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FIRST-TIME OBSERVATIONS OF FINE PARTICLE MATTER ($PM_{2.5}$) AT A RURAL SITE IN SOUTH INDIA – A CASE STUDY

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A B S T R A C T

For the first time, atmospheric fine particulate matter ($PM_{2.5}$) concentrations were measured using a low-cost particulate sensor in Bhimavaram (16.55°N; 81.52°E; 17 m above MSL), a rural site and coastal station in the southern state of Andhra Pradesh, India. The study utilized preliminary data collected between April and May 2023. Throughout this period, $PM_{2.5}$ concentrations exhibited notable temporal variations, with daily mean levels fluctuating between 5 and 60 µg/m^3. Additionally, there were instances of hourly concentrations reaching as high as 100 µg/m^3. The diurnal pattern of $PM_{2.5}$ concentrations revealed a distinct morning peak, a mid-afternoon minimum, and a broad secondary peak in the late evening. The temporal and diurnal variations in $PM_{2.5}$ concentrations are associated with the local sources (traffic, residential sources), local meteorology, and boundary-layer dynamics. This study provides valuable preliminary data on $PM_{2.5}$ concentrations in Bhimavaram, highlighting the need for further research to understand the sources, dynamics, and health impacts of air pollution in rural locations.

1. INTRODUCTION

The global hazards presented by climate change and air pollution are mostly caused by pollutants released into the atmosphere. Most vulnerable people are frequently the ones who suffer the most from these crises' detrimental effects. One of the biggest risks to global health is exposure to air pollution, which results in millions of early deaths and poor health each year. According to recent estimates, there are between 4 and 9 million premature deaths worldwide each year (Vohra et al., 2021) due to this unavoidable catastrophe.

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In rural regions, there is often a strong dependence on conventional cooking practices, predominantly using bio-fuels. However, these methods can result in the emission of pollutants such as particulate matter (PM), carbon monoxide (CO), and volatile organic compounds (VOCs). It is crucial to comprehend the nature of these pollutants to evaluate their potential implications for respiratory health and overall well-being. India, being an agrarian-based economy, still relies on agriculture. It is to be noted that many rural areas in India are involved in agriculture, and certain farming practices can contribute to air pollution. Pesticide use, crop residue burning, and other agricultural activities release pollutants that may affect air quality. All in all, air pollution studies in Indian rural and remote stations are essential for safeguarding public health, preserving ecosystems, informing policy decisions, and promoting sustainable development.

Recognizing these concerns, numerous prominent institutions and research and development organizations across India have initiated various endeavors to quantify air pollution (Balakrishnan et al., 2019). For instance, within India's state-level disease burden initiative on air pollution, it was reported that the annual population-weighted mean exposure to ambient PM2.5 in the country reached 89.9 $\mu g/m^3$ in 2017. In most states, approximately 76.8% of the Indian population faced an annual population weighted mean PM2.5 exceeding 40 $\mu g/m^3$, surpassing the limit recommended by the National Ambient Air Quality Standards (NAAQS) in India. In 2017, Delhi recorded the highest annual population-weighted mean PM2.5, followed by Uttar Pradesh, Bihar, and Haryana in northern India, all with mean values surpassing 125 $\mu g/m^3$. Various research studies from different parts of India employing low-cost sensors, including those at IIT Kanpur, Duke University campuses, and two selected sites in the Delhi National Capital Region, have been documented in the literature (Sahu et al., 2020, Zheng et al., 2018, 2019).

As far as the pollution studies at Indian rural stations are concerned, Indian rural areas, home to approximately 892 million (i.e., 66% of India's population), remain largely unmonitored. Though India's Pollution Control Board (CPCB) has installed 793 operating stations, 200 of which are continuous air pollution monitoring stations (https://cpcb.nic.in/monitoring-network-3/), these monitoring stations are sparse compared to other countries and, most importantly, the majority of sensors are located in urban locations only. This implies that there is a great dearth of pollution data at Indian rural locations. In this research, an attempt has, therefore, been made to measure particulate matter concentrations using a low-cost PM sensor that was installed in April 2023 at Shri Vishnu Engineering College for Women campus near Bhimavaram, a south Indian rural station located near the coast. With the following points in mind, the present study is carried out to know the pollution concentrations in remote and rural areas, how the geography of the location influences pollution levels and the potential impacts of pollution by local industries and livelihoods in rural areas.

