A Project Report on

SPATIOTEMPORAL ASSESSMENT OF AIR QUALITY: URBAN IMPACT, CAMPUS INFILTRATION, AND INDOOR VARIATIONS AT NIT WARANGAL

ABSTRACT

Urban air pollution poses serious health risks, especially in India, where indoor air quality (IAQ) remains unregulated despite worsening ambient conditions. This study assessed the spatiotemporal air pollution dynamics at NIT Warangal, focusing on urban pollutant infiltration and IAQ variation across campus facilities.

A year-long comparison of ambient pollution between Warangal city and the NITW campus established the urban impact on campus air. Boundary PM_{10} levels were quantified using a High-Volume Sampler (HVS), particularly during peak wind-driven inflow from the city.

In March 2025, facility-wise IAQ monitoring covered $PM_{2.5}$, PM_{10}, HCHO, and CO_2, with special attention to buildings exposed to urban wind corridors. Floor-wise profiling also revealed vertical pollutant gradients shaped by ventilation and architectural design. The results confirmed distinct spatial patterns linked to wind direction, proximity to urban sources, and structural airflow limitations—highlighting the need for formal IAQ guidelines and interventions like enhanced ventilation and green buffers in Indian institutional spaces.

Keywords: Urban air pollution, Indoor air quality, PM10 infiltration, Wind-driven dispersion, NIT Warangal.

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Urban Air Pollution and Campus Vulnerability

Air pollution has emerged as one of the most critical environmental health challenges in modern urban ecosystems. The exponential growth of industrial activities, vehicular emissions, and construction dust has caused cities to witness alarming levels of particulate matter (PM2.5 and PM10) and gaseous pollutants such as carbon dioxide (CO_2) and formaldehyde (HCHO).

Despite being perceived as semi-isolated entities, educational campuses like the National Institute of Technology Warangal (NITW) are not immune to this threat. Their open layouts, proximity to expanding urban zones, and reliance on natural ventilation systems make them vulnerable to the infiltration of urban pollutants. Wind patterns and topographical features create micro-environments where pollutants from the city can seep into the campus, affecting indoor and outdoor air quality alike. This scenario raises concerns about the health and cognitive well-being of students, faculty, and support staff who spend extended periods within these premises.

The dynamic relationship between outdoor pollution loads and indoor air quality in such institutional settings is under-researched, especially in the Indian context, where climate variability and infrastructural heterogeneity further complicate exposure patterns.

1.2 Regulatory Gaps: Indoor vs. Ambient Air Quality in India

India has formulated and implemented National Ambient Air Quality Standards (NAAQS) to monitor and regulate the concentration of harmful pollutants in outdoor environments. These standards act as a benchmark for air quality management in cities and industrial areas across the country. However, despite the existence of these outdoor guidelines, indoor air quality (IAQ) — particularly in non-industrial, public, and semi-public spaces such as educational institutions, offices, and recreational facilities — remains an area that is both under-regulated and under-monitored. This oversight creates a considerable gap in environmental policy, especially when global research consistently highlights that people typically spend approximately 85% to 90% of their time inside enclosed environments rather than outdoors.

Indoor environments are often mistakenly assumed to be inherently safer than outdoor ones in terms of air quality. However, this perception is misleading. Air pollutants can infiltrate indoor spaces from the outdoors through ventilation systems, open doors, windows, and structural leaks. In addition to this external inflow, indoor air quality is further compromised by pollutant sources generated within the building itself — including emissions from construction and furnishing materials, off-gassing from cleaning products and chemical agents, particulate matter from human occupancy and activity, and inadequate ventilation design. The combined effect of these sources can sometimes result in pollutant concentrations inside buildings that are equivalent to, or even surpass, the levels found outdoors, especially during periods of high pollution.

In the Indian context, the absence of enforceable indoor air quality guidelines, particularly for academic and institutional campuses, exposes students, faculty, and staff to persistent and often unnoticed health risks due to poor air quality. This regulatory void also contributes to a lack of widespread public awareness and results in inconsistent or insufficient mitigation strategies at both administrative and policy-making levels.

