the major focus for any country but air quality in the rural area is ignored in many developing nations. PurpleAir, a widely used low- cost sensor is used in many countries to establish a network. The Plantower PMS sensor is one of the most widely used for low-cost PM measurements and it forms the basis of the PurpleAir monitor, a compact low-cost platform with advanced online data reporting capabilities (Stavroulas et al., 2021). Monitoring the air quality of rural areas of Bangladesh with these low-cost sensors will provide a comprehensive perception about the air quality of Bangladesh.

2.2 Air Pollution of Bangladesh

Air pollution of Bangladesh is the one the major problems. Air pollution was the second-largest risk factor that caused most deaths and disability in Bangladesh in 2019, with four of the top five causes of total deaths in the country being directly associated with air pollution: stroke, heart disease, chronic obstructive pulmonary disease, and lower respiratory tract infection (HEI 2020).

Bangladesh has got diversified land use activities across the country due to the massive development activities. Various activities of the human, transport exhaust and emission from industrial activities are main sources of the air pollution in Bangladesh. Air pollution of Bangladesh for outdoor and indoor is caused due to increasing population, associated motorization, industrial emissions, and use of biomass fuels during cooking with poor ventilation (Haque et al., 2017).

Air pollution of the urban areas is apparently bad from the rural area as the concentration of the industries and human activities are more in urban areas. Besides industrial development in urban areas, the pollution is increased due to transport exhaust specially exhausts from two-stroke engine and diesel-run vehicles. Bangladesh is the country with the worst air pollution in the world, according to a 2021 report by IQAir. According to the WHO report on the ambient air quality published on 28th April 2022 the air quality of different cities of Bangladesh is stated at Table 2.1. It is observed that most of the cities exceed the WHO guidelines.

Table 2.1: WHO report on the ambient air quality in Bangladesh

City	Measurement Year	$PM_{2.5}$ (µg/m^3)	PM_{10} (µg/m^3)	NO_2 (µg/m^3)
Barisal	2018	21.77	106.93	41.17
Chittagong	2018	56.36	148.99	36.96
Dhaka	2019	86.48	-	-
Gazipur	2018	95.33	156.08	19.78
Khulna	2018	61.24	77.61	37.57
Narayangonj	2018	102.7	224.73	38.67
Rajshahi	2018	72.45	159.41	
Sylhet	2018	59.77	110.55	13.74

Dhaka, the capital of Bangladesh experienced the worst air quality among the other urban areas. Dhaka ranked as the second most polluted capital in the world, surpassed only by India's New Delhi. Density of population, development activities, brick kiln around the city, traffic exhaust and industrial activities are the main sources of air pollution in Dhaka. According to the report by World Bank, the CAMS data suggest that Dhaka was the most polluted division in Bangladesh between 2013 and 2021 with an average $PM_{2.5}$ concentration of 87 micrograms per cubic meter ($\mu g/m^3$) while Sylhet was the least polluted, with an average $PM_{2.5}$ concentration of 46 $\mu g/m^3$. Other urban areas are also experiencing a similar kind of air pollution. It is widely circulated in the common mass of Bangladesh that air pollution of urban areas is more comparing to the rural areas of Bangladesh (Gupta et al., 2020). This study will give an idea with relevant data about the air quality of rural areas.

2.3 Air Quality Standard in Bangladesh

The air quality standards declare the highest limits on a specific pollutant in the air for a given time. The priority behind these standards was the protection of human health. These limitations and guidelines are extremely valuable because they serve as a link between the source of these pollutants and the receptors in downstream locations.

Table 2.2 provides air quality standards in Bangladesh, and standards set by the United States Environment Protection Agency (USEPA) and the World Health Organization (WHO) which shows that, our local standards listed on the table almost like USEPA. Different standards are set for different pollutants based on their average exposure time, as this is the primary cause of health risks. DoE is the focal organization for country to monitor the air quality. They are also responsible for setting the allowable limit for various pollutants of our country. They also have the legislative authority to fine the organization or individual for violating the law or any act against the clean environment. DoE recently published Air Pollution Control Rule where they revised the limit of various pollutants. Table 2.2 presents the ambient air quality standards in Bangladesh and their comparison with WHO and USEPA standards and it is sourced from the Air Pollution Control Rules-2022, WHO report on the global air quality guidelines (updated 2022), and NAAQS for USA (updated 2015).

Table 2.2: Ambient air quality standards in Bangladesh and their comparison with WHO and US standards

Pollutant	Pollutant (observation realized)	Bangladesh standard	WHO guideline (Interim-1)	USEPA
CO (ppm)	8 hr	9	7	9
	1 hr	35	-	35
NO_2 (µg/m^3)	Annual	100	40	53 ppb
PM_{10} (µg/m^3)	Annual	50	70	-
	24 hr	150	150	150
$PM_{2.5}$ (µg/m^3)	Annual	15	35	15
	24 hr	65	75	35
Ozone (O_3) (µg/m^3)	1 hr/Peak Season	235	100	-
	8 hr	157	160	0.070 ppm
SO_2 (µg/m^3)	Annual	80	125	
	1 hr	365	-	75 ppb

2.4 Effects of Air Pollution

2.4.1 Human Health Effects

Aged people and children are the most vulnerable group among all due to the air pollution. Among all the diseases, cardiovascular disease is most common among all the groups of human beings. People exposed to air pollutants for long time may experience irritation of the eyes, nose, throat, wheezing, coughing, chest tightness, and breathing difficulties. Besides, long-term exposure to air pollution can cause more dangerous diseases like cancer and damage to the organs. In India, (Delhi) air pollution has been reported to cause between 10,000 to 30,000 deaths every year (Gopalaswami et al., 2016), acute and chronic problems are due to inhalation of PM_{10} and $PM_{2.5}$ (Ezeh et al., 2016), and damage to respiratory organs (Moses et al., 2015).

2.4.2 Environmental Effects

Air pollution has direct and indirect effect on the environment. Acid rain and eutrophication are effects of the environment due to air pollution. Acid rain may be formed due to the air pollution which has wet or dry precipitation on the earth surface affecting tree, wildlife and streams or rivers (Asafu et al., 2003). This effect also directly affects the human body through food cycle or chain. Eutrophication also has an effect on water bodies by generating algae in the water body and in turn affects the food chain of the human (Asafu et al., 2003). Traffic and industrial emission also affect the environment by creating haze in the atmosphere. This in turn creates many diseases in human (Saurabh et al., 2018).

2.4.3 Climate Change

Climate change and air pollution are interrelated. Air pollution started since the industrial revolution, and it is increasing at a rapid rate. Large consumption of fossil fuels, changes in transportation, the agricultural pattern and standards of living are the main reasons for the increase in pollution levels in the atmosphere (Saurabh et al., 2018). The average temperature of the earth is increasing because of the emission increasing rate of emission of GHGs. To explore the most cost-effective way to keep the temperature rise below 2^{o}C various emission reduction technologies, along with policy implementation, have been taken into consideration to ultimately avoid the unmanageable risks of climate change (IPCC, 2014).

2.4.4 Economic Growth

The effect of air pollution on the environment and economy is almost similar in nature. The impact of air pollution on the environment is visible and people can feel the physical effect but the effect on the economy is not visible, which can only be felt (Saurabh et al., 2018). This effect on the economy is slow but has a great effect on our society. It leads to a plethora of burdens on society in the form of health issues, reduced productivity, reduced labor, and reduced ecological services, which can pose a huge cost to any nation (Saurabh et al., 2018).

2.4.5 Ecosystem

Air pollution has a significant effect on the ecosystem by changing the physical components. Acid rain, damage of Ozone, increase of temperature etc. are few components which occurred due to the air pollution (Rana et al., 2019). Aquatic ecosystems are seriously affected by air pollution. Most species of animals are sensitive to air pollution and its effects.

2.4.6 Biodiversity

A study examined the relationship between biodiversity and economic growth using an indicator of species diversity and per capita income, which indicated that economic growth has adverse impact on biodiversity (Asafu et al., 2003). The countries with high agricultural output are found to have comparatively higher biodiversity loss and this can be due to faulty agricultural practices or other human interventions in ecological system (Asafu et al., 2003). Air pollution has an effect on wildlife which in turn affects the biodiversity of the nation.

2.4.7 Crop and Forest Damage

Plants and vegetation can be damaged by air pollution in direct and indirect ways. Air pollutants deplete the Ozone layer while accumulating in the upper atmosphere. Therefore, crops and vegetation are subjected to a much higher rate of harmful ultraviolet (UV) radiation (Rana et al., 2019). Ground level Ozone formation due to air pollution also affects the growth of plants, vegetables, and trees. Air pollution also causes acid rain which affects and damage plants, crops, and forest.

2.5 Fine Particulate Air Pollution ($PM_{2.5}$)

Airborne particulate matter (PM) contains particles from numerous sources, with myriad of chemical species and a varies of sizes ranges between 10 nm to several micrometer. (Abulude et al., 2016). PM is known to be the major contributor to the adverse health effects of air pollution. From size point of view, PM is classified into several subgroups: (1) total suspended particulates (TSP, with aerodynamic diameter < 30 microns (µm), (2). PM_{10} with an aerodynamic diameter of less than 10µm (coarse), (3) $PM_{2.5}$ with an aerodynamic diameter of less than 2.5µm (fine), and (4) Ultrafine PM with diameter of less than 0.1 microns. Currently, two subgroups of particles are commonly used to measure and characterize exposure to inhalable particles: $PM_{2.5}$ and PM_{10} mass concentrations and their unit is µg/m^3. The particles which are < 2.5 µm particles are regarded as the fine particles ($PM_{2.5}$) and particles with size <10 µm are the coarse particles.

PM sources and its concentration mostly depend on the local sources in urban areas (industrial activities, brick kiln emission, construction work) and transport emission of the air pollutants (Rana et al., 2019). The PM sources in developing countries are much more than those from developed countries. This is because of the existing condition and rapid transition between rural and urban economies. Sources of PM in the urban and rural are different, while in rural cooking with solid fuels is the most common source of the PM, but in the urban areas burning of fossil fuel and transport exhaust are most common source of PM (Rana et al., 2019).

2.6 Sources and Composition of $PM_{2.5}$

Numerous sources and processes contribute to ambient $PM_{2.5}$ levels. These particles can emit directly from sources, referred to as primary $PM_{2.5}$, or form in the atmosphere through precursor emissions and atmospheric chemistry, known as secondary $PM_{2.5}$. Primary $PM_{2.5}$ is emitted from various activities such as fuel combustion exhaust from traffic, biomass burning, and industrial emissions (Hinds et al., 2022). Examples of primary $PM_{2.5}$ include black carbon and organic carbon. Additionally, construction dust, resuspended road dust, and particles emitted from the wear and tear of brakes and tires contribute to primary $PM_{2.5}$.

On the other hand, secondary $PM_{2.5}$ forms from gaseous precursor emissions like nitrogen dioxide, sulfur dioxide, volatile organic compounds (VOCs), and ammonia (NH_3). These precursors come from multiple sources, including transportation, industrial activities, and agriculture (Gupta et al., 2020). Secondary particles are formed through gas-to-particle conversion in atmospheric chemistry and major species in this category include sulfate, nitrate, ammonium, and secondary organic aerosols (SOA) (Hinds et al., 2022). In many environments, secondary $PM_{2.5}$ plays a dominant role in overall ambient $PM_{2.5}$ levels and can account for up to 50-80% of the total $PM_{2.5}$ concentration (Gupta et al., 2020). Secondary $PM_{2.5}$ has an important role in dominating regional background $PM_{2.5}$ levels whereas primary $PM_{2.5}$ has an important role in dictating near sources $PM_{2.5}$ exposure levels.

2.7 Measuring $PM_{2.5}$ Using Low-cost Sensors (LCS)

Traditionally, ambient $PM_{2.5}$ levels have been measured using reference grade monitors at continuous air monitoring stations, which provide high-quality data but come with significant capital investment and maintenance costs (Hossen et al.,2017). However, the recent emergence of sensor based real-time $PM_{2.5}$ measurements offers a more affordable and accessible alternative. These low-cost sensors (LCS) allow for real-time monitoring at a fraction of the cost of traditional monitors, making it feasible to deploy them at numerous locations (Malings et al., 2020).

Table 2.3: General operating principles and price of commonly used low-cost PM sensors (Giordano et al.,2021)

Make	Model	Light Wavelength	Output	Price (USD)
Shinyei	PPD42NS	Infrared	Lo Pulse Occupancy (%)	~20
Sharp	GP2Y 1010AU0F	Infrared	Lo Pulse Occupancy (%)	~20
Samyoung	DSM501	Infrared	Lo Pulse Occupancy (%)	~20
Nova	SDS011	Red Laser	Particle Mass concentrations (PM2.5, PM10)	~20
Dylos	DC1700	Laser	Particle number concentrations	~450
Plantower	PMS1003	650 nm	Particle Mass concentrations	20+
Sensirion	SPS30	660 nm	Particle Mass concentrations (PM1, PM2.5, PM4, PM10)	~40
Honeywell	HPMA115C0	650 nm	Particle Mass concentrations (PM1, PM2.5, PM4, PM10)	~40
MetOne	NPM2	670 nm	Particle Mass concentration	~2000
Alphanese	OPC-N2	658 nm	Particle number concentrations	~500

In Table 2.3, we provided a list of commonly available LCS models to aid researchers and practitioners in their selection for air quality monitoring applications (Giordano et al., 2021). The application of low-cost sensors in routine air quality monitoring has brought about several benefits. Notably, their affordability enables data collection at multiple locations without straining budgets (Malings et al., 2020). Moreover, their compatibility with various setups allows for easy deployment in different locations, facilitating the establishment of large-scale dense sensor networks. These networks can offer valuable insights into $PM_{2.5}$ levels across wide geographical areas. In past research, researchers and projects have employed LCS in various scales, from citizen science initiatives to city-wide distributed network deployments (Malings et al., 2020). Some well-known LCS models, such as the Airbeam monitor, Plume Labs Flow monitor, and PurpleAir have gained popularity in the field.

2.8 PurpleAir Low-cost $PM_{2.5}$ Sensors

PurpleAir is widely used as a low-cost sensor for measuring both indoor and outdoor $PM_{2.5}$ levels. Its popularity has grown in recent years due to its compact design, reliable data quality, transparency in storing raw data, good agreement with reference monitors, and reasonable cost (approximately $300 per unit). In this study PurpleAir PAII SD model sensors were used.

The PurpleAir sensor contains two Plantower PMS5003 sensors. These sensors operate in alternating 10-second intervals and provide 2-minute averaged data. Furthermore, the PA-II sensor provides additional data for temperature, relative humidity, and barometric pressure of the study area. Deatail description of the low-cost sensors used for this study is stated in Appendix D. This comprehensive dataset from the PurpleAir sensor makes it a valuable tool for monitoring $PM_{2.5}$ levels both indoors and outdoors with reliable accuracy.