2. SITE DESCRIPTION

The monitoring station is situated within the Engineering College campus in Bhimavaram. The measurement site is located close to Kovvada which is a rural location, situated about 3 km away from Bhimavaram Municipality in the south, and about 24 km from the nearest coastline in the south. The total population of Bhimavaram as per the 2011 census was 146,961, and the current population as of 2023 is estimated to be about 200,000 (Population Census, 2023). To obtain background atmospheric parameters (Temperature, Relative Humidity, Wind Speed, and Wind Direction), we utilized measurements from Rajahmahendravaram airport, located about 60 km away from the measurement site.

3. EXPERIMENTAL DETAILS & METHODOLOGY

A PM sensor (M/S Atmos) was installed on the campus of Shri Vishnu Engineering College for Women, Bhimavaram, India in April 2023. This sensor is designed to measure various environmental parameters every minute, including ambient particulate matter with aerodynamic diameters of less than 2.5 microns (PM2.5), 10 microns (PM10), and 1 micron (PM1.0), as well as temperature (°C) and relative humidity (%).

The sensor also records the hourly mean of all the parameters mentioned. The sensor has a 15 MB internal memory that can store data for more than 30 days. However, the data was regularly downloaded every week into a PC using an RS-232 cable to process it offline. The installed low-cost sensor in Bhimavaram is shown in Figure 1.

Figure 1. Shows the Atmos particulate matter sensor installed inside a room of the Engineering College Campus, Bhimavaram, India

The sensor has a dashboard that has several facilities, including real-time visualization of pollution data (PM2.5 & PM10), temperature (in °C), relative humidity (RH, in %), station name (Bhimavaram), the hourly average of particulate matter, and others. More details about the instrument can be found in the papers by Sahu et al. (2020), and Zheng et al. (2018). Table 1 shows the data sources used for this study.

3.1 LOCAL METEOROLOGY

Bhimavaram is a prominent municipality situated in the West Godavari district of Andhra Pradesh, India. Positioned at an elevation of 10 meters above mean sea level (MSL), it experiences a typical tropical climate. Figure 3 illustrates the variations in daily minimum & maximum temperatures, relative humidity (RH), wind speed, and wind direction throughout the study period.

The temperature varies significantly throughout the year. The months of April and May represent summer/pre-monsoon season with higher surface temperatures. The data during the study period shows that the minimum temperature ranged between 24 °C and 31°C, and the maximum temperature ranged between 28°C and 44°C, with a daily temperature range (maximum–minimum) of 4°C to 18°C. The relative humidity (RH) indicated moderate to high humid conditions with values ranging between 56% and 92% (average of about 74%).

The winds during the study period were typically weaker and the daily average values ranged between 1.5 and 3.6 m s^{-1}. However, there were lots of fluctuations in the wind direction during the study period. The winds from April 24th to May 7th were mostly directed from the East / Northeast / Southeast. However, winds changed direction between May 8 and May 11. Thereafter, the winds were mostly directed from the West / Southwest / Northwest), with a few exceptions.

Table 1. List of data sources employed in the present study

Parameter (units)	**Data Source**	**Temporal resolution**
$PM_{1.0}$ / $PM_{2.5}$ / PM_{10} (μg m^{-3})	ATMOS PM Sensor	1 minute / 1 hour
Temperature (°C) RH (%) Wind Speed (m s^{-1}) Wind Direction (°)	Rajahmahendravaram Meteorological Station https://mesonet.agron.iastate.edu/request/download.phtml?network=IN__ASOS	1 hour