Given these circumstances, this study seeks to address this critical knowledge and regulatory gap by conducting a structured and systematic investigation into indoor air pollutant concentrations, while also exploring their correlation with outdoor pollution levels across a variety of campus environments and facilities.

1.2.1 Overview of Key Pollutants Monitored

This study focuses on the monitoring of specific particulate and gaseous pollutants that pose direct health risks to humans in both outdoor and indoor environments:

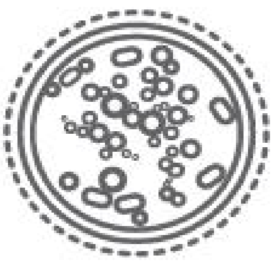


Figure 1.2.1a: Illustration of $PM_{2.5}$ (Particulate Matter ≤2.5 µm). Sourced from temptopus.com.

- PM2.5 (Particulate Matter 2.5) refers to fine particles with diameter of 2.5 micrometers or less. Due to its tiny size, PM2.5 can be absorbed into bloodstream and the lungs, so that long-term exposure to high concentration of PM2.5 environment may cause eye and nose irritation, cough, asthma, emphysema, lung disease, heart attacks, cancer and etc.

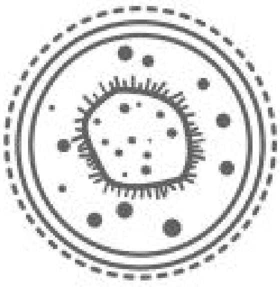


Figure 1.2.1b: Illustration of PM_{10} (Particulate Matter ≤10 µm). Sourced from temtopus.com

- PM10 (Particulate Matter 10) refers to particulates with a diameter of 10 micrometers or less. Due to the larger size, it's inhalable but penetrates no further than bronchi as larger particles can be filtered out by cilia and mucus of nose and throat. It normally considered as less harmful to health than PM2.5.

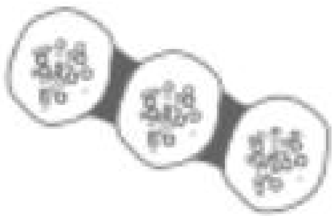


Figure 1.2.1c: Illustration of Carbon Dioxide (CO_2) molecules. Sourced from temtopus.com

- **CO2:** Carbon dioxide is a colorless and odorless gas that is usually derived from the breath of humans and animals. High CO2 concentration means that fresh air or ventilation is required, otherwise it may cause problems such as drowsiness, dizziness, loss of attention, and cognitive impairment.

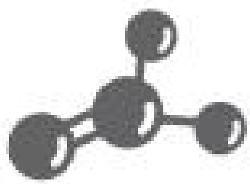


Figure 1.2.1.4: Illustration of Formaldehyde (HCHO). Sourced from temtopus.com

- Formaldehyde (HCHO) is a colorless and strong-smelling gas with formula CH20, which has been classified by IARC as Group 1 carcinogen. Long-term exposure to just low doses could cause chronic respiratory diseases, nasopha- ryngeal carcinoma, colon cancer, brain tumors, nuclear gene mutation and etc.

1.3 Objectives of the Study

The primary aim of this study is to assess the spatiotemporal variations in air quality within the NIT Warangal campus and understand its interaction with urban pollution inflow from the surrounding city of Warangal. The specific objectives of the study are:

- To analyze long-term ambient air quality trends in Warangal city and compare them with campus-level data to understand the broader exposure scenario.
- To evaluate the infiltration of PM10 from city surroundings into the NITW campus, especially along the dominant wind direction, using High Volume Sampling (HVS).
- To conduct a comprehensive facility-wise and floor-wise indoor air quality assessment during March 2025, covering particulate matter (PM2.5 and PM10) and gaseous pollutants (CO_2 and HCHO) using calibrated monitoring equipment.
- To suggest mitigation strategies and policy recommendations that can reduce the exposure risks for campus residents and advocate for structured IAQ monitoring frameworks.

1.4 Scope and Limitations

This research study is centered on examining both the spatial distribution and temporal variation of particulate and gaseous air pollutants within the NIT Warangal campus, an educational institution situated in close proximity to the urbanized areas of Warangal city. A major focus of this investigation is directed toward analyzing the degree to which pollutants originating from the external urban atmosphere infiltrate into the campus environment, as well as understanding the behavior of these pollutants once they enter indoor spaces across a variety of campus facilities.