2.9 Application of Low-cost Sensors in Previous Studies

Many studies and research were carried out to find ambient air pollution and PM concentration using low-cost sensors across the globe. Airborne particulate matter monitoring in Kenya using calibrated low-cost sensors was carried out where it shows that, calibrated low-cost sensors can be successfully used to measure air pollution in cities like Nairobi (Pope et al., 2018). A study was carried out on low-cost sensors to evaluate sensors and ambient air quality where low-cost particulate matter sensors (Plantower PMS 1003/3003) were used by a community air-quality network in a controlled wind-tunnel environment and in the ambient environment during wintertime

(Stavroulas et al., 2020). The PMS sensor correlates well with research-grade instruments in the wind-tunnel tests, and its response is linear over the concentration range tested (200–850 μg/m^3). In the ambient tests, this PM sensor correlates better with gravimetric methods than previous studies with correlation coefficient of 0.88 (Stavroulas et al., 2020). Field Evaluation of Low-Cost PM Sensors (PurpleAir PA-II) under variable urban air quality conditions was conducted where evaluation of PurpleAir PA-II devices (low-cost PM sensors) is performed in two urban environments and across three seasons in Greece, in comparison to different types of reference instruments (Karagulian et al., 2015). Measurements were conducted in Athens. $PM_{2.5}$ sensor output correlates strongly with reference measurements (R^2 = 0.87 against a beta attenuation monitor and R^2 = 0.98 against an optical reference-grade monitor). Deviations in the sensor-reference agreement are identified as mainly related to elevated coarse particle concentrations and high ambient relative humidity (Karagulian et al., 2015).

2.10 Past Studies in Bangladesh on Ambient $PM_{2.5}$

Particulate pollution in Bangladesh exhibits a strong seasonal pattern, with concentrations being approximately 2-4 times higher during winter compared to the rainy seasons. The pollution levels in Dhaka city are influenced significantly by both local and regional sources, such as brick kilns and meteorological factors. Additionally, these irrespirable particles have been found to contain various toxic heavy metals (Salam et al., 2008). Transboundary air pollution has also been identified as a significant contributor to $PM_{2.5}$ levels in Dhaka city (Salam et al., 2008).

An analyze was conducted on hourly $PM_{2.5}$ concentrations measured at the U.S. Embassy in Dhaka over the 2016–2021 time period and found that concentrations are seasonally dependent with the highest occurring in winter and the lowest in monsoon seasons (Sarwar et al.,2023). A comparison was made between observations and the Community Multiscale Air Quality (CMAQ) model. The comparison of results suggests that the model can reproduce the seasonal variation of observed data but underpredicts observed $PM_{2.5}$ in winter months. In the model, organic aerosol is the largest component of $PM_{2.5}$, of which secondary organic aerosol plays a dominant role (Sarwar et al.,2023). Transboundary air pollution has a large impact on the modeled $PM_{2.5}$ concentration in Dhaka.

Dhaka city air quality was assessed where they focused on air pollution in capital city and its impact from nearby brick kilns (Motalib et al., 2014). The study found that PM_{10} and $PM_{2.5}$ particle levels were significantly high, surpassing both national averages and WHO standards. Other pollutants like SO_x, NO_x, SO_2, CO, and O_3 remained within acceptable limits (Motalib et al., 2014). PM_{10} and $PM_{2.5}$ were the main contributors to pollution, warranting targeted measures to address their effects and enhance air quality in the city.

In the commercial city of Chottogram, a study showed that the 24-hour average concentrations of PM_{10} and $PM_{2.5}$ were within the National Ambient Air Quality Standard (NAAQS) levels during April-October. However, these concentrations increased about threefold during the non-monsoon period (November-March) (Hossen et al., 2018).

Regarding prediction models, a meteorological-based $PM_{2.5}$ model was developed for the megacity Dhaka. This study utilized statistical models with linear terms of meteorological variables and their first-order interactions to predict $PM_{2.5}$ concentration in Dhaka city (Afrin et al., 2020). The model for $PM_{2.5}$ explained up to 57% of the daily $PM_{2.5}$ concentration variability, while the model for the coarser fraction ($PM_{2.5-10}$) explained up to 35% of its variability, indicating that $PM_{2.5}$ is more influenced by meteorology than $PM_{2.5-10}$ (Afrin et al., 2021). Key meteorological variables like temperature, wind speed, and wind direction were found to account for 94% of the total $PM_{2.5}$ variability explained by the model, while relative humidity contributed to 75% of the total $PM_{2.5-10}$ variability (Afrin et al., 2021).

Furthermore, a source apportionment study conducted by the Atomic Energy Commission in Dhaka identified brick kiln emissions and resuspension from dusty roads as major sources of particulate matter (Begum et al., 2005). This study also revealed that 50% of particulate matter in Dhaka comes from brick kiln emissions (Begum et al., 2010). Additionally, road dust and transportation sectors are also significant contributors to $PM_{2.5}$ levels in the region.

An assessment was conducted to identify the impact of $PM_{2.5}$ due to biomass combustion in megacity Dhaka. In this study, seasonal concentrations, and back-wind trajectories of sulfur-related $PM_{2.5}$ and adjusted potassium-related $PM_{2.5}$ were assessed. The findings highlighted that Dhaka's air quality is impacted by both local and long-range pollution sources (Rahman et al.,2020). However, the most severe pollution instances coincide with periods of transported biomass burning pollution. Although local sources dominate during less polluted days, peak $PM_{2.5}$ pollution in Dhaka is significantly influenced by transboundary biomass burning pollution from the the Indo-Gangetic Plain (Rahman et al.,2020).

Research was conducted to identify the impact of COVID-19 on $PM_{2.5}$ Pollution in the fastest-growing megacity, Dhaka (Sarkar et al.,2022). This research aimed to analyze the impact of COVID-19 lockdown on $PM_{2.5}$ pollution in the capital. Ground-based observation data was used to assess air quality for $PM_{2.5}$ from January 1, 2017, to August 1, 2020. The study divided the periods into pre-COVID-19, during COVID-19, and post-COVID-19 lockdowns. $PM_{2.5}$ pollution exhibited consistent annual patterns from 2017 to 2020, with an average concentration of 87.47 $\mu g/m^3$. The current COVID-19 lockdown period showed a notable 11.31% reduction in $PM_{2.5}$, equivalent to a 7.15 $\mu g/m^3$ decrease, compared to historical data (Sarkar et al.,2022).

A recent study was carried out on assessment of temporal shifting of $PM_{2.5}$, lockdown effect, and influences of seasonal meteorological factors over the fastest-growing megacity, Dhaka. The study examined hourly, shifting, seasonal fluctuations in particulate matter ($PM_{2.5}$), the effects of seasonal meteorological variables, and the lockdown effect over the megacity of Dhaka from 2019 to 2021 (Faisal et al., 2022). The results indicate the daily average $PM_{2.5}$ concentration between 2019 and 2021 was 112.49 $\mu g/m^3$, about four times higher than the WHO limit and two times higher than the Bangladesh standard. Daily $PM_{2.5}$ concentrations were high during morning and evening pick-up hours. One of the major sources of $PM_{2.5}$ emissions in Dhaka City is the transportation sector, especially trucks and buses. Analysis shows that $PM_{2.5}$ dangerously worsened during the winter season and exceeded Bangladesh standards multiple times, while the average concentration level remained within the Bangladesh standard during the rainy season (Faisal et al., 2022). This study identified winter as the most polluted season and the rainy season as the least polluted season. The correlation of ambient airborne pollution with urban health issues is now a significant point of discussion among urban planners, policymakers, and changemakers. As a result of rapid urbanization, industrial smog and vehicle exhaust create a dense layer of $PM_{2.5}$ in urban areas.

Recent studies on the air pollution at Bangladesh is focused on the urban areas due to data coverage and existence of the DoE reference station (Gupta et al.,2020). Rural sites measurement and establishing a network across the country are required to determine the overall air quality of the country which will help us to understand the dynamics of the air pollution of our country.

2.11 Summary

Air pollution is a major global concern, causing millions of premature deaths and impacting human health, particularly heart and respiratory conditions. Bangladesh faces severe air pollution, driven by industrial activities, motorization, and urbanization, exceeding WHO guidelines. Monitoring air quality in both urban and rural areas is crucial for effective management. Poor air quality leads to acid rain, eutrophication, and climate change, affecting the environment and biodiversity.

Ambient $PM_{2.5}$ levels come from two sources: primary (directly emitted) and secondary (formed through gas-to-particle conversion). Primary $PM_{2.5}$ includes emissions from fuel combustion and industrial sources, while secondary $PM_{2.5}$ results from gaseous precursors like nitrogen dioxide and sulfur dioxide. Addressing both sources is essential to manage $PM_{2.5}$ pollution effectively. Low-cost sensors offer an affordable alternative for real-time $PM_{2.5}$ monitoring. These LCS provide reliable data both indoors and outdoors, aiding accurate measurements. PurpleAir is a popular low-cost sensor for $PM_{2.5}$ monitoring, providing reliable data both indoors and outdoors.

Calibrated low-cost sensors, such as Plantower PMS and Purple Air PA-II, have shown success in measuring ambient air pollution and PM concentration. They correlate well with research-grade instruments and offer reliable measurements in different environments, making them valuable tools for monitoring air quality.

Particulate pollution in Bangladesh exhibits a strong seasonal pattern, with higher concentrations in winter than rainy seasons. Dhaka city's pollution is influenced by local and regional sources, including brick kilns and transboundary air pollution. Meteorological factors significantly impact $PM_{2.5}$ levels. Transportation sectors, dusty roads, and brick kiln emissions are major sources of air pollution in Dhaka.

Chapter 3

METHODOLOGY

3.1 Introduction

A network of low-cost sensors has been established to monitor PM2.5 concentrations at 20 rural sites across the country. Ten low-cost PurpleAir sensors (PA-II-SD; purpleair.com) have been used to collect data at 20 locations through a rotating network. Before deploying these sensors in rural areas, they were calibrated against a reference $PM_{2.5}$ monitor at a DoE continuous air monitoring station. The calibration models derived from these co-location experiments were then used to adjust the raw data collected from the rural locations. The resulting quality-assured data was analyzed to investigate spatial and temporal trends in $PM_{2.5}$ concentrations within rural settings. To provide context, the rural measurements were compared with urban concentration levels measured at DoE CAMS stations in Dhaka. The entire methodology of the study is visually presented in Figure 3.1.

3.2 Performance Evaluation of Low-cost $PM_{2.5}$ Sensors

Before deploying the sensors in rural areas, ten PurpleAir $PM_{2.5}$ sensors underwent co-location experiments at a DoE CAMS station in Darussalam, Dhaka. The purpose was to collect data while the sensors were placed alongside a reference-grade $PM_{2.5}$ monitor (Beta Attenuation Monitor, MetOne BAM 1020). These co-location experiments were conducted during two seasons, with continuous data collection over one month in each season: the wet season (April-May 2022) and the dry season (November 2022). The data was stored on an SD card at two-minute intervals, and the PurpleAir sensors measured $PM_{2.5}$ levels along with temperature and relative humidity. Figure 3.2 shows photos from colocation experiments at DoE CAMS. Throughout the co-location period, $PM_{2.5}$ data, as well as temperature and relative humidity readings, were collected from the DoE reference monitor at hourly intervals. To compare this data with the PurpleAir readings, the PurpleAir data was down averaged to hourly resolution. Data from different sensors were compared among themselves, as well as with the data from the reference monitor, to ensure accuracy and consistency. Regression models were then developed by comparing the PurpleAir data with the reference monitor data.

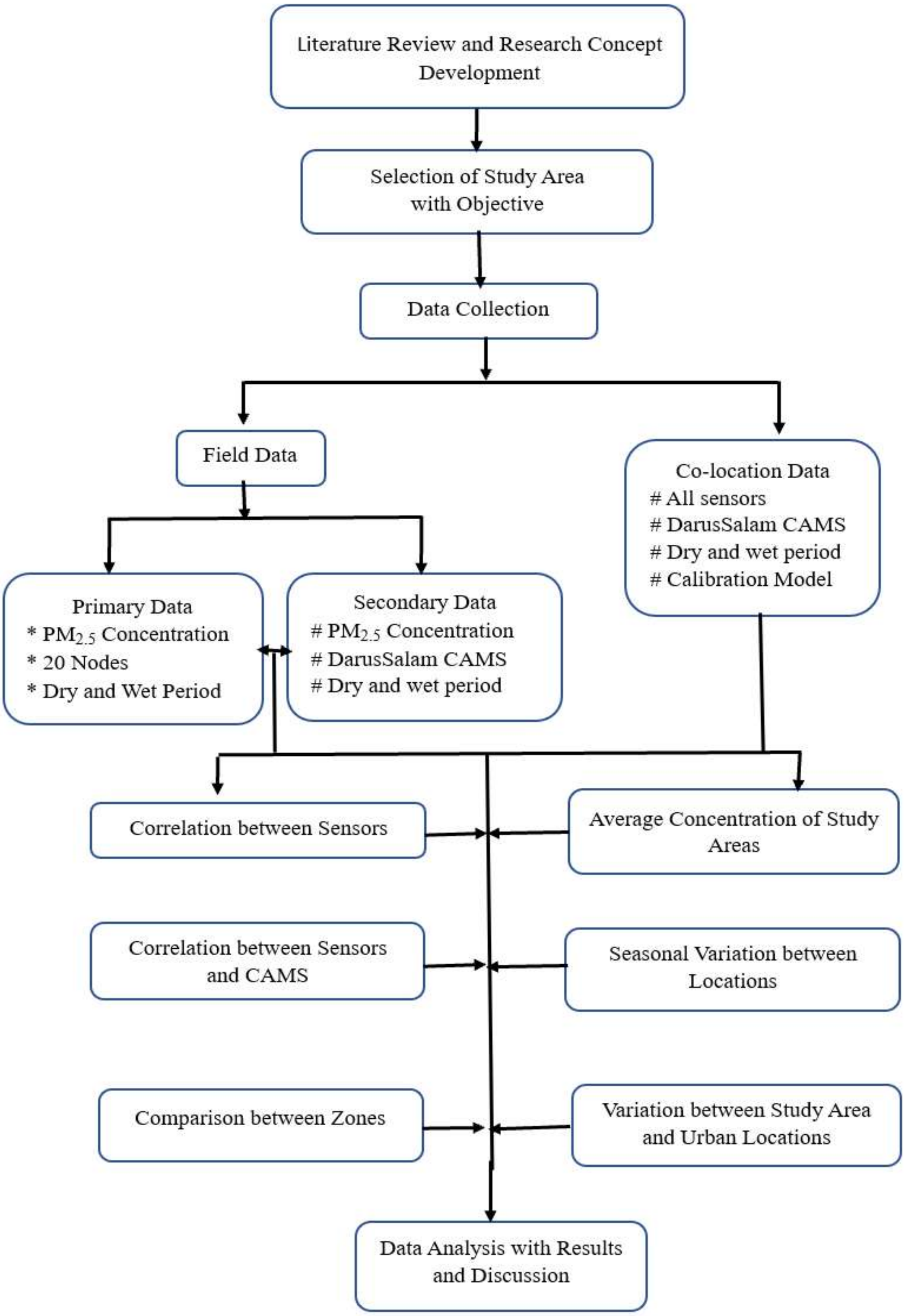

Figure 3.1: Flow chart of research methodology

(a) (b)

Figure 3.2: Co-location at Darussalam CAMS (a) Wet period (b) Dry period

3.3 Brief Description of Selected Rural Sites

To characterize $PM_{2.5}$ concentration levels across diverse rural sites in Bangladesh, a total of 20 sensors were strategically deployed at selected locations. These locations were carefully chosen to cover various geographical regions, including the eastern, central, and western parts of the country. The selected sites were located away from city centers, ensuring that they were located in remote areas of Bangladesh. Moreover, the sensors were carefully positioned at these sites, ensuring they were away from any active pollution sources, such as brick kilns or household cooking activities. Sources from indoor air pollution also kept in active consideration while setting the sensors in host sites.