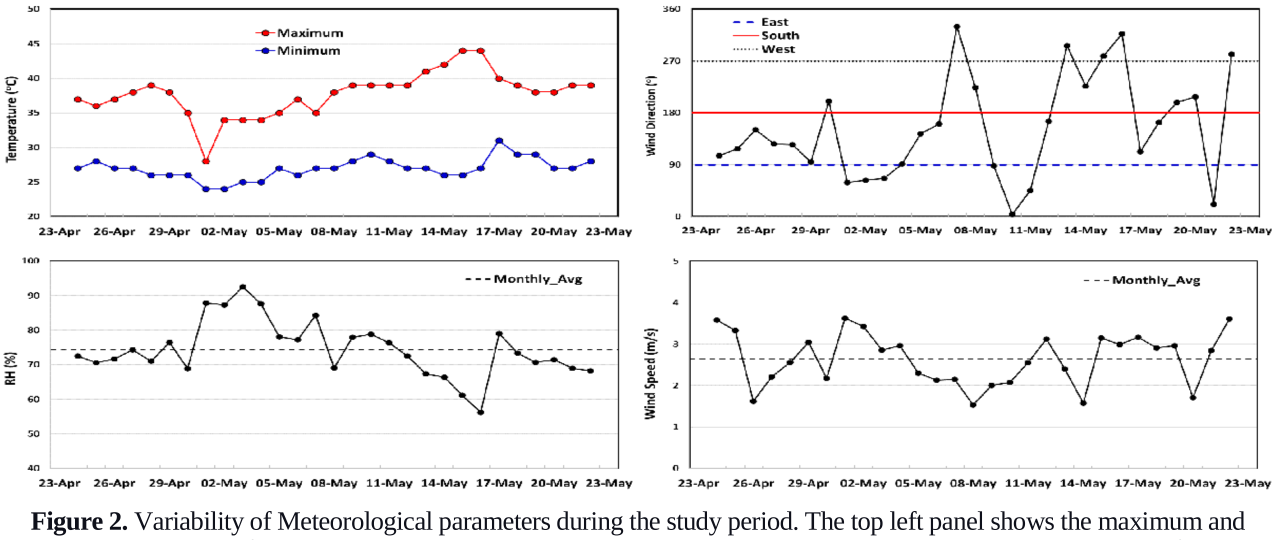

Figure 2. Variability of Meteorological parameters during the study period. The top left panel shows the maximum and minimum Temperature (°C), the bottom left shows Relative Humidity (%), the top right shows the Wind Direction (°), and the bottom right shows the Wind Speed (m/s). The horizontal lines in the plots of RH and Wind speed represent the mean for the entire study period. The horizontal lines in the Wind direction indicate winds directed from different directions (0°/360° represents wind directed from the North, 90° represents East, 180° represents South, and 270° represents West, respectively)

4. RESULTS AND DISCUSSION

Studying the seasonal and diurnal variations of particulate matter is crucial for understanding the local and regional air quality, as well as the potential impact of these particles on human health and climate. Researchers use various monitoring techniques, such as ground-based measurements, and satellite observations, to collect data and analyze these variations over time.

Wind patterns, temperature inversions, and atmospheric stability can all influence the dispersion and accumulation of PM2.5 (Brahmanandam et al., 2023). Further investigation into these factors is crucial for understanding the observed variations. Boundary-layer dynamics: The atmospheric boundary layer, the lowest layer closest to the ground, plays a crucial role in mixing and dispersing pollutants. Understanding its dynamics is essential for predicting and mitigating PM2.5 levels.

The study period spans over one month, requiring further research over longer periods to capture seasonal variations and establish robust patterns. Investigating specific local sources (traffic emissions, specific industrial activities) through source apportionment studies would provide valuable insights for targeted mitigation strategies. Modeling the influence of meteorology and boundary layer dynamics on PM2.5 transport and dispersion can enhance predictive capabilities and inform air quality management decisions.