The scope of this research encompasses a multi-pronged approach, including a comparative analysis between ambient air quality data collected from the official monitoring station located in Warangal city and the data recorded within the boundaries of the NIT Warangal campus. This comparison serves to assess the extent of pollutant drift and its subsequent infiltration into what is generally assumed to be a more controlled and less polluted institutional environment.

As part of this study, the infiltration of PM10 particles was specifically examined using high-volume sampling (HVS) techniques, allowing for the quantitative capture and evaluation of larger particulate matter typically associated with urban emissions, construction dust, and natural sources such as soil and pollen. In addition to outdoor assessments, the research involved a targeted evaluation of indoor air quality (IAQ) across a carefully selected set of campus facilities — including classrooms, hostels, dining areas, and sports complexes — as well as different vertical building levels such as ground, mid-level, and upper floors. These indoor sampling exercises were carried out primarily during the month of March 2025, a period characterized by transitional weather patterns and shifting wind directions, both of which are known to significantly affect pollutant dispersion, atmospheric dilution, and the rate of infiltration into buildings.

Beyond basic measurement and comparison, the study also aims to investigate and document the influence of environmental and structural factors such as prevailing wind direction, the architectural orientation of buildings, and patterns of human occupancy and facility usage on indoor air pollutant concentrations. Through this multi-dimensional approach, the study aspires to offer practical insights into the distinctive vulnerabilities that educational institutions and similar public infrastructure face, especially in relation to both external air pollution intrusions and emissions generated within their own premises.

Nonetheless, it is important to acknowledge the inherent limitations of this research. The indoor air quality data collection was conducted over a limited timeframe — specifically during a short-term monitoring campaign in March 2025 — which inherently restricts the study's ability to capture long-term pollutant variability or seasonal fluctuations that may influence air quality under different meteorological conditions. Additionally, the scope of fieldwork was partially constrained by the availability of measurement equipment, with particular dependence on the Temtop M2000 air quality monitor for real-time data acquisition. Due to these logistical and resource-based limitations, the study was unable to implement an extended, multi-seasonal or longitudinal measurement campaign, which would have provided a more comprehensive and robust understanding of air quality dynamics over varying environmental conditions.

CHAPTER 2

LITERATURE REVIEW

2.1 Air Quality Dynamics in Semi-Open Institutional Spaces

Semi-open institutional environments—such as universities, colleges, and school campuses—occupy a unique position between fully enclosed indoor spaces and open outdoor surroundings, operating primarily under passive or hybrid ventilation systems that rely heavily on natural airflow (Asrani & Shah, 2024). This architectural and operational design inherently makes the indoor air quality (IAQ) in such spaces highly sensitive and directly responsive to variations in ambient outdoor pollution levels, especially during periods of high urban emissions or seasonal shifts (Datta et al., 2017).

In the Indian context, the lack of dedicated research and monitoring frameworks for such settings is particularly concerning. Out of an estimated 172 peer-reviewed studies on indoor air quality conducted across India, only 36 (≈ 21 %) specifically address the conditions within educational environments such as schools, colleges, and other academic institutions (Vijay & Sarasamma, 2024). This statistical shortfall highlights both a significant research gap and a broader regulatory oversight in a country where a large population of students and staff spend extended hours in semi-open facilities, often under the assumption that these spaces offer safer air than the surrounding urban outdoors (The Union, 2021).

The limited studies consistently point toward a core set of pollutants that dominate concern in such settings—namely carbon monoxide (CO), fine and coarse particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), volatile organic compounds (VOCs), and biological aerosols such as pollen and mold spores (Singh et al., 2017). Alarmingly, measurements frequently show that indoor concentrations can approach or even surpass outdoor levels, particularly during periods of peak traffic density or limited atmospheric dispersion (Datta et al., 2017).