The chosen sites were spread across Bangladesh, providing a representative sample of rural areas. For a visual representation of the deployed locations, Figure 3.3 shows the locations of sensors on the map of Bangladesh. Appendix A provides the list of sites with geo-coordinates and specific sampling dates in each season. In the subsequent subsections of this section, each of the selected sites is briefly described.

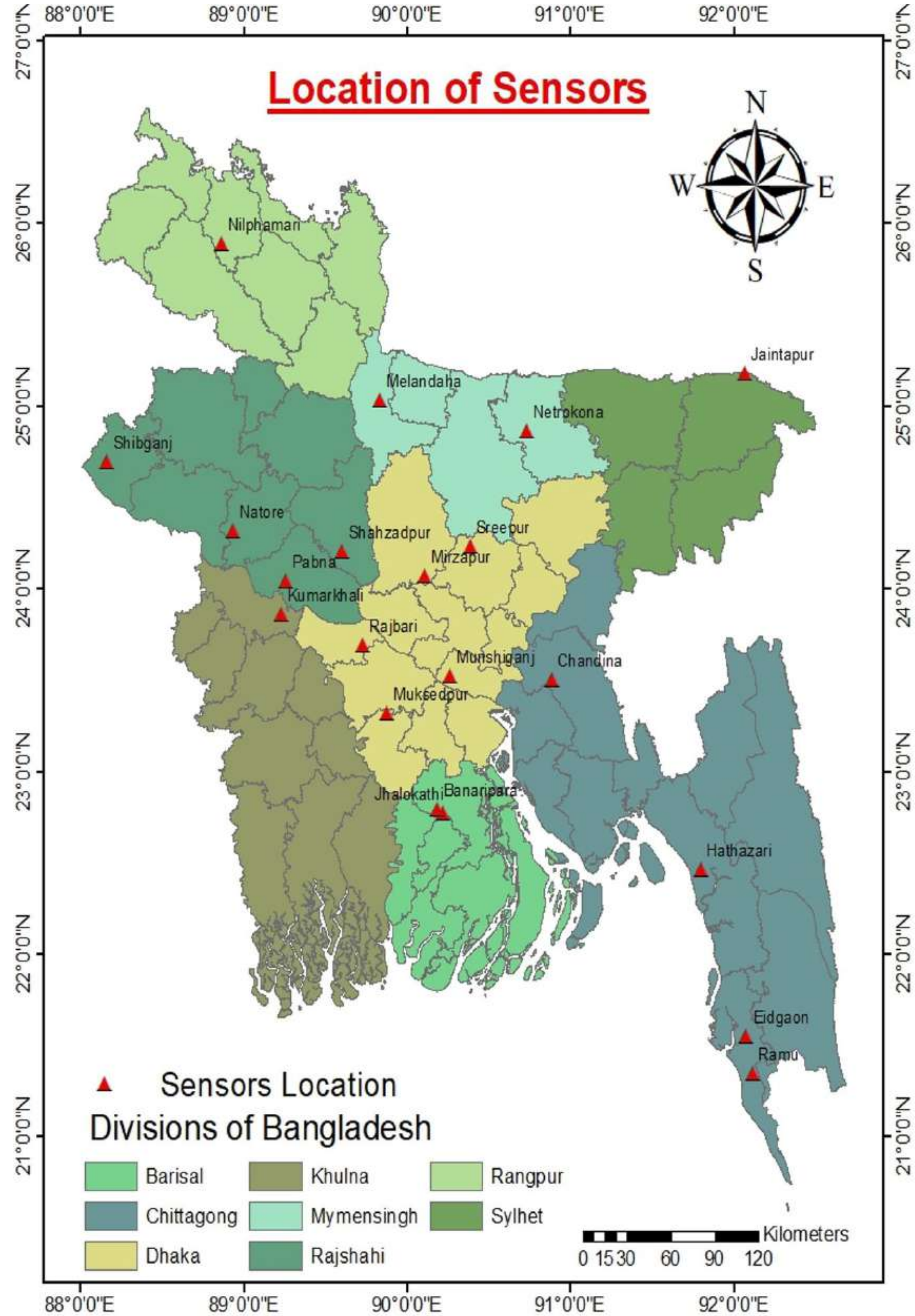

Figure 3.3: Rural deployment locations across Bangladesh

3.3.1 Banaripara. Banaripara ia an upazila in Barishal district under the Barishal division. The district headquarters is 27 kilometers away from upazilla. Sensor was placed in a tin shed building of the rural site of upazila which is 20 km away from Sadar. The coordinate of the sensor is 22° 47′ 31″ N; 90° 11′00″ E. Location of sensor at Banaripara is shown in Figure 3.4.

Figure 3.4: Location of sensor at Banaripara

3.3.2 Shibganj. Shibganj is located at the northwest side of Bangladesh, near the international border with India. Shibganj upazilla is Bangladesh's most western upazilla. The sensor was placed at the 3rd floor of a house in Shibganj sadar. Location of sensor is 24° 41′ 29″ N; 88° 09′35″ E. Location of sensor at Shibganj is shown in Figure 3.5.

Figure 3.5: Location of sensor at Shibganj

3.3.3 Chandina. Chandina is an upazila of the Cumilla district. The Dhaka-Chottogram highway connects Chandina to the far North of the upazila. This upazila is surrounded by Debidar and Muradnagar Upazila to the north, Kachua in the south, Daudkandi in the west and Burirchang in the east. Sensor was placed at the roof top of a tin shed house and its coordinate is 22° 29′ 53″ N; 92° 04′ 22″ E. Location of sensor at Chandina is shown in Figure 3.6.

Figure 3.6: Location of sensor at Chandina

3.3.4 Eidgaon. Eidgaon is an upazila in the Cox's Bazar district. Eidgaon upazila is flanked to the East by Ramu upazila. Sensor was placed at rural area of a tin shade building which is 10 km away from the upazila sadar. The name of the sensor location is Chandergola and coordinate is 21° 33′ 08″ N; 90° 53′05″ E. Location of sensor at Eidgaon is shown in Figure 3.7.

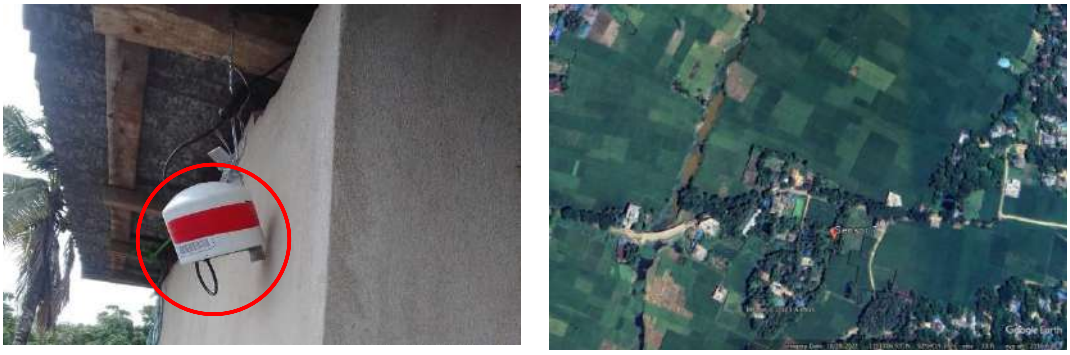

Figure 3.7: Location of sensor at Eidgaon

3.3.5 Hathazari. Hathazari is an upazila of the Chattogram district. The sensor was placed close to the Chottogram university (close to forest department) in a farmhouse. It was set at the outside of a building. Coordinate of the sensor is 22° 27′ 33″ N; 91° 47′ 51″ E. Location of sensor at Hathazari is shown in Figure 3.8.

Figure 3.8: Location of sensor at Hathazari

3.3.6 Melandaha. Melandaha is an upazila under Jamalpur district which shares northeastern international border with the Indian state of Meghalaya. Sensor is located at Tonki Bazar which is 15 km away from the upazilla sadar. The sensor was placed on the roof top of one storied building. Coordinate of the sensor is 25° 01′ 49″ N; 89° 49′ 46″ E. Location of sensor at Melandaha is shown in Figure 3.9.

Figure 3.9: Location of sensor at Melandaha

3.3.7 Jhalokathi. The district of Jhalokathi is in the southern part of Bangladesh. It is in the division of Barishal. Gaba is the name of the union under Jhalokathi upazila where sensor was set. Sensor was placed in a tin shed house and the coordinate of the sensor is 22° 46′ 06″ N; 90° 13′ 16″ E. Location of sensor at Jhalokathi is shown in Figure 3.10.

Figure 3.10: Location of sensor at Jhalokathi

3.3.8 Kumarkhali. Kumarkhali is a district under the Kushtia. Sensor was placed at Elongipara which is close to the upazila sadar. The sensor was placed on a rooftop of a one storeyed house located inside a farm house. Coordinate of the sensor is 23° 51′ 37″ N; 89° 13′ 46″ E. Location of sensor at Kumarkhali is shown in Figure 3.11.

Figure 3.11: Location of sensor at Kumarkhali

3.3.9 Mirzapur. Mirzapur is in Tangail district under Dhaka division. Sensor was located at Charpara under Sadar upazila and placed on a rooftop of a one storeyed house at the rural site. Coordinate of the sensor is 24° 04′ 12″ N; 90° 06′ 11″ E. Location of sensor at Mirzapur is shown in Figure 3.12.

Figure 3.12: Location of sensor at Mirzapur

3.3.10 Muksudpur. Muksudpur is an upazila in the Gopalganj district. Sensor was placed in a peri urban area on the rooftop of a building. Tengrakhola is the name of the sensor location which is inside the Sadar upazila. Coordinate of the sensor is 23° 19′ 00″ N; 89° 52′ 19″ E. Location of sensor at Muksudpur is shown in Figure 3.13.

Figure 3.13: Location of sensor at Muksudpur

3.3.11 Natore. Natore district under Rajshahi division is surrounded by Naogaon and Bogura districts on the North., Tomaltola which is 15 km away from the Natore town where the sensor was set. It was placed on the rooftop of a building. Coordinate of the sensor is 24° 18′ 48″ N; 88° 56′ 07″ E. Location of sensor at Natore is shown in Figure 3.14.

Figure 3.14: Location of sensor at Natore

3.3.12 Netrokona. Netrokona is a district in the northern part of Bangladesh. It is surrounded by the Indian state of Meghalaya to the north. Sensor is located at Kurpara which is a peri urban area of the Sadar upazila. The sensor was placed at the rooftop of a building of the peri urban area. Coordinate of the sensor is 24° 51′ 47″ N; 90° 43′ 48″ E. Location of sensor at Netrokona is shown in Figure 3.15.

Figure 3.15: Location of sensor at Netrokona

3.3.13 Pabna. Pabna is a district at central Bangladesh. Sensor is located at Haribaria which is farmhouse with 12 ponds and sensor was placed at tin shed building of the farmhouse. Coordinate of the sensor is 24° 02′ 30″ N; 89° 15′ 37″ E. Location of sensor at Pabna is shown in Figure 3.16.

Figure 3.16: Location of sensor at Pabna

3.3.14 Rajbari. District Rajbari is in the Dhaka division. The sensor was set close to the Patutria ferry ghat on a roof top of a building. Coordinate of the sensor is 23° 42′ 19″ N; 89° 42′ 33″ E. Location of sensor at Banaripara is shown in Figure 3.17.

Figure 3.17: Location of sensor at Rajbari

3.3.15 Ramu. Ramu is an upazila of Cox's Bazar district. Sensor was located in Dariardighi which is close to the Ramu cantonment. Sensor was placed on the roof top of the building and the coordinate of the sensor is 21° 20′ 34″ N; 92° 06′ 38″ E. Location of sensor at Ramu is shown in Figure 3.18.

Figure 3.18: Location of sensor at Ramu

3.3.16 Shahzadpur. Shahzadpur is an upazilla under Sirajganj district. A rural site at Sarisakol was selected for the sensor, and it was placed on the roof top of a tin shed building. Coordinate of the location is 24° 12′ 21″ N; 89° 34′ 54″ E. Location of sensor at Shahzadpur is shown in Figure 3.19.

Figure 3.19: Location of sensor at Shahzadpur

3.3.17 Sreepur. Sreepur is an upazilla located in Gazipur district. The location is 40 km away from Dhaka city. Sensor was placed on the roof top of a tin shed building. Coordinate of the location is 24° 13′ 42″ N; 90° 23′ 06″ E. Location of sensor at Sreepur is shown in Figure 3.20.

Figure 3.20: Location of sensor at Sreepur

3.3.18 Jaintapur. Jaintapur is located at the border of Sylhet division. It is an upazilla bordered with Meghalaya state of India on the north. Sensor was placed outside the rest house which is only 200 m away from the international border. It was placed in a tin shed building and the coordinate of the location is 25° 10′ 53″ N; 92° 03′ 46″ E. Location of sensor at Jaintapur is shown in Figure 3.21.

Figure 3.21: Location of sensor at Jaintapur

3.3.19 Nilphamari. Nilphamari is an upazilla located in the Northern side of the country. The site is close to the international border. The sensor was located at the Darwani textile bazar, and it was placed outside of a tin shed building. Coordinate of the location is 25° 53′ 18″ N; 88° 51′ 48″ E. Location of sensor at Nilphamari is shown in Figure 3.22.

Figure 3.22: Location of sensor at Nilphamari

3.3.20 Munshiganj. Munshiganj is an upazilla close to Dhaka. The sensor was set at Damla which is close to Sreenagar. A rural site was selected for the sensor, and it was placed outside of a tin shed building. Coordinate of the location is 23° 31′ 10″ N; 90° 15′ 38″ E. Location of sensor at Munshiganj is shown in Figure 3.23.