4.1. Daily variations in PM2.5

Figure 3 depicts the daily averaged PM2.5 concentrations in Bhimavaram throughout April – May 2023. In the PM2.5 graph, the vertical bars represent standard deviations of the mean, and the black horizontal dashed line signifies the average for the entire study period. The figure also includes 24-hour average PM2.5 permissible limits according to India's National Ambient Air Quality Standard (NAAQS, red dashed line) and the World Health Organization (WHO, blue dashed line).

The study uncovers daily mean PM2.5 concentrations higher than expected, ranging from 5 to 60 µg/m³. Hourly averages exceeded 100 µg/m³ on multiple occasions, particularly in May. Notably, except for three days in May 2023, all PM2.5 values fall within the NAAQS's daily average limits of 60 µg/m3 (CPCB, 2020). During May 12-14, 2023, PM2.5 daily average values were notably high (with large standard deviations), approaching the NAAQS limit. However, more than 75% of the days in April and May 2023 surpass the World Health Organization's 24-hour guideline value of 15 µg/m³, indicating potential air quality concerns (WHO, 2021). The study period (April-May) falls within the pre-monsoon season, known for high dust loading and potentially higher PM2.5 levels compared to other seasons. Analyzing data across different seasons is needed for a more complete picture. The factors influencing the day-to-day variability could be local sources, and vehicular emissions, particularly during traffic peak hours, which can contribute significantly to morning and evening peaks. Residential activities like cooking and burning of agricultural waste could contribute to elevated PM2.5 levels.

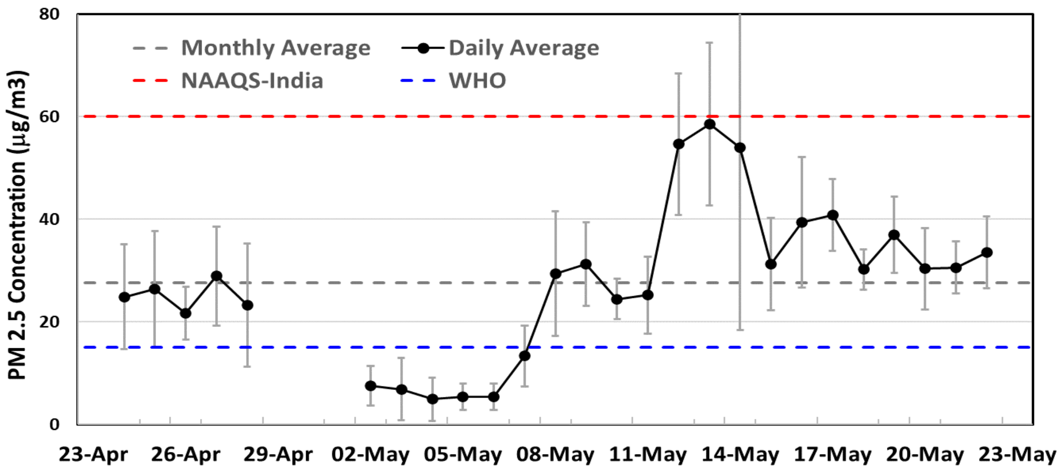

Figure 3. Shows the daily averaged PM2.5 concentrations over the measurement site near Bhimavaram from April 24 to May 22, 2023. The vertical bars indicate the standard deviations of the mean. The horizontal lines show the (a) average for the entire study period (black dashed line), (b) NAAQS-India permissible limit (red dashed line), and (c) WHO permissible limit as per the guidelines set in 2021 (blue dashed line) for 24-hr averaged PM2.5 concentratio