Field investigations in non-residential Delhi buildings reported indoor $PM_{2.5}$ at 22.8 µg/m³ and PM_{10} at 30.5 µg/m³, with indoor-to-outdoor (I/O) ratios > 0.8—a clear sign of strong outdoor infiltration along major roadways (Datta et al., 2017). Similarly, primary school classrooms in

Hamirpur ventilated only by ceiling fans and windows recorded $PM_{2.5}$ peaks of 191 µg/m³—≈ 80 % of the outdoor 237 µg/m³ peak—and CO_2 fluctuations between 435–590 ppm (Shree et al., 2019). These results underscore that semi-open spaces, despite their design, are not inherently protected from outdoor pollution.

2.2 Wind-Driven Pollution Infiltration: Mechanisms and Mitigation

Wind direction and velocity emerge as the foremost drivers of pollutant ingress in naturally ventilated or semi-open institutional buildings (Asrani & Shah, 2024). When wind currents strike a building façade, they generate pressure differentials: the windward side experiences higher dynamic pressure, forcing ambient air—and its pollutant load—into cracks, openings, and ventilation inlets, while the leeward side, under relative suction, sees much lower penetration (Datta et al., 2017). Computational Fluid Dynamics (CFD) studies reinforce this, reporting that windward façades can register PM_{10} infiltration factors of 0.6–0.8 under moderate wind speeds (3–5 m/s), compared to baseline values of 0.3–0.5 on sheltered façades where flow separation and eddies reduce particle entry (Datta et al., 2017).

The episodic nature of wind-driven events—ranging from localized gust fronts to large dust storms—can precipitate dramatic indoor air quality excursions. Field measurements in college buildings during convective gust episodes have recorded indoor $PM_{2.5}$ surges from background levels of 67 ± 32.5 µg/m³ to peaks near 215 ± 93.7 µg/m³ within minutes, illustrating how short-duration high-velocity winds can overwhelm natural ventilation pathways (Shree et al., 2019). Even moderate, sustained winds (> 2 m/s) throughout a day can elevate 24-hour average infiltration factors by 20–30 %, underscoring the critical need to account for prevailing meteorological conditions in IAQ assessments (Asrani & Shah, 2024).

To curb such wind-driven pollutant ingress, a variety of mitigation techniques have been proposed:

- Vegetative Barriers: Strategically planted hedges, green walls, and buffer strips can intercept and deposit coarse particulates before they reach building envelopes. Studies show a 25–30 % reduction in $PM_{2.5}$ infiltration when dense vegetation is placed upwind, acting as both a physical barrier and a bio-filter (Asrani & Shah, 2024).

- ❖ Air Curtain Systems: Electrically powered air-curtains installed over major openings generate a high-velocity laminar flow that repels outdoor air, proven to lower infiltration by up to 40 % in field trials.
- ❖ HEPA Filtration Units: Portable or integrated HEPA filters capture > 90 % of coarse particulates (PM_{10}) and a substantial fraction of $PM_{2.5}$, maintaining indoor levels below 50 µg/m³ even when outdoor concentrations exceed 200 µg/m³ (Datta et al., 2017; Sahu et al., 2020).

Despite clear efficacy, adoption of these strategies on Indian institutional campuses remains limited (The Union, 2021). The high upfront investment for green-infrastructure establishment and the recurring costs of HEPA filter replacements, power consumption, and vegetation maintenance pose significant financial and logistical barriers for public-sector educational institutions. Integrating passive design measures—such as optimized building orientation, adjustable louvered vents, and wind-deflecting architectural features—offers a cost-effective compromise, leveraging natural forces to reduce infiltration without continuous operational expenses (Asrani & Shah, 2024; The Union, 2021).