Figure 3.23: Location of sensor at Munshiganj

3.4 Data Collection at Rural Sites

Data collection at each selected rural location spanned approximately two months for each season. With a total of ten available sensors, a rotating network was employed to gather data at these locations. The process involved deploying the first set of sensors at the DoE site for one month in April-May 2022. Afterward, these sensors were deployed at 10 rural locations for two months, covering the period from May to July 2022 for wet season data collection. Subsequently, the same set of sensors was relocated to another 10 rural locations for data collection during the wet season, spanning from August to October 2022.

During November 2022, the sensors were moved back to the DoE site to collect dry season co-location data. Following this, the sensors were redeployed to the previously selected rural locations for additional data collection in December 2022 and January 2023 for the first batch of locations for dry season data collection. Finally, between February and March 2023, the remaining ten locations were covered for dry season data collection. Appendix A presents the details on the field data collection period with coordinates of the study area.

Throughout the data collection period, continuous measurements were obtained, and the data were stored on an SD card at two-minute intervals. The collected data comprised $PM_{2.5}$ mass concentrations, as well as temperature and humidity measurements. Appendix B and Appendix C provide daily average $PM_{2.5}$ concentrations from the rural sites for wet and dry period respectively.

3.5 Data Analysis

Data analysis in this study involved characterizing $PM_{2.5}$ pollution levels in both wet and dry seasons at each rural location using data collected from PurpleAir sensors. Each sensor had two identical plant tower sensors, both logging $PM_{2.5}$ concentrations at two-minute intervals. These sensors recorded two types of data: one using factory calibration ($PM_{2.5}$_cf1) and another adjusted for atmospheric conditions (temperature and humidity) using the internal calibration factor ($PM_{2.5}$_atm). Typically, $PM_{2.5}$_cf1 concentrations were higher than $PM_{2.5}$_atm. Further details on PurpleAir sensor and its data structure are given in Appendix D.

Co-location calibration against a DoE monitor revealed that $PM_{2.5}$_atm data closely matched the data from the reference monitor. The consistency of measurements from both sensors in a PurpleAir unit was cross-checked, and in most cases, the measurements matched within ±10%. In instances where deviations beyond ±10% occurred, those data points were discarded, though they constituted less than 5% of the dataset over an entire season. Subsequently, the hourly averages were computed for further analysis. These hourly average data from PurpleAir were then corrected using calibration models developed from co-location experiments at DoE CAMS, with the resulting data considered as BAM (Beta Attenuation Monitor) equivalent concentrations.

The corrected $PM_{2.5}$ concentrations from each sensor were analyzed to investigate the spatial and seasonal variability in measured concentrations at rural locations. For context, these rural data were compared with measurements from Dhaka city center, collected at the DoE CAMS station over the period of rural measurements. This comparison allowed for insights into the regional background and localized urban $PM_{2.5}$ levels in Bangladesh.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter presents the main findings of the study, including the performance evaluation of low-cost sensors, the spatial and seasonal trends in measured $PM_{2.5}$ concentrations at 20 rural locations across Bangladesh, and a comparison with measurements from Dhaka CAMS locations.

4.2 Performance Evaluation of Low-cost Sensors

4.2.1 Co-location Data Set

Figures 4.1 and 4.2 display the co-location data sets collected during the wet and dry seasons, respectively. The visual representation of the time series data indicates that the responses from all sensors are consistent and follow a similar trend to that measured by the reference $PM_{2.5}$ monitor. Good agreements were observed between the data from all sensors and the reference monitor in both seasons.

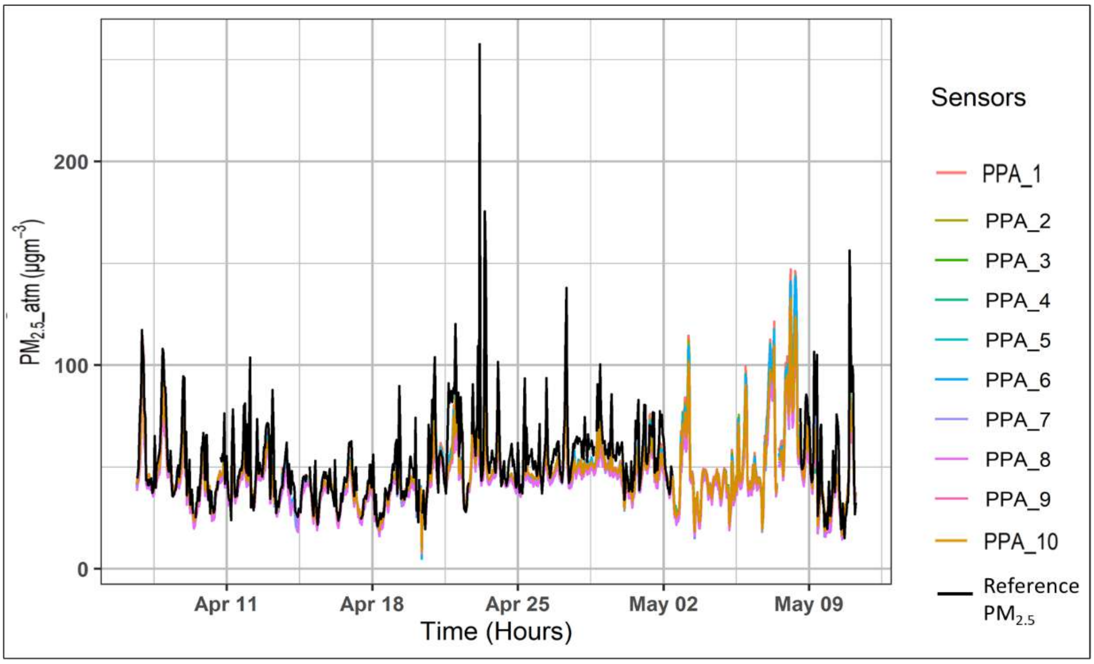

Figure 4.1: Hourly timeseries of co-location data set collected at DoE CAMS site during wet season

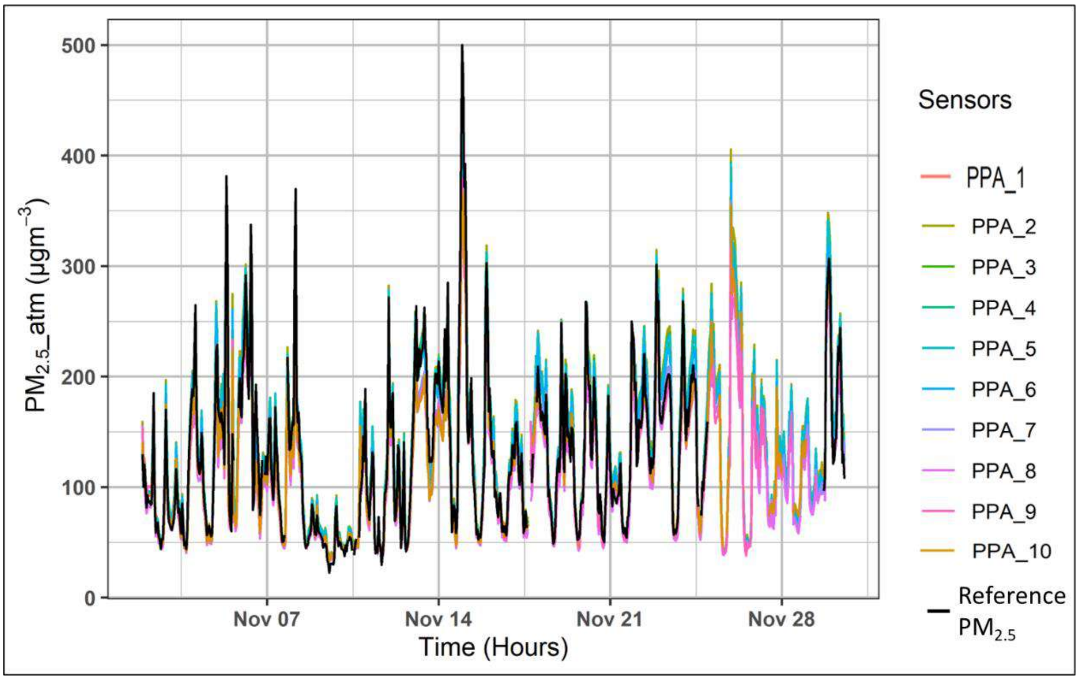

Figure 4.2: Hourly timeseries of co-location data set collected at DoE CAMS site during dry season

4.2.2 Consistency across Sensors

The measured concentrations from all sensors consistently showed agreement with each other. The pairwise coefficient of determination (R^2) values, as presented in Table 4.1 and 4.2 for the data collected during both wet and dry seasons, respectively ranged from 0.8 to 0.98, with an average of 0.9. Throughout the study, the sensors were placed in close proximity to each other and positioned within two feet of the reference station's probe. They were subjected to the same atmospheric conditions to establish relationships and correlations.

During the wet period, it was observed that all sensors exhibited a strong correlation with R^2 values above 0.9. The highest correlation value of 1 was found between number of sensors, while the lowest value of 0.86 was found between sensor 8 and sensor 1. Similarly, in the dry period, all sensors displayed good correlation, with most correlation values exceeding 0.9. The highest value of 1 was also observed between the number of sensors, and the lowest value of 0.82 was observed between sensor 8 and sensor 2.

Table 4.1: Pairwise correlation between the hourly time series data measured by different PurpleAir sensors and the reference monitor during co-location in the wet season

	PA_1	PA_2	PA_3	PA_4	PA_5	PA_6	PA_7	PA_8	PA_9	PA_10	Reference Station
PA_1	1										
PA_2	0.99	1									
PA_3	0.98	1	1								
PA_4	0.99	1	0.99	1							
PA_5	0.98	1	1	0.99	1						
PA_6	0.99	1	1	1	1	1					
PA_7	0.92	0.95	0.97	0.95	0.96	0.95	1				
PA_8	0.86	0.9	0.92	0.9	0.92	0.91	0.98	1			
PA_9	0.96	0.98	0.98	0.98	0.98	0.98	0.97	0.93	1		
PA_10	0.96	0.98	0.98	0.98	0.98	0.98	0.97	0.93	1	1	
Reference Station	0.74	0.69	0.66	0.66	0.67	0.69	0.55	0.47	0.62	0.62	1

Table 4.2: Pairwise correlation between the hourly time series data measured by different PurpleAir sensors and the reference monitor during co-location in the dry season

	PA_1	PA_2	PA_3	PA_4	PA_5	PA_6	PA_7	PA_8	PA_9	PA_10	Reference Station
PA_1	1										
PA_2	0.98	1									
PA_3	1	0.99	1								
PA_4	0.99	0.98	0.99	1							
PA_5	0.99	1	0.99	0.99	1						
PA_6	0.99	0.97	0.99	0.99	0.98	1					
PA_7	0.95	0.9	0.94	0.95	0.92	0.97	1				
PA_8	0.89	0.82	0.88	0.89	0.84	0.92	0.98	1			
PA_9	0.94	0.89	0.93	0.94	0.91	0.96	0.99	0.98	1		
PA_10	0.95	0.9	0.94	0.94	0.92	0.97	0.99	0.97	0.99	1	
Reference Station	0.93	0.92	0.93	0.94	0.93	0.94	0.91	0.86	0.91	0.9	1

The correlation between the sensors and reference station data was also determined for both the dry and wet periods. It was found that all the sensors showed moderate correlation with reference station during wet season, with correlation values from 0.47 to 0.74. The highest correlation value of 0.74 was observed between sensor 1 and reference station during the wet period, and the lowest value of 0.47 was observed between sensor 8 and reference station. In the dry period, the highest correlation value of 0.93 was observed between sensor 1 and reference station, and the lowest value of 0.86 was observed between sensor 8 and reference station. The effect of high relative humidity (RH) during wet season is likely a cause for observing relatively lower correlation value in wet season compared to the dry season.

4.2.3 Calibration Model

Season specific linear regression models were developed using $PM_{2.5}$ concentrations from all sensors compared to the data from the reference monitor, with hourly time resolution data. Initially, multiple models were explored using data from individual sensors. During the initial analysis, it was found that a combined model utilizing data from all sensors and all seasons performed nearly as well as the sensor specific models.

Figure 4.3 presents a visualization of the data from various sensors and seasons in comparison to the reference monitor data from DoE CAMS. In Figure 4.3, the blue line on the plot represents the linear regression line of the dataset for wet period and the green line on the plot represents the linear regression line of the dataset for dry period.

A relationship between reference $PM_{2.5}$ and PurpleAir measured $PM_{2.5}$ was established, represented as $y = 0.958x – 3.33$ for dry period, and $y = 1.41x – 10.87$ for wet period where 'x' represents the sensor data. The R^2 value of this relationship is 0.84 for wet period and 0.92 for dry period, indicating a strong correlation. Additionally, the root mean square error (RMSE) of this model is 8.65 $\mu g/m^3$ for wet period and 20.96 $\mu g/m^3$ for dry period providing a measure of the accuracy of the predictions. When normalizing the RMSE by mean concentrations from the reference monitor, it was found that the normalized RMSE remained within 15-20% for both seasons, further supporting the reliability of the model.