4.2. Diurnal variations

Figure 4 illustrates diurnal variations in hourly average PM2.5 concentrations. Moderate PM2.5 levels are observed during midnight, followed by a gradual increase in the morning, reaching a sharp peak at approximately 7:00 hr local time (LT). The morning peak may be influenced by local anthropogenic activities associated with the morning traffic rush and residential fuel use for cooking. Contributing to this peak could be the fumigation effect in the boundary layer, bringing aerosols from the nocturnal residual layer shortly after sunrise (Stull, 1988; Brahmanandam et al., 2020). As the day progresses, PM2.5 concentrations steadily decrease, reaching a minimum around 13:00 - 14:00 hr LT. Solar heating later in the day leads to increased turbulent effects and a deeper boundary layer, promoting faster dispersion of particulate matter and subsequent dilution of PM2.5 concentrations near the surface. The well-developed boundary layer likely contributes to the observed lower concentrations in the afternoon hours. Subsequently, the PM2.5 concentration exhibits a gradual increase, reaching a secondary maximum at around 19:00 – 21:00 hr local time (LT). The late evening peak in PM2.5 concentrations can be partially attributed to the evening traffic rush and residential activities, coupled with a shallower nocturnal boundary layer. As the night progresses and with no active sources of PM2.5, the concentration decreases to reach a secondary minimum between 23:00 and 01:00 hr LT. These observations of diurnal variations in aerosol and PM2.5 concentrations are not new and have been previously reported by various investigators across different geographical locations (Dobson et al., 2021; Saha & Despiau, 2009).

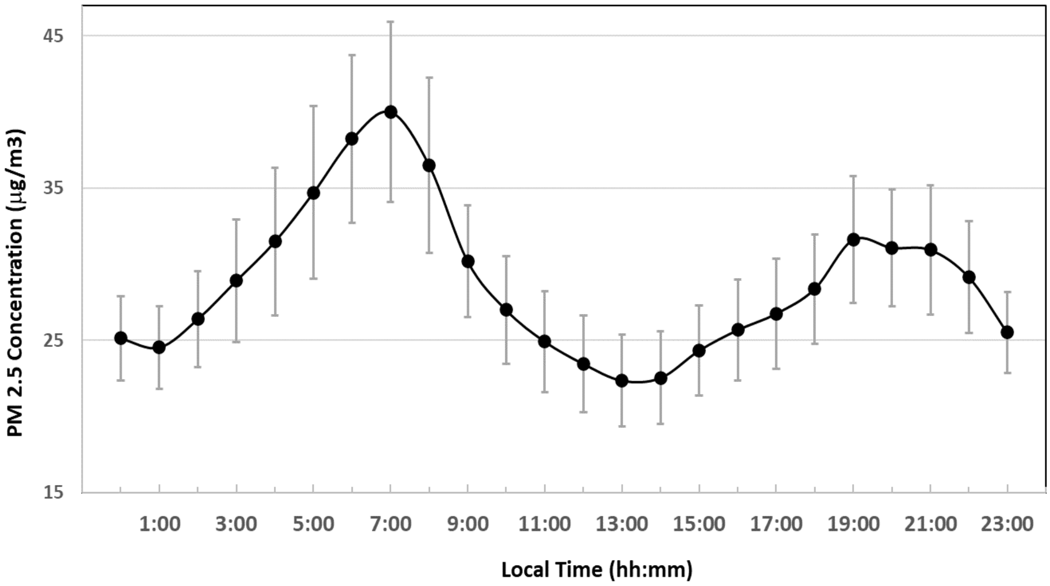

Figure 4. Hourly average diurnal variations of PM2.5 concentrations. The vertical represent the standard error in the measurements

5. CONCLUSIONS AND FUTURE DIRECTIONS

Atmospheric PM2.5 concentrations were measured for the first time at a rural site near Bhimavaram in Andhra Pradesh, India, utilizing low-cost particulate sensors in April - May 2023. The study yields the following conclusions:

- PM2.5 concentrations displayed notable temporal variations, with daily mean concentrations ranging from 5 to 60 $\mu g/m^3$, and occasional hourly average concentrations reaching as high as 100 $\mu g/m^3$ on several days.
- Diurnal patterns revealed distinct features, including a robust morning peak, a mid-afternoon minimum, and a broad secondary peak in the late evening.
- Temporal and diurnal variations in PM2.5 concentrations were found to be associated with local sources such as traffic and residential activities. Additionally, they were influenced by local meteorology and boundary-layer dynamics.
- The study underscores the necessity for further research to comprehensively grasp the sources, dynamics, and health impacts of air pollution in rural locations. It emphasizes the critical importance of investigating air quality in such rural settings.

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