2.3 Measurement Techniques for PM and Gaseous Pollutants

The accurate measurement of particulate matter (PM) and gaseous pollutants forms the backbone of any robust indoor air quality (IAQ) investigation, particularly when the objective is to determine source attribution, human exposure levels, and regulatory compliance. Among the commonly adopted techniques for particulate assessment, high-volume samplers (HVS) stand out as the gravimetric gold standard, particularly for PM_{10} analysis (Instrumex India, 2021). These instruments function at regulated flow rates typically set between 1.1 and 1.7 cubic meters per minute, ensuring that airborne particles are sampled representatively over extended collection periods. HVS devices rely on pre-weighed, high-efficiency glass fiber filters—usually standardized at 8 inches by 10 inches—which are pre-conditioned in laboratory settings at controlled temperatures of 20–25 °C and relative humidity levels of 45–50% for at least 16 hours prior to deployment, ensuring accuracy by minimizing moisture-driven mass variability (Instrumex India, 2021). During the collection process, ambient air is drawn continuously through these filters for durations typically spanning 24 to 48 hours, allowing for sufficient particulate accumulation. Once sampling concludes, the filters are re-conditioned under identical environmental conditions and reweighed; the difference in mass directly corresponds to the PM_{10} concentration for the period, expressed in micrograms per cubic meter

($\mu g/m^3$). Additionally, the particulate-laden filters can be subjected to chemical analysis, offering valuable insights into pollution composition and likely emission sources (Instrumex India, 2021).

In addition to these precise yet labor-intensive gravimetric techniques, the emergence of low-cost, optical particle counters has significantly expanded real-time air quality surveillance, especially for studies operating under financial or operational constraints. Devices such as the Temtop M2000 are exemplary of this category, employing laser-based light scattering to estimate concentrations of $PM_{2.5}$ and PM_{10}, along with gaseous pollutants such as carbon dioxide (CO_2) and formaldehyde (HCHO) (Temtopus, 2024). These portable instruments typically log data at one-minute intervals, enabling near-instantaneous detection of short-term pollutant fluctuations and dynamic occupancy-related exposure trends. While such sensors cannot rival the absolute accuracy of reference-grade monitors, validation efforts have shown that the Temtop M2000 can achieve an error margin within ±15% of beta attenuation monitor (BAM) benchmarks, provided regular calibration is maintained and environmental variables like humidity are accounted for (Sahu et al., 2020). This mix of affordability, portability, and dependable performance has positioned such devices as a practical option for IAQ monitoring across schools, offices, and institutional campuses, especially in Indian contexts where budgetary and infrastructural limitations often rule out the use of regulatory-grade instrumentation (Vijay & Sarasamma, 2024).

2.4 Research Gaps and Project Relevance

Despite steady advancements in the understanding of indoor air quality, key knowledge gaps persist within the Indian academic and institutional context. One major shortfall is the limited exploration of vertical stratification of indoor pollutants, especially in multi-story educational and residential buildings. Existing research has primarily concentrated on single-room or ground-level sampling, with only isolated studies, such as the investigation conducted in Hamirpur classrooms, highlighting floor-wise variations in $PM_{2.5}$ and PM_{10} concentrations (Shree et al., 2019). This leaves an unresolved question regarding how particulate matter disperses between lower and upper floors in hostels, academic blocks, and libraries—an issue particularly significant in light of phenomena like thermal stratification, the stack effect, and uneven ventilation patterns, all of which can create disparate exposure risks for occupants at different elevations. Parallel to this technical gap, a regulatory shortcoming compounds the problem: while India's National Ambient Air Quality

Standards (NAAQS) provide defined thresholds for outdoor $PM_{2.5}$ and PM_{10} concentrations, these benchmarks—set at 40 µg/m³ (annual) and 60 µg/m³ (24-hour) for $PM_{2.5}$, and 60 µg/m³ (annual) and 100 µg/m³ (24-hour) for PM_{10}—have no equivalent standards specifically governing indoor air in non-industrial public buildings (The Union, 2021). This absence of clear indoor air guidelines often forces institutions to either adopt outdoor standards uncritically or operate without meaningful reference points, risking prolonged exposure of students and staff to pollutant levels that may exceed safe limits for indoor environments. Adding to the complexity, while international bodies like ASHRAE recommend fresh air supply rates of 10 L/s per person for enclosed spaces, these guidelines are rarely applied within Indian campuses, owing to infrastructure limitations, climate variability, and the cost implications of continuous mechanical ventilation (Asrani & Shah, 2024). To bridge these gaps, the present study employs a combined methodological approach—incorporating boundary-condition measurements for PM_{10} via high-volume samplers (Instrumex India, 2021), real-time indoor monitoring of $PM_{2.5}$, CO_2, and HCHO with Temtop M2000 sensors (Temtopus, 2024), and systematic floor-wise pollutant profiling across various facilities. This layered strategy allows for a direct comparison of indoor air quality against outdoor baselines and facilitates the development of interim indoor exposure benchmarks while proposing affordable, location-appropriate mitigation measures such as targeted air purification for vulnerable floors and the refinement of natural ventilation schemes. Ultimately, the intertwined influences of outdoor emissions, building design, occupant density, and local wind patterns call for comprehensive, site-specific IAQ studies like this one, particularly as educational institutions in India continue to expand and evolve. The adoption of evidence-based, scalable air quality management practices will be essential to ensuring safe and sustainable learning environments for the future (Vijay & Sarasamma, 2024).