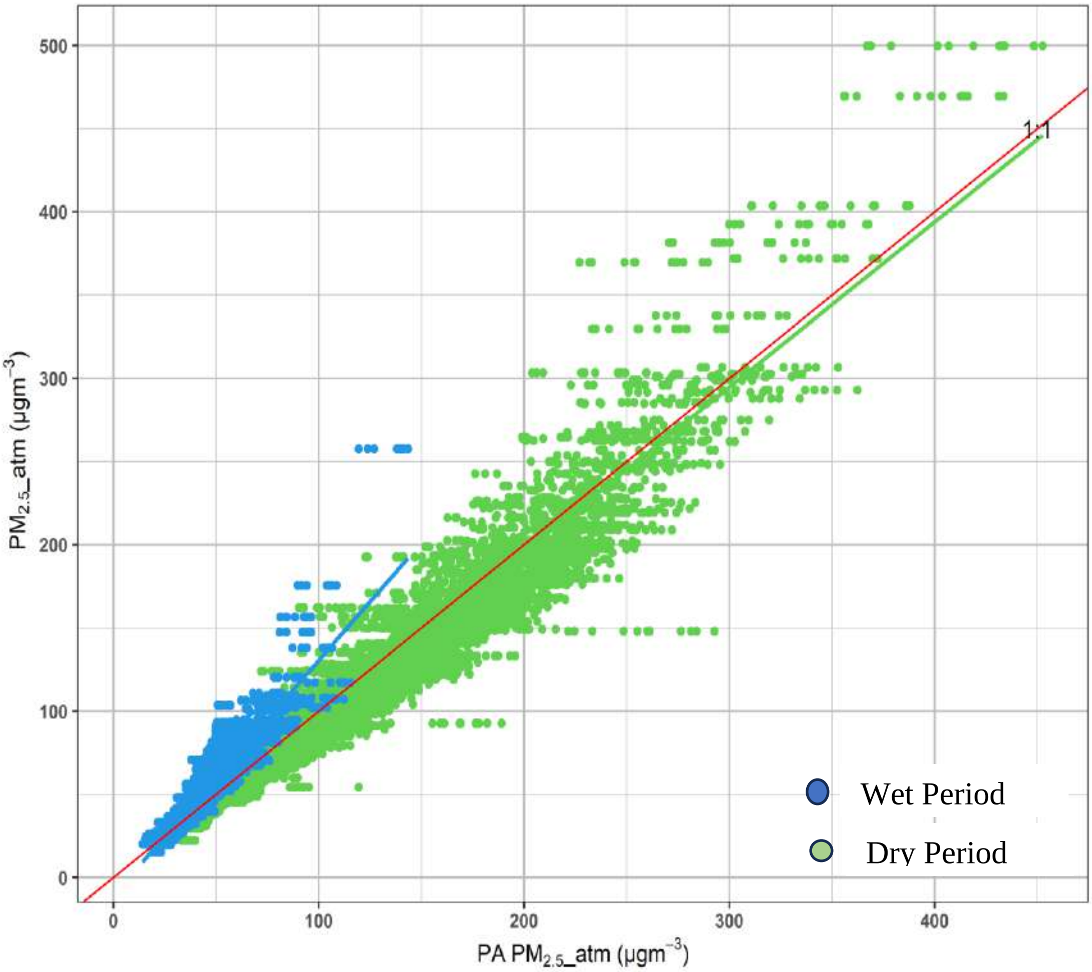

Figure 4.3: A scatter plot of co-located $PM_{2.5}$ concentration measurements from the reference $PM_{2.5}$ monitor at DoE CAMS site and PurpleAir measured $PM_{2.5}$

4.3 Measured $PM_{2.5}$ in Rural Areas

4.3.1 Measured Average $PM_{2.5}$ Levels at Rural Sites

During dry and wet periods, sensors were deployed at twenty locations for a duration of sixty days (two months). The data coverage from each study area was generally high, with over 90% of data received from most of the stations. The lowest data frequency was 42 days out of 60 days, mainly due to occasional power interruptions and short periods of sensor malfunctions. However, the data from the Moksudpur site during the dry period were not considered in the analysis. This decision was made because the sensor at this site recorded extremely unreasonable concentrations, around 3000 μg/m^3, throughout the entire deployment period, indicating sensor failure. Consequently, data from this site was discarded.

Table 4.3 and 4.4 present the descriptive statistics of $PM_{2.5}$ concentrations during the wet and dry seasons, respectively. Data collected from the rural sites and corrected by the calibration models according to the seasons are displayed in the tables with mean. median, maximum, minimum, and standard deviation data.

The average concentration of $PM_{2.5}$ ranged between 49-98 $\mu g/m^3$ during the wet period and 55-214 $\mu g/m^3$ during the dry period. During the wet period, the $PM_{2.5}$ concentrations showed relatively similar levels across all locations. The highest concentration was found in Shibganj (98 $\mu g/m^3$), while the lowest concentration was observed in Melandaha (49 $\mu g/m^3$). In contrast, during the dry period, the highest concentration was recorded in Nilphamari (214 $\mu g/m^3$), and the lowest concentration was observed in Jaintapur (55 $\mu g/m^3$).

The concentration during the dry period was 2-3 times higher than during the wet period. The bar graphs in Figures 4.4 and 4.6 visually depict the average concentrations from each site during the wet and dry seasons, respectively. During the wet period, the average concentration at all locations exceeded the WHO guidelines (Figure 4.4), but some locations fell within the National Ambient Air Quality Standards (NAAQS) range. However, during the dry period, the $PM_{2.5}$ concentration remained significantly high across the entire country. The average concentration of all locations exceeded both the NAAQS and WHO guidelines during this period (Figure 4.6).

While Figures 4.4 and 4.6 shows season-wise average concentration from each site, to show the variability in measured concentrations, Figures 4.5 and 4.7 present the box-whisker plot of data set collected in rural locations during wet and dry season, respectively. Overall, the measured data set highlights that air quality in rural areas of the country is a concern, particularly during the dry season, as pollution levels often surpass the tolerable limits.

Table 4.3: Descriptive statistics of measured $PM_{2.5}$ concentrations at various rural locations during the wet season

Sr	Location	Mean (μg/m³)	Median (μg/m³)	Max (μg/m³)	Min (μg/m³)	SD (μg/m³)
1	Melandaha	49	43	171	12	28
2	Eidgaon	53	53	69	39	6
3	Mirzapur	53	51	80	38	10
4	Ramu	55	47	147	18	28
5	Hathazari	56	53	82	45	10
6	Shahzadpur	56	56	77	37	11
7	Rajbari	57	55	82	39	11
8	Banaripara	58	54	97	44	11
9	Jaintapur	58	56	89	44	11
10	Muksudpur	64	63	103	41	11
11	Natore	65	61	105	39	16
12	Sreepur	67	65	106	36	19
13	Kumarkhali	68	66	112	41	16
14	Pabna	71	68	110	40	16
15	Netrokona	73	72	103	47	13
16	Chandina	73	71	110	51	14
17	Munshiganj	77	64	148	42	27
18	Jhalokathi	79	76	116	32	20
19	Nilphamari	87	90	132	55	18
20	Shibganj	98	98	101	92	1

Table 4.4: Descriptive statistics of measured $PM_{2.5}$ concentrations at various rural locations during the dry season

Sr	Location	Mean (μg/m³)	Median (μg/m³)	Max (μg/m³)	Min (μg/m³)	SD (μg/m³)
1	Melandaha	114	101	376	29	56
2	Eidgaon	154	151	242	99	29
3	Mirzapur	135	132	237	54	47
4	Ramu	159	159	220	97	24
5	Hathazari	166	158	551	60	57
6	Shahzadpur	210	213	290	115	39
7	Rajbari	110	106	189	41	36
8	Banaripara	95	100	183	28	38
9	Jaintapur	55	53	109	17	21
10	Natore	201	200	289	154	34
11	Sreepur	122	122	212	43	48
12	Kumarkhali	121	117	219	47	41
13	Pabna	122	113	295	11	66
14	Netrokona	213	213	310	112	42
15	Chandina	139	141	237	51	49
16	Munshiganj	95	94	167	29	36
17	Jhalokathi	87	86	193	28	39
18	Nilphamari	214	215	302	120	46
19	Shibganj	196	204	263	112	37

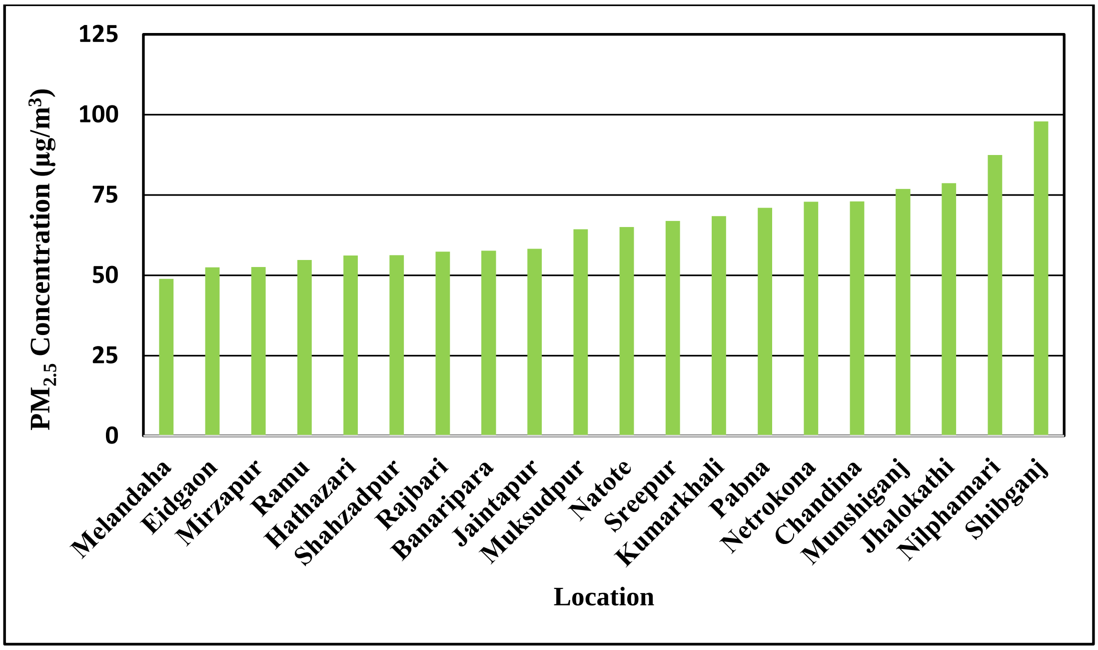

Figure 4.4: Average $PM_{2.5}$ concentrations measured at rural sites during the wet season

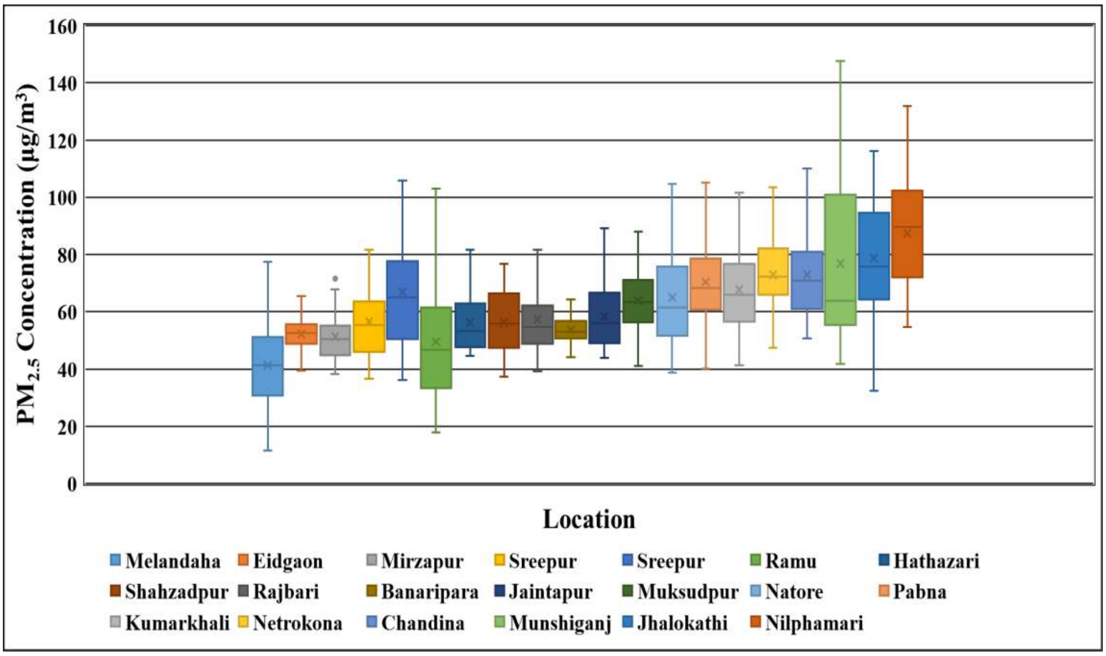

Figure 4.5: Box-Whisker plot of hourly $PM_{2.5}$ concentrations measured at rural sites during the wet season

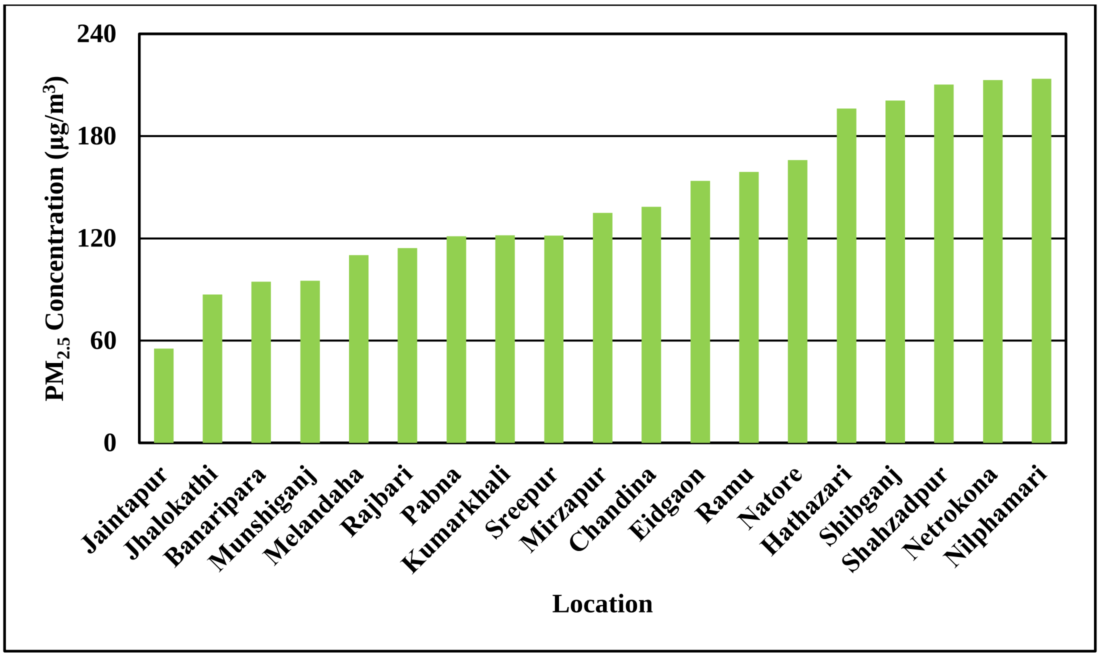

Figure 4.6: Average $PM_{2.5}$ concentrations measured at rural sites during the dry season

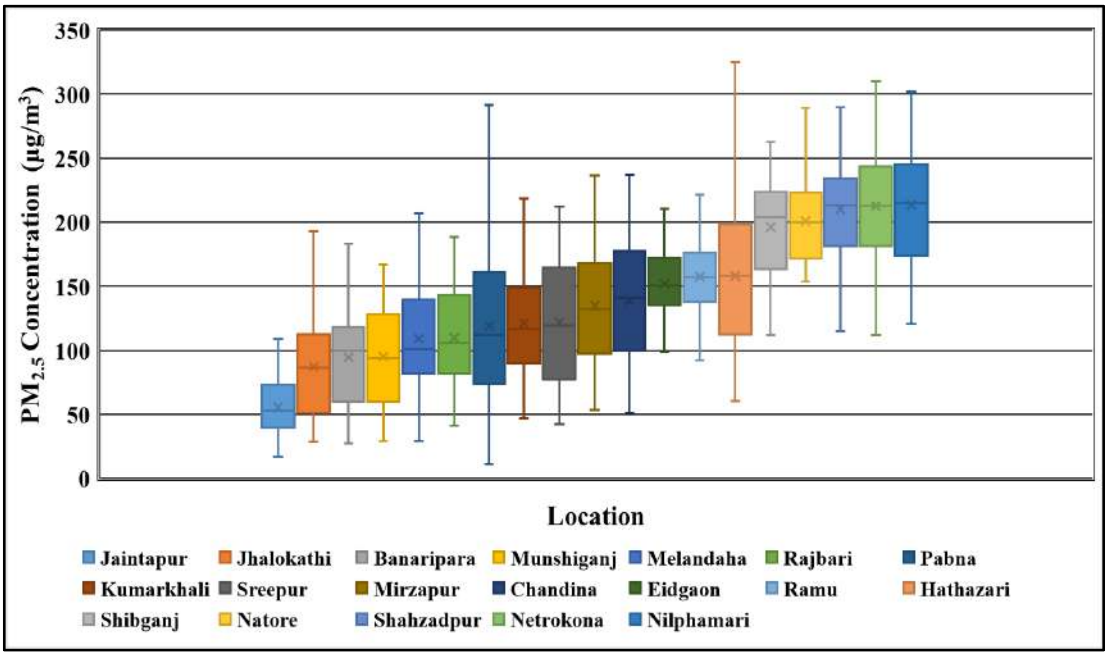

Figure 4.7: Box-Whisker plot of hourly $PM_{2.5}$ concentrations measured at rural sites during the dry season

4.3.2 Seasonal Variation in Measured $PM_{2.5}$ Levels at Rural Sites

Figure 4.8 summarizes the seasonal variations in measured $PM_{2.5}$ concentrations at different rural sites across Bangladesh. On average, concentrations during the dry season are consistently 2-3 times higher than during the wet season. This strong seasonal difference in $PM_{2.5}$ concentrations aligns with findings from previous studies conducted in urban areas (Faisal et al., 2022).