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Study Area: NIT Warangal and Warangal City

This study focuses on assessing air quality spatially and temporally across the NIT Warangal campus, comparing it with ambient air data from Warangal city, Telangana. The city's air quality data were sourced from the Telangana State Pollution Control Board (TSPCB) through the Balasamudram Continuous Ambient Air Quality Monitoring Station (CAAQMS), providing a city-wide perspective on pollution levels. In contrast, the campus data were collected from the on-campus Airlink sensor system, installed near the administrative block, serving as an internal baseline for comparison, as shown in Figure 3.1. This initial phase of the research relied solely on secondary data, with no field deployment involved. The data were analyzed to understand the general pollution trends and fluctuations over a specific annual period, establishing a comparison between the city's ambient air quality and that of the campus. The use of secondary data from reputable sources like TSPCB and Airlink ensured reliable findings, enabling the research to compare local pollution levels against global benchmarks and laying the groundwork for future studies that will incorporate primary data collection.

NIT WARANGAL								
14/2/24 12:00 AM : 1 Year								
	NIT Warang	NIT Warang	NIT Warang	NIT Warang	NIT Warang	NIT Warang	NIT Warang	NIT Warangal AQI
	AirLink	AirLink	AirLink	AirLink	AirLink	AirLink	AirLink	AirLink
Date & Time	AQI	High AQI	PM 1 - ug/m	High PM 1 -	PM 2.5 - ug/	High PM 2.5	PM 10 - ug/	High PM 10 - ug/m³
14-02-2024 18:15	96	142	40	51	58	73	71	81
14-02-2024 18:30	127	215	47	64	69	95	80	108
14-02-2024 18:45	148	208	50	63	75	93	85	105
14-02-2024 19:00	133	190	47	57	70	87	82	107
14-02-2024 19:15	91	139	37	48	55	72	70	82
14-02-2024 19:30	78	88	31	37	47	53	60	71
14-02-2024 19:45	79	86	32	35	47	52	60	71
14-02-2024 20:00	85	100	34	39	51	60	66	75
14-02-2024 20:15	84	95	34	40	51	57	66	75
14-02-2024 20:30	84	93	34	38	51	56	65	72
14-02-2024 20:45	84	95	34	38	50	57	65	73
14-02-2024 21:00	83	93	33	38	50	56	64	73
14-02-2024 21:15	85	108	34	39	51	63	65	75
14-02-2024 21:30	83	95	33	38	50	57	64	73
14-02-2024 21:45	84	97	34	39	50	58	64	73
14-02-2024 22:00	82	93	33	36	50	56	63	71
14-02-2024 22:15	87	115	34	40	53	65	67	79
14-02-2024 22:30	93	115	36	44	56	65	71	79
14-02-2024 22:45	92	111	36	43	55	64	70	77

Figure 3.1 Airlink sample data screenshot. Sourced from weatherlink.com

3.2 Instrumentation: HVS, Temtop M2000, and Calibration Protocols

For ground-level data collection, two instruments were employed:

High Volume Sampler (HVS):

The High-Volume Sampler (HVS) setup operates with a calibrated airflow rate of 25–50 ft^3/min, drawing ambient air through a pre-weighed 8" × 10" glass fiber filter, as shown in Figure 3.2a and Figure 3.2b. To ensure precision in measurements, the filter is conditioned at 20–25°C for 16 hours before the sampling process begins. As air passes through the filter, particulate matter is trapped, and the mass difference between the filter before and after sampling is used to quantify PM_{10} concentrations directly. This technique offers a robust and accurate way to assess particulate pollution levels, making it highly effective for long-duration sampling, which typically spans 24–48 hours. During this period, the filter accumulates particulate matter, allowing for subsequent chemical and morphological analysis of the collected particles — a key advantage over sensor-based devices like the Temtop, which cannot provide this level of granular detail.