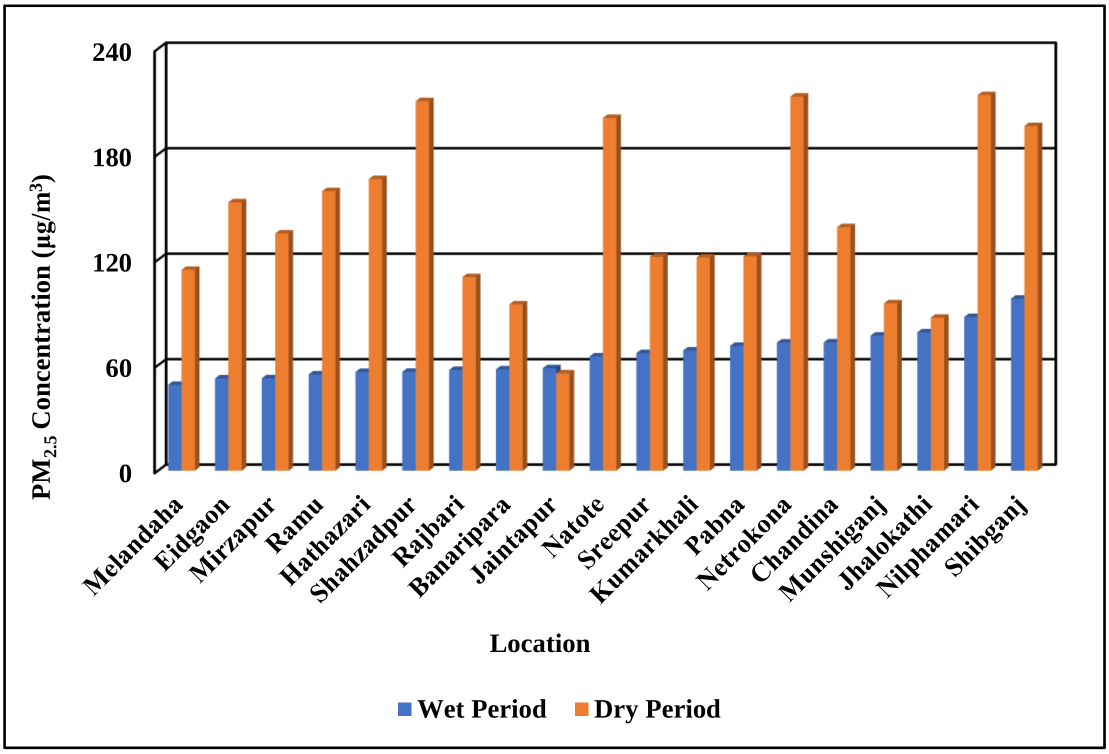

Figure 4.8: Seasonal variations in measured $PM_{2.5}$ concentrations at different rural locations.

The observed strong seasonal differences in measured concentrations are likely influenced by meteorological conditions, influx of transboundary air pollution, and seasonal sources. During the wet seasons, pollution is washed out through precipitation processes. The predominant wind during the monsoon season comes from the Bay of Bengal, leading to lower influx of transboundary air pollution from neighboring Indian states.

The lower mixing height in the dry season causes a reduced dispersion of pollution, leading to higher concentrations (Gopalaswami et al.,2016). Additionally, seasonally varying sources such as biomass burning in brick production and construction activities have strong influence in local and regional air pollution during dry season (Begum et al.,2010). Furthermore, the predominant westerly wind during the dry season results in a substantial influx of transboundary pollution from the Indo-Gangetic Plains (IGP) states of India (Rahman et al.,2020). These combined factors contribute to the significant increase in $PM_{2.5}$ concentrations during the dry season compared to the wet season.

4.3.3 Regional Variation in Measured $PM_{2.5}$ Levels at Rural Sites

While strong seasonal variations in measured concentrations exist at rural locations, within each season, concentrations vary significantly across sites. Table 4.5 and 4.6 provide a summary of the average concentrations from each site during the wet and dry seasons, respectively, grouped by regional zones (western, central, and eastern). To provide a visual representation of these regional zones, Figure 4.9 illustrates the boundaries of these zones on the map of Bangladesh.

Regional patterns can be observed in these variations, with concentrations generally being higher in locations in the western part of the country compared to the central and eastern parts. Influx of transboundary air pollution is likely an important factor for this spatial trend. Central zone also experiences high concentration of $PM_{2.5}$.

In the dry period, elevated concentration was observed at some sites in eastern zone, indicating variation in local sources could play a role in observed concentration at different sites. Rural sites of the eastern zone which are close to the coastal area may have an influence of local sources such as sea salt particles.

Table 4.5: Average measured $PM_{2.5}$ concentrations from different rural locations during the wet season, grouped by regional zone

Western Zone	**Mean** (μg/m^3)	**Central Zone**	**Mean** (μg/m^3)	**Eastern Zone**	**Mean** (μg/m^3)
Shibganj	98	Munshiganj	77	Jaintapur	58
Pabna	71	Sreepur	67	Hathazari	56
Natore	65	Mirzapur	53	Netrokona	73
Shahzadpur	56	Moksudpur	64	Ramu	55
Nilphamari	87	Melandaha	49	Chandina	73
Kumarkhali	68	Rajbari	57	Eidgaon	53
Average	**74**		**61**		**61**

Table 4.6: Average measured $PM_{2.5}$ concentrations from different rural locations during the dry season, grouped by regional zone

Western Zone	**Mean** (μg/m^3)	**Central Zone**	**Mean** (μg/m^3)	**Eastern Zone**	**Mean** (μg/m^3)
Shibganj	196	Munshiganj	95	Jaintapur	55
Pabna	122	Sreepur	122	Hathazari	166
Natore	201	Mirzapur	135	Netrokona	213
Shahzadpur	210	Moksudpur	-	Ramu	159
Nilphamari	214	Melandaha	114	Chandina	139
Kumarkhali	121	Rajbari	110	Eidgaon	154
Average	**177**		**115**		**148**

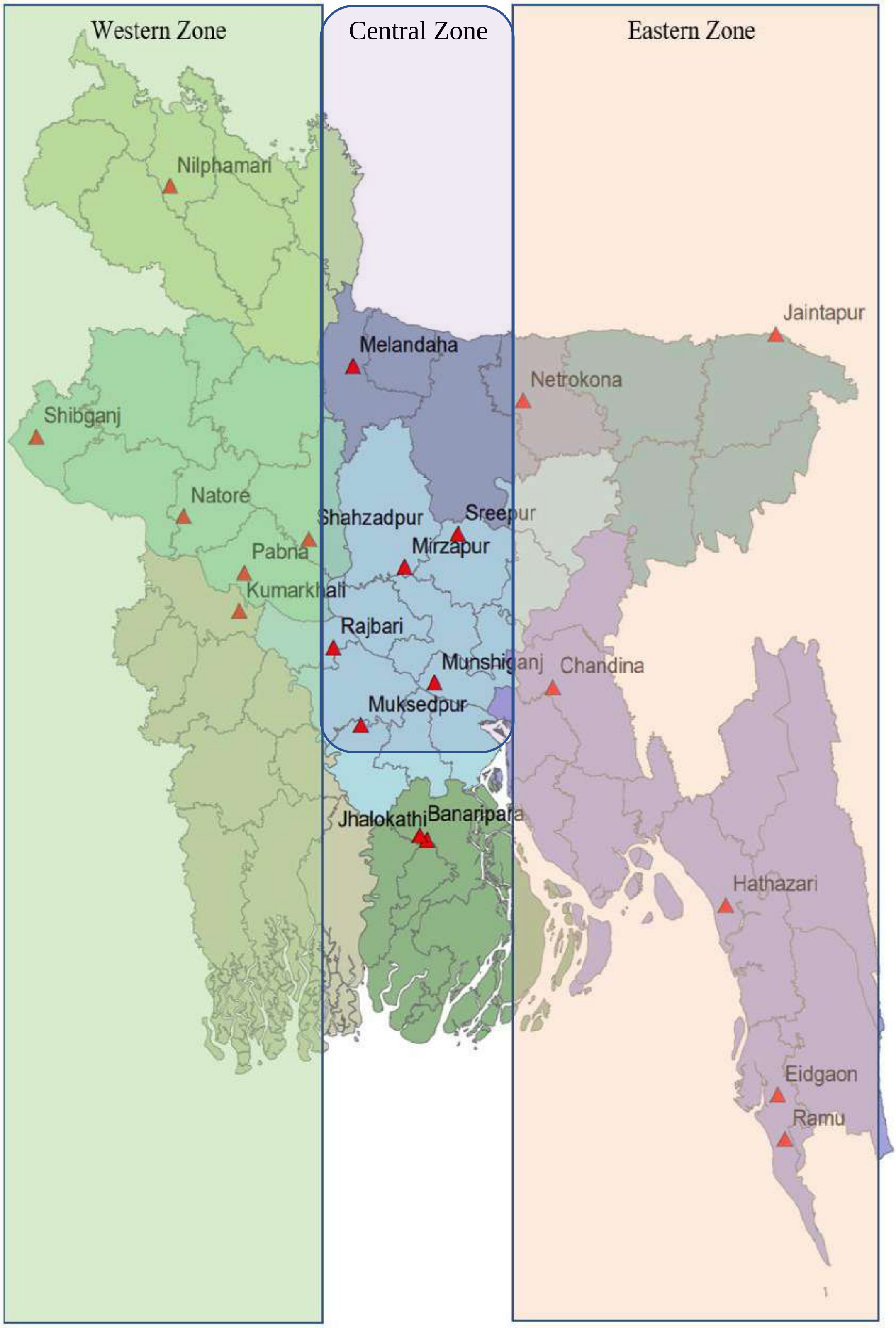

Figure 4.9: Regional zone boundaries for comparing variation in measured $PM_{2.5}$ levels at rural sites

4.4 Comparison of Rural $PM_{2.5}$ Levels with Dhaka City Center

To provide context, the measured average $PM_{2.5}$ concentrations from rural locations were compared with concentrations from Dhaka city during the measurement period. Dhaka is one of the most polluted megacities in South Asia, often experiencing extreme episodes of $PM_{2.5}$ pollution. For this comparison, $PM_{2.5}$ data from two sites within Dhaka city were used: one from the DoE CAMS at Darussalam and another from the $PM_{2.5}$ monitor at the US Embassy in Dhaka. The hourly average concentrations from these sites for the period when rural measurements were available were compared. Figures 4.10 and 4.11 display these comparisons for the wet and dry seasons, respectively.

The analysis indicated that the measured $PM_{2.5}$ concentrations at rural locations were either comparable to or remained within 10-15% of the concentration levels measured in Dhaka city. Concentrations measured at the two sites within Dhaka city also showed some variations, ranging between 10-15%. Generally, the concentration levels measured in rural locations were slightly lower than the levels in Dhaka city, with the difference remaining within 10-15%. However, in many locations, the concentrations measured in rural areas were higher than the levels in Dhaka city, particularly in the western part of the country.

These relatively minor differences between rural and city center $PM_{2.5}$ concentration levels highlight the dominance of regional $PM_{2.5}$ levels in Bangladesh. While urban city centers show slightly higher concentration levels due to the intensity of local sources, a major part of $PM_{2.5}$ pollution levels across Bangladesh is dominated by regional pollution, consistent with the regional nature of $PM_{2.5}$ pollution. A significant portion of this regional pollution is likely from secondary $PM_{2.5}$, which is expected to be distributed homogeneously across the region. The higher pollution levels observed in the western part of the country are likely driven by transboundary influx of pollution from neighboring areas.