Figure 3.2a: High-Volume Sampler (HVS) setup

Figure 3.2b: Glass fiber filter paper used for PM_{10} sample collection.

Temtop M2000 Air Quality Monitor:

The Temtop M2000 uses laser scattering technology to measure particulate matter (PM_{10} and $PM_{2.5}$), non-dispersive infrared (NDIR) sensors for CO_2 measurement, and electrochemical sensors for formaldehyde (HCHO) detection, as illustrated in Figure 3.2c, Figure 3.2d, and Figure 3.2e. Before starting the sampling process, the device requires a 15-minute warm-up period to stabilize its internal sensors. During operation, it records minute-by-minute data over a 15-minute sampling interval, providing both short-term data snapshots and trends that are useful for real-time analysis. To avoid spatial bias, especially in larger open areas like stadiums or grounds, the device is repositioned at multiple points—usually three—in a triangular arrangement, and the resulting values are averaged. For smaller, more confined spaces like gyms, classrooms, or hostel rooms, a single point of measurement is sufficient. To ensure data reliability, the device's calibration is checked regularly using span protocols both before and after each sampling session, maintaining the accuracy of the readings throughout the study. This approach allows for consistent, reliable measurements even in dynamic or variable environments, ensuring that the data collected is accurate for analysis.

Figure 3.2c: Temtop M2000 in-use during air quality monitoring

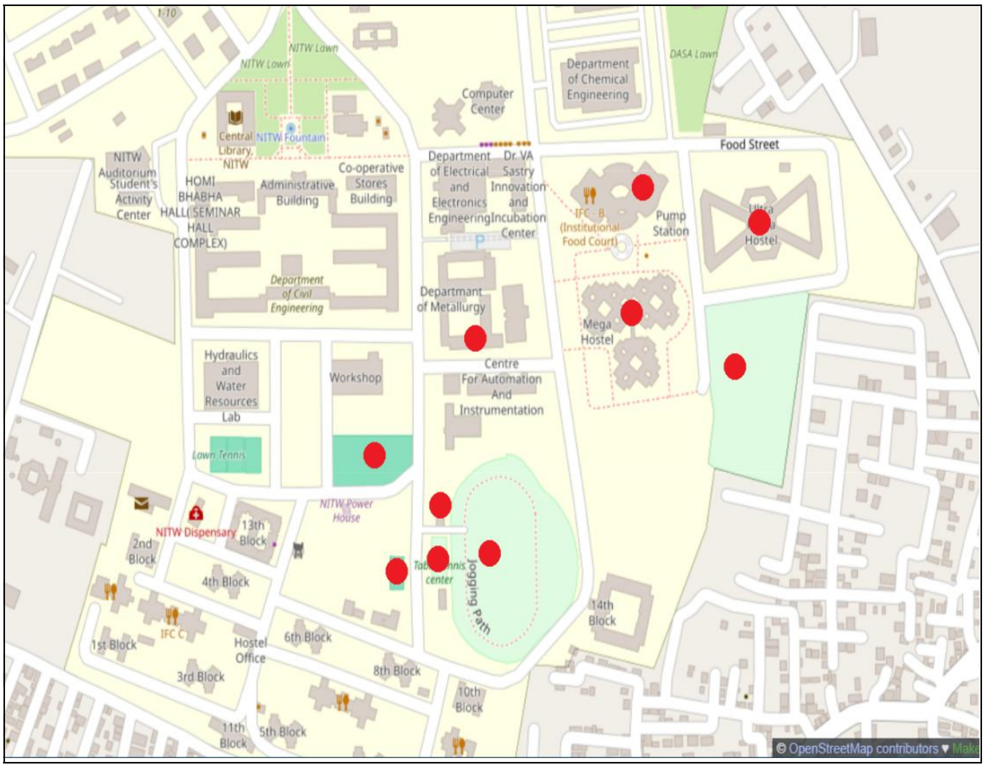


Figure 3.2d: Mapped locations of the sampled facilities at NIT Warangal.