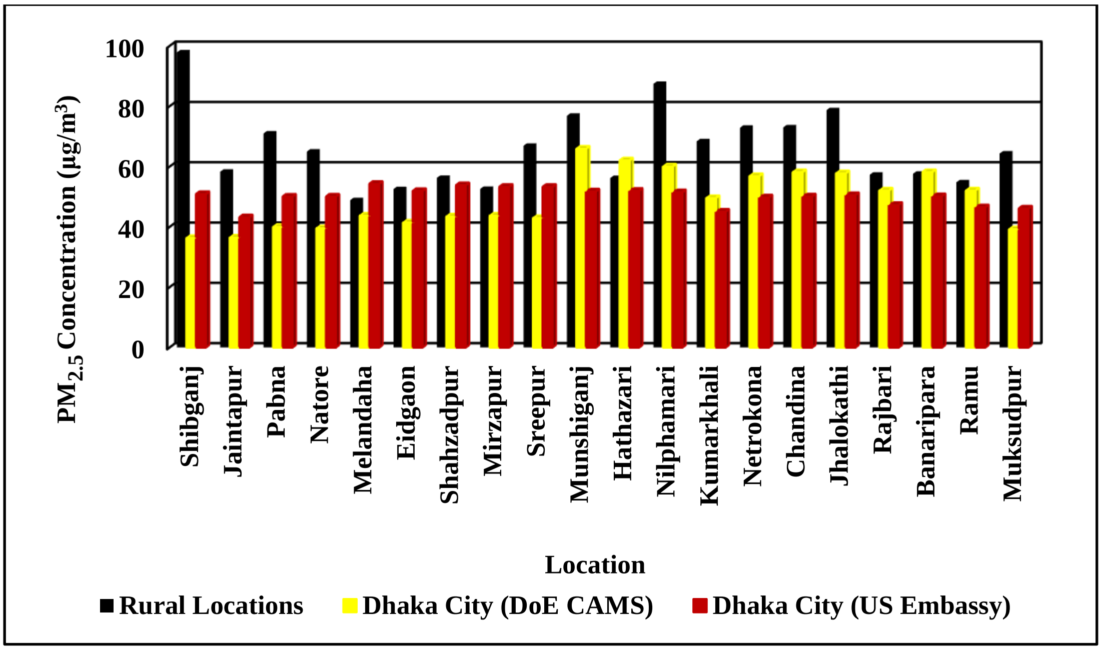

Figure 4.10: Comparison of average $PM_{2.5}$ levels from the wet season measured at different rural locations with concentration levels measured at two sites in Dhaka city over the same period

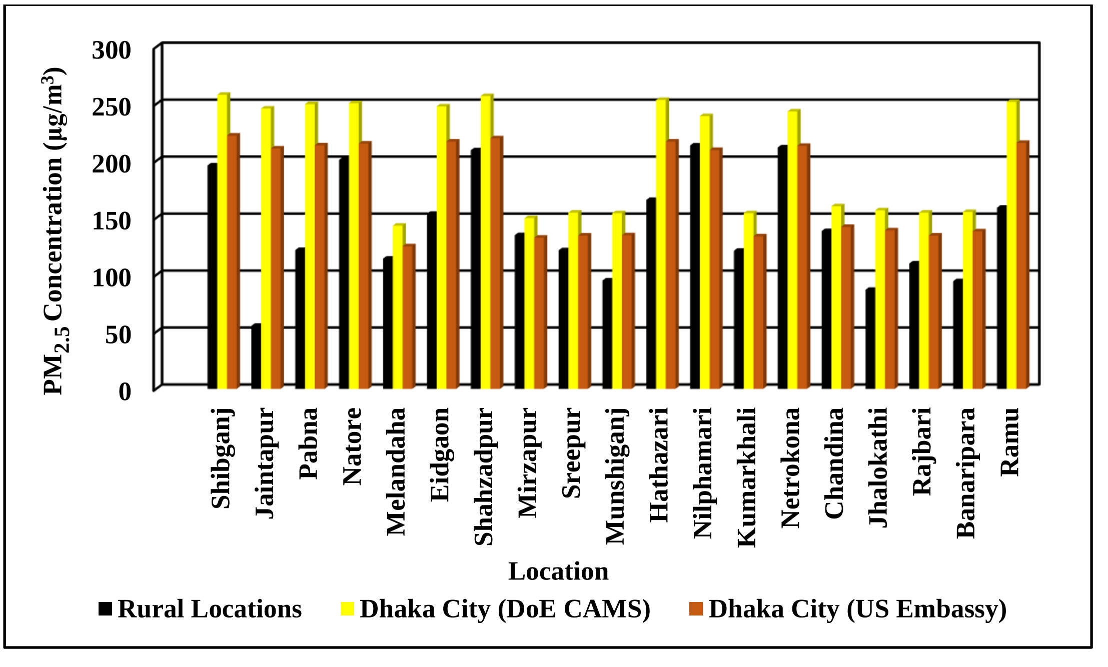

Figure 4.11: Comparison of average $PM_{2.5}$ levels from the dry season measured at different rural locations with concentration levels measured at two sites in Dhaka city over the same period

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 General

This study aims to characterize the levels of fine particulate matter ($PM_{2.5}$) pollution across Bangladesh using a network of low-cost sensors. Before deploying these sensors to rural sites, they were calibrated against a reference $PM_{2.5}$ monitor at DoE continuous air monitoring stations. This calibration process involved gathering data continuously for one month during the dry season and another month during the wet season**.**

Over the course of four months, including two months in the dry season and two months in the wet season, continuous measurements were taken at 20 rural sites. The raw data collected from these rural deployments were then corrected using calibration models developed from the co-location deployments.

After ensuring the data's quality, a thorough analysis was conducted to determine pollution levels at rural sites and their seasonal variability. Additionally, a comparison was made between the pollution levels at rural sites and those at the urban city center, specifically Dhaka.

The subsequent sections of this study provide a summary of the key findings obtained from these analyses.

5.2 Conclusions

The major findings and conclusions are summarized below:

a. Calibration of low-cost sensors against the reference monitor showed excellent agreement, with consistent sensor-to-sensor performance throughout the calibration process. The linear calibration models achieved an R^2 of 0.85 - 0.9, with a normalized RMSE between 10-15%.
b. The overall average levels of $PM_{2.5}$ measured across the 20 rural sites ranged from 50 to 215 μg/m^3. These levels were found to be substantially higher than the WHO interim target-1 of 35 μg/m^3, indicating that rural locations in Bangladesh have much higher pollution levels than what the WHO recommends.

c. Comparing pollution levels in rural areas to those in Dhaka, one of the most polluted South Asian megacities, revealed that pollution levels in many rural sites are comparable or within 10-20% of the levels in Dhaka. This suggests that regional pollution is the major driver of $PM_{2.5}$ pollution across the country, with an additional 10-20% contribution from local sources in urban city centers. As a result, focusing solely on urban areas and local sources may not be enough to improve air quality throughout Bangladesh.

d. Measured pollution levels in rural areas across Bangladesh exhibited a regional spatial gradient, with higher concentrations observed in the western and central parts of the country compared to the eastern part. This points to the influence of transboundary pollution from neighboring Indian states, particularly the Indo-Gangetic Plain (IGP) states in India.

e. During the wet season, measured $PM_{2.5}$ levels in rural areas ranged from 49 to 98 $\mu g/m^3$, while during the dry season, they varied between 55 and 214 $\mu g/m^{3.}$ This 2-3 times seasonal variability aligns with typical patterns observed in urban locations at DoE CAMS stations. These variabilities are primarily driven by meteorological factors, seasonal influx of transboundary pollution, and variations in local sources.

5.3 Recommendations for Future Study

The findings of this study emphasize the significant role of regional pollution in shaping $PM_{2.5}$ levels throughout Bangladesh. It is clear that addressing air quality issues requires strategies that go beyond localized urban efforts. Furthermore, the study sheds light on the seasonal variability and the impact of external transboundary pollutants on air quality in the country. Since these seasonal variations are primarily influenced by meteorological factors, which are not easily modifiable, addressing them directly may be challenging.

Given the substantial influence of regional and transboundary pollution, along with contributions from urban local sources, it is evident that a regional air shed approach to air quality management will be necessary to effectively tackle $PM_{2.5}$ pollution levels across Bangladesh. This approach should consider a broader geographical scope and cooperation between different regions to collectively address the issue. Implementing coordinated efforts on a regional scale will be crucial in making significant improvements in air quality and safeguarding public health throughout the country.

This study marks the first efforts in Bangladesh to comprehensively characterize pollution levels across the country. While data were collected over two seasons, it is important to acknowledge that, to capture the long-term dynamics of pollution levels, continuous measurements throughout the years would be essential.

The application of low-cost sensors in this study provided an excellent opportunity for affordable pollution measurements. However, it is crucial to conduct further research to characterize the long-term performance of these sensors over several years. If low-cost sensors can consistently collect good-quality data for 2-3 years with minimal disruption, they could be deemed suitable for long-term applications in rural areas. Thus, investigating the performance and reliability of low-cost sensors over extended periods should be a priority in future research.

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APPENDIX A

LOCATION OF STUDY AREA AND DATA COLLECTION PERIOD

Table A-1 Location of study area and data collection period

Ser	Location	Coordinates	Wet Period		Dry Period	
			Start	End	Start	End
1	Muksudpur	23° 19′ 00″ N 89° 52′ 19″ E	31-05-22	20-08-22	05-02-23	08-04-23
2	Shibganj	24° 41′ 29″ N 88° 09′35″ E	07-0622	12-08-22	07-12-22	30-01-23
3	Jaintapur	25° 10′ 53″ N 92° 03′ 46″ E	09-06-22	23-08-22	02-12-22	04-02-23
4	Pabna	24° 02′ 30″ N 89° 15′ 37″ E	29-05-22	08-08-22	01-12-22	31-01-23
5	Natore	24° 18′ 48″ N 88° 56′ 07″ E	29-05-22	30-07-22	02-12-22	30-01-23
6	Melandaha	25° 01′ 49″ N 89° 49′ 46″ E	20-05-22	04-08-22	19-02-23	11-04-23
7	Eidgaon	21° 33′ 08″ N 90° 53′05″ E	28-05-22	03-08-22	03-12-22	04-02-23
8	Shahzadpur	24° 12′ 21″ N 89° 34′ 54″ E	25-05-22	04-08-22	05-12-22	31-01-23
9	Mirzapur	24° 04′ 12″ N 90° 06′ 11″ E	23-05-22	22-07-22	17-02-23	15-04-23
10	Sreepur	24° 13′ 42″ N 90° 23′ 06″ E	21-05-22	30-07-22	08-02-23	11-04-23
11	Munshiganj	23° 31′ 10″ N 90° 15′ 38″ E	27-08-22	30-10-22	16-02-23	16-04-23
12	Hathazari	22° 27′ 33″ N 91° 47′ 51″ E	25-08-22	26-10-22	03-12-22	31-01-23
13	Nilphamari	25° 53′ 18″ N 88° 51′ 48″ E	25-08-22	22-10-22	02-12-22	12-02-23
14	Kumarkhali	23° 51′ 37″ N 89° 13′ 46″ E	08-08-22	11-10-22	13-02-23	16-04-23
15	Netrokona	24° 51′ 47″ N 90° 43′ 48″ E	20-08-22	18-10-22	05-12-22	12-02-23
16	Chandina	22° 29′ 53″ N 92° 04′ 22″ E	19-08-22	20-10-22	01-02-23	02-04-23
17	Jhalokathi	22° 46′ 06″ N 90° 13′ 16″ E	20-08-22	21-10-22	04-02-23	05-04-23
18	Rajbari	23° 42′ 19″ N 89° 42′ 33″ E	13-08-22	14-10-22	09-02-23	11-04-23
19	Banaripara	22° 47′ 31″ N 90° 11′00″ E	19-08-22	22-10-22	04-02-23	06-04-23
20	Ramu	21° 20′ 34″ N 92° 06′ 38″ E	12-08-22	13-10-22	03-12-22	01-02-23

APPENDIX B

FIELD DATA (DAILY AVERAGE) - WET PERIOD

Table B-1 Field data (daily average) -wet period

Day Count	Muksudpur	Shibganj	Jaintapur	Pabna	Natore	Melandaha	Eidgaon	Shahzadpur	Mirzapur	Sreepur
D 1	42	61	40	67	65	31	31	75	48	45
D 2	46	62	28	83	65	27	25	95	85	58
D 3	46	48	31	50	61	47	36	79	66	48
D 4	41	49	22	52	49	53	21	64	54	90
D 5	48	54	21	53	45	109	27	86	74	73
D 6	38	59	17	55	42	129	24	81	67	68
D 7	41	50	14	47	46	85	24	73	66	61
D 8	46	46	13	43	47	77	16	60	79	76
D 9	45	45	10.	42	44	62	14	82	59	74
D 10	40	53	14	51	53	54	31	50	67	62
D 11	31	45	17	49	58	71	22	64	53	62
D 12	34	41	16	43	47	88	38	50	44	55
D 13	37	46	10	40	36	63	25	49	40	49
D 14	37	58	18	41	49	54	35	58	41	60
D 15	35	49	11	42	42	52	34	55	48	52
D 16	40	60	9	42	61	45	33	59	41	51
D 17	38	42	11	36	37	34	36	42	40	61
D 18	33	38	25	43	40	44	30	39	38	49
D 19	29	32	11	38	41	42	36	48	42	52
D 20	33	33	10	26	33	40	21	46	42	49
D 21	22	34	11	30	35	49	21	40	35	48
D 22	25	31	7	34	32	41	19	44	36	49
D 23	29	39	8	36	39	47	18	47	30	48
D 24	20	33	10	38	47	40	12	30	27	46
D 25	18	40	14	44	50	35	16	35	32	34
D 26	17	39	7	23	30	37	5	39	26	42
D 27	24	39	16	23	28	45	28	34	49	42
D 28	25	36	25	20	23	45	11	32	45	41
D 29	25	40	25	14	22	30	30	43	22	58
D 30	22	26	24	16	30	40	18	29	20	49
D 31	24	30	10	18	22	42	30	22	27	39
D 32	21	20	16	19	30	41	22	24	21	32
D 33	23	28	20	30	29	43	27	23	17	30
D 34	20	35	18	29	39	38	22	22	15	39
D 35	31	24	8	37	20	36	22	24	19	31
D 36	29	24	12	20	28	36	30	24	30	37
D 37	28	20	15	32	32	31	27	33	37	42
D 38	57	16	22	34	15	31	27	35	33	45

Table B-1 Field data (daily average) -wet period

D 39	26	20	9	32	25	30	18	34	27	41
D 40	32	25	6	34	17	24	23	22	33	35
D 41	43	21	9	19	17	38	26	30	38	36
D 42	22	24	21	41	20	37	36	41	25	45
D 43	24	35	25	19	12	37	24	28	31	52
D 44	37	41	9	22	17	30	21	32	18	34
D 45	47	39	25	39	15	31	16	21	20	47
D 46	40	34	10	34	8	43	22	27	16	35
D 47	18	26		11	19	58	31	23	15	30
D 48	13	22		26	11	23	22	19	14	29
D 49	20	37		13	10	36	37	20	14	17
D 50	25	35		39	14	31	21	20	14	20
D 51	21	35		17	23	44	21	19	17	22
D 52	19	43		23	36	32	30	28	18	22
D 53	24	50		36	30	24	28	20	14	30
D 54	44	52		34	31	23	16	19	13	27
D 55	59	48		54	31	22	12	20	28	24
D 56	74	51		56	25	16	19	23		33
D 57	23	57		25	30	22	24	38		37
D 58	22	42		48	33	23	34	35		48
D 59		38		32	31	20	37	39		44
D 60		30		31	51	24	41	37		43
D 61		34		30	52	24	35	29		37
D 62		31		39	39	41	29	28		35
D 63		31		41		37	30	38		43
D 64		18		46		23	26	38		53
D 65		18		47		38	23	40		63
D 66		22		64		24	32	42		52
D 67		33		65		39		38		62
D 68				68		27		37		48
D 69				46		37		44		
D 70				55		48		52		
D 71				33		67		59		
D 72				39		53		48		
D 73						37				
D 74						27				
D 75						45				
D 76						81				
D 77						30				

Table B-2 Field data (daily average) -wet period

Day Count	Munshiganj	Hathazari	Nilphamari	Kumarkhali	Netrokona	Chandina	Jhalokathi	Rajbari	Banaripara	Ramu
D 1	67	41	41	15	27	26	47	19	18	7
D 2	26	33	33	11	30	26	48	18	16	3
D 3	42	59	58	15	33	39	49	24	31	6
D 4	34	26	49	12	25	48	41	34	36	17
D 5	34	42	54	33	15	27	56	66	21	27
D 6	9	34	70	26	32	23	35	67	20	38
D 7	19	34	68	16	54	46	47	26	35	30
D 8	20	33	62	22	66	43	66	26	40	13
D 9	28	19	55	45	36	46	67	34	41	13
D 10	23	25	44	73	35	26	42	54	25	21
D 11	32	123	48	61	47	42	30	36	26	24
D 12	37	48	47	23	41	50	24	20	23	7
D 13	32	64	54	18	33	40	69	42	13	17
D 14	32	55	60	35	36	37	32	45	19	22
D 15	10	52	41	56	43	36	41	57	14	36
D 16	6	19	32	39	32	39	45	35	16	20
D 17	5	19	36	24	37	31	41	44	29	18
D 18	11	115	29	37	35	31	30	37	26	20
D 19	14	113	24	50	40	38	35	25	24	22
D 20	18	66	30	69	26	33	34	26	26	20
D 21	26	152	31	38	34	51	34	26	25	16
D 22	38	38	44	38	18	31	42	39	26	19
D 23	45	20	48	36	6	26	18	49	10	15
D 24	14	50	61	47	8	9	65	42	16	14
D 25	9	67	63	46	11	15	23	42	13	13
D 26	17	15	82	31	15	32	48	54	23	15
D 27	27	28	44	50	34	23	30	39	22	14
D 28	30	32	44	48	42	30	36	44	22	16
D 29	34	26	47	47	63	38	48	28	31	18
D 30	43	40	56	55	54	58	44	14	39	4
D 31	89	38	53	62	30	64	26	11	38	4
D 32	49	32	33	42	14	19	23	25	16	4
D 33	81	33	45	53	21	21	43	27	20	6
D 34	83	34	55	32	37	27	29	27	24	15
D 35	54	31	64	13	54	39	42	39	32	12
D 36	75	39	56	14	40	45	49	51	33	20
D 37	33	33	70	18	49	46	50	69	36	30
D 38	7	40	72	44	40	54	73	34	35	16
D 39	11	39	69	33	44	61	48	20	40	5

Table B-2 Field data (daily average) -wet period

D 40	7	39	35	37	68	68	50	29	33	7
D 41	16	36	19	56	43	94	66	32	43	19
D 42	22	40	30	77	58	75	48	41	54	26
D 43	36	26	40	36	74	64	47	47	51	32
D 44	24	28	46	14	30	66	43	53	40	36
D 45	13	22	56	37	12	35	35	60	32	27
D 46	9	28	41	36	18	23	29	51	18	22
D 47	14	33	46	43	16	20	34	65	16	21
D 48	13	22	33	53	38	28	40	39	20	33
D 49	36	24	29	44	66	41	50	52	23	47
D 50	79	20	43	51	56	48	29	64	27	43
D 51	54	16	53	71	37	59	38	34	36	25
D 52	57	20	72	61	39	40	24	28	22	6
D 53	75	25	81	46	26	45	38	28	24	14
D 54	67	21	78	72	32	25	23	26	17	18
D 55	70	24	72	77	47	42	78	26	13	15
D 56	59	35	76	28	77	45	66	36	29	16
D 57	64	41	81	30	55	61	63	39	26	27
D 58	87	39	67	23		76	54	34	54	26
D 59	34	34	51	33		74	80	25	49	18
D 60	37	26		31		85	68	22	52	25
D 61	47	22		36		83	60	25	68	24
D 62	92	37		49		69	70	30	59	17
D 63	89	28		44		72		39	66	10
D 64	75			34					64	
D 65	57			21					69	

APPENDIX C

FIELD DATA (DAILY AVERAGE) - DRY PERIOD

Table C-1 Field data (daily average)-dry period

Day Count	Eidgaon	Hathazari	Jaintapur	Natore	Netrokona	Nilphamari	Pabna	Ramu	Shahzadpur	Shibganj
D 1	156	90	38	173	314	146	76	192	124	186
D 2	169	102	27	168	188	164	28	156	172	182
D 3	173	81	27	171	175	195	30	131	190	172
D 4	184	87	29	183	187	172	23	152	205	155
D 5	153	103	28	175	188	172	91	144	204	198
D 6	141	119	26	187	237	190	156	136	210	243
D 7	112	66	21	186	226	187	173	100	233	267
D 8	174	68	24	191	221	160	170	122	265	252
D 9	148	215	33	182	266	228	210	183	305	160
D 10	154	122	41	216	287	211	164	162	299	174
D 11	210	291	54	242	259	237	217	176	239	229
D 12	188	169	55	287	237	280	256	192	252	233
D 13	217	579	59	305	238	292	312	207	257	206
D 14	223	112	70	243	215	297	308	188	248	206
D 15	162	82	81	205	276	298	270	167	216	251
D 16	133	115	48	242	296	264	218	148	212	199
D 17	127	123	34	221	294	175	122	172	244	193
D 18	156	87	36	197	259	172	139	183	247	217
D 19	150	231	49	193	202	228	132	200	210	225
D 20	141	174	48	237	218	271	130	186	263	259
D 21	164	282	45	227	246	243	117	166	207	217
D 22	157	230	48	228	125	232	185	208	229	170
D 23	158	212	52	224	162	214	203	172	204	243
D 24	110	194	56	234	152	252	147	162	244	234
D 25	118	208	77	283	193	253	171	185	240	241
D 26	113	201	91	241	180	220	153	165	184	216
D 27	140	247	88	201	197	311	120	119	185	268
D 28	181	209	78	215	257	206	118	188	190	157
D 29	191	127	62	227	257	214	150	235	183	155
D 30	209	155	77	227	226	268	173	180	138	161
D 31	107	222	65	209	174	212	91	142	132	182
D 32	162	243	52	198	193	245	134	263	168	247
D 33	185	196	45	179	220	164	185	206	144	239
D 34	148	201	51	186	212	129	186	146	191	221
D 35	143	143	67	164	230	175	75	137	236	278
D 36	184	228	82	164	212	176	31	168	243	220
D 37	150	139	75	193	183	148	93	129	214	206
D 38	192	151	67	243	204	205	104	143	223	260
D 39	177	145	41	179	270	234	53	148	223	274
D 40	256	169	36	213	323	258	79	171	279	231

Table C-1 Field data (daily average)-dry period

D 41	195	143	43	212	228	209	98	202	231	173
D 42	165	207	66	200	192	250	119	192	184	151
D 43	167	157	117	257	214	277	107	211	194	175
D 44	180	136	107	247	195	276	179	189	197	184
D 45	149	128	98	171	254	263	251	151	237	207
D 46	139	173	81	178	272	239	130	193	242	222
D 47	176	247	85	183	275	254	113	167	246	216
D 48	191	192	85	221	327	317	105	173	249	232
D 49	185	188	79	237	296	319	110	171	287	235
D 50	175		61	226	233	255	79	152	306	237
D 51	157		57	233	232	283	30	166	264	234
D 52	134		68	279	260	303	15	200	267	121
D 53	160		78	300	241	315	155	158	268	132
D 54			84	248	249	217	82	136	213	144
D 55			81	234	217	222	38	177	178	162
D 56			81	221	195	222	53	186	217	
D 57			87		224	246	164	161	247	
D 58			101		229	179		162	253	
D 59			97		199	211		177		
D 60			57		121	182		147		
D 61			49		172	211		138		
D 62			62		196	161				
D 63			67		248	185				
D 64			56		262	231				
D 65			51		272	260				
D 66					172	303				
D 67					172	244				
D 68					232	242				
D 69					241	135				
D 70					176	152				
D 71						214				
D 72						236				

Table C-2 Field data (daily average) -dry period

Day Count	Banaripara	Jhalokathi	Chandina	Muksudpur	Sreepur	Rajbari	Mirzapur	Munshiganj	Kumarkhali	Melandaha
D 1	194	176	192	3327	147	171	178	149	97	198
D 2	195	188	245	3328	210	172	243	178	151	175
D 3	182	205	218	3328	185	127	230	172	191	166
D 4	124	126	198	3327	92	70	207	147	232	116
D 5	80	97	137	3301	140	102	182	155	212	99
D 6	120	121	151	3327	168	148	110	109	204	91
D 7	154	143	195	3326	194	181	95	92	179	109
D 8	151	120	179	3326	209	178	132	82	156	187
D 9	121	96	157	3322	225	170	159	93	136	220
D 10	77	102	144	3325	214	153	187	142	102	155
D 11	108	136	160	3327	175	153	220	135	107	131
D 12	138	156	188	3327	166	124	186	126	142	123
D 13	140	148	216	3326	116	76	222	142	144	108
D 14	153	126	246	3324	99	80	251	152	153	107
D 15	136	118	251	3323	108	90	238	141	180	124
D 16	142	79	226	3326	101	116	220	130	189	396
D 17	134	75	201	3318	154	140	204	118	192	165
D 18	91	75	187	3321	185	158	186	146	209	140
D 19	74	80	131	3316	141	168	147	103	193	193
D 20	76	90	109	3308	183	200	141	95	184	206
D 21	84	102	136	3315	208	184	152	106	184	186
D 22	106	82	139	3313	206	164	154	140	168	172
D 23	113	93	139	3310	212	162	207	155	167	124
D 24	89	105	172	3307	188	166	140	157	140	150
D 25	124	121	164	3307	176	145	133	138	120	138
D 26	131	44	185	3307	181	114	162	127	162	138
D 27	123	109	196	3302	152	97	162	124	155	98
D 28	108	128	191	3302	143	95	169	115	130	96
D 29	107	119	179	3301	161	116	143	112	142	99
D 30	124	129	153	3302	186	151	153	133	153	37
D 31	123	102	155	3302	137	106	111	144	136	34
D 32	121	95	165	3302	129	119	59	93	129	55
D 33	119	113	140	3303	159	158	78	37	97	57
D 34	146	120	193	3310	153	115	87	34.	121	68
D 35	146	62	206	3315	117	113	108	55	90	81
D 36	130	33	186	3304	109	98	109	57	53	95
D 37	123	34	172	3294	135	119	103	68	88	73
D 38	112	43	124	3286	91	107	141	61	88	117
D 39	126	51	150	3317	53	47	79	50	124	102
D 40	89	57	138	3319	59	62	117	64	101	83

Table C-2 Field data (daily average) -dry

D 41	98	48	138	3306	103	68	102	68	105	89
D 42	110	45	98	3327	82	521	83	59	73	64
D 43	116	84	96	3314	73	513	89	65	101	86
D 44	65	78	114	3327	86	387	73	71	106	92
D 45	32	48	69	3324	70	575	88	60	59	82
D 46	40	57	57	3314	64	516	106	51	70	69
D 47	45	46	104	3310	96	117	111	55	59	95
D 48	57	53	73	3305	77	86	68	49	86	108
D 49	84	51	87	3309	70	538	100	51	92	115
D 50	60	64	112	3298	48	500	98	65	82	110
D 51	52	47	74	3299.	59	77	138	83	69	109
D 52	75	81	69	3300	83	88	153	99	95	157
D 53	90		117	3299	76	106	147	93	105	
D 54	54		86	3299	80	111	153	105	121	
D 55	66		77	3304	66	68	141	118	104	
D 56	45		57	3316	77	100	141	99	119	
D 57	56		87	3327	106	98	126	93	114	
D 58	58		63	3296	115	138	150	89	134	
D 59	62			3276	110	120		90	125	
D 60	47			3275	109	109		129	136	
D 61	51			3268	157	157			80	
D 62	43			3255						
D 63				3261						
D 64				3310						
D 65										
D 66										
D 67										
D 68										
D 69										
D 70										
D 71										
D 72										

APPENDIX D

DESCRIPTION OF PURPLEAIR LOW -COST SENSOR

1. Description of PurpleAir Low-Cost Sensor

The PurpleAir sensor contains two Plantower PMS5003 sensors. These sensors are labeled as channel A and Channel B. These sensors operate for alternating 10s intervals and provide 2 min averaged data. Plantower sensors measure 90° light scattering with a laser using 680 ± 10 nm wavelength light (Sayahi et al., 2019) and are factory calibrated using ambient aerosol across several cities in China (Malings et al., 2020). The Plantower sensors estimate particle matter which have aerodynamic diameters < 1 µm (PM_1), < 2.5 µm $PM_{2.5}$, and < 10 µm (PM_{10}). PM data are reported in two ways, labeled as cf_1 and cf_atm, in the PurpleAir dataset. Cf_atm data gives the direct value as received from the sensor and cf_1 indicates the data after applying a correction factor set by the manufacturer. The cf_atm data in the purpleAir data set gives a lower measurement of $PM_{2.5}$ than Cf_1. The PMS5003 sensor provides digital outputs for 12 data fields of PM for both the sensors. The first three correspond to the mass concentrations of PM_1, $PM_{2.5}$, and PM_{10} without applying any correction, and they are labeled cf_atm. The next three correspond to PM_1, $PM_{2.5}$, and PM_{10} after applying correction factor developed by Plantower Ltd. The PA-II also provides data for temperature, relative humidity, dew point, and barometric pressure of the study area. Remaining two fields record sensor operational time and date. Figure D-1 shows the key elements of PAIISD model sensor.

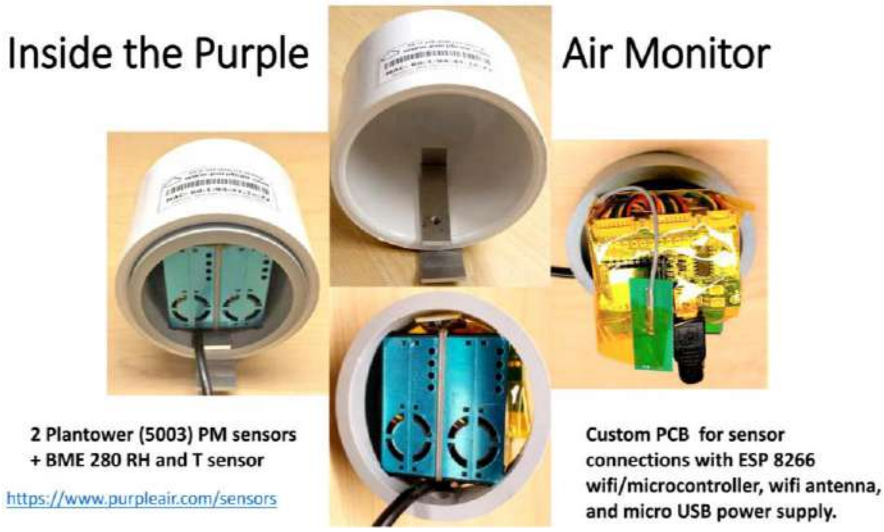

Figure D-1: Key elements of a PurpleAir $PM_{2.5}$ sensor, specifically the sensor model: PAII SD. The figure is sourced from www.purpleair.com.