A	B	C	D	E	F	G	H
DATE	PM2.5(ug/m	PM10(ug/m	CO2(ppm)	HCHO(mg/m	TEMPERATU	HUMIDITY(	TEMPUNIT
18-03-2025 08:27	69.7	109.5	690	0.082	90.6	58.3	F
18-03-2025 08:28	67.8	106.6	679	0.054	89.8	59.4	F
18-03-2025 08:29	62.6	100.1	678	0.046	89.4	60.2	F
18-03-2025 08:30	65.6	101.6	681	0.041	89.2	60.7	F
18-03-2025 08:31	62.8	98.6	681	0.036	88.9	61.1	F
18-03-2025 08:32	63.7	102	672	0.033	88.9	61.4	F
18-03-2025 08:33	57.8	92.9	664	0.032	88.5	61.9	F
18-03-2025 08:34	65	102.3	666	0.032	88.1	62.6	F
18-03-2025 08:35	62.6	99.3	686	0.033	88.3	62.8	F
18-03-2025 08:36	61.6	96.5	681	0.031	88.1	63	F
18-03-2025 08:37	57.8	92.5	679	0.03	88.2	63.1	F
18-03-2025 08:38	59.1	91	684	0.031	87.8	63.7	F
18-03-2025 08:39	58.4	92	689	0.03	87.9	63.4	F
18-03-2025 08:40	54.8	84.8	677	0.029	87.7	63.7	F
18-03-2025 08:41	54.6	87	664	0.028	87.6	63.9	F

Figure 3.2e: Sample data screenshot from Temtop M2000, displaying real-time $PM_{2.5}$, PM_{10}, CO_2, and HCHO values with minute-wise time stamps.

3.3 Sampling Design: Spatial Stratification and Temporal Resolution

To capture realistic and meaningful air quality patterns, the sampling process was strategically structured across both spatial and temporal dimensions. This design allowed for a comprehensive understanding of how different environmental and operational factors influenced air quality at various locations on campus over time.

Sampling Design: Site Selection and Environmental Factors

Sampling sites were meticulously selected based on the function of the space and their exposure to prevailing wind patterns, which play a crucial role in pollutant dispersion, as illustrated in Figure 3.3a and Figure 3.3b. The goal was to capture a diverse range of environments, from highly ventilated open spaces to more enclosed areas with limited airflow. During the early to mid-February period, when High-Volume Sampler (HVS) data was being collected, wind predominantly flowed from the North-East, influencing the spread of pollutants. By mid to late March, as the wind direction shifted to the South-East, this change was expected to result in different exposure levels across campus, with southeastern-facing facilities becoming more vulnerable to pollutant infiltration.

The campus structures were classified into two main categories for sampling purposes:

Closed Buildings: These are enclosed spaces with limited natural ventilation, where air exchange is predominantly dependent on mechanical systems. Sampling sites included the Physical Education

Department Gym, the Indoor Badminton Court, the IFC A Dining Hall, and academic classrooms. These areas were considered critical in assessing indoor air quality, as they tend to accumulate pollutants without sufficient air movement to disperse them.

Open Facilities: These spaces are more directly exposed to the outdoor environment and are heavily influenced by ambient air quality and weather conditions. These included the Stadium, 1K Hostel Ground, Volleyball Court, and Basketball Court. These sites provided insights into how outdoor air pollution infiltrates open spaces and how it is mitigated or exacerbated by weather conditions and building orientation.

Additionally, floor-wise sampling was conducted in the hostels to understand vertical pollutant stratification, as pollutant concentrations can vary at different heights due to factors like air circulation and building design. In the 1K Hostel, data was collected from floors 0, 3, and 6, while in the 1.8K Hostel, floors 1, 4, 7, and 9 were chosen. This approach allowed for a more detailed assessment of how vertical stratification and the efficiency of ventilation systems impact pollutant levels, providing a deeper understanding of air quality dynamics within multi-story buildings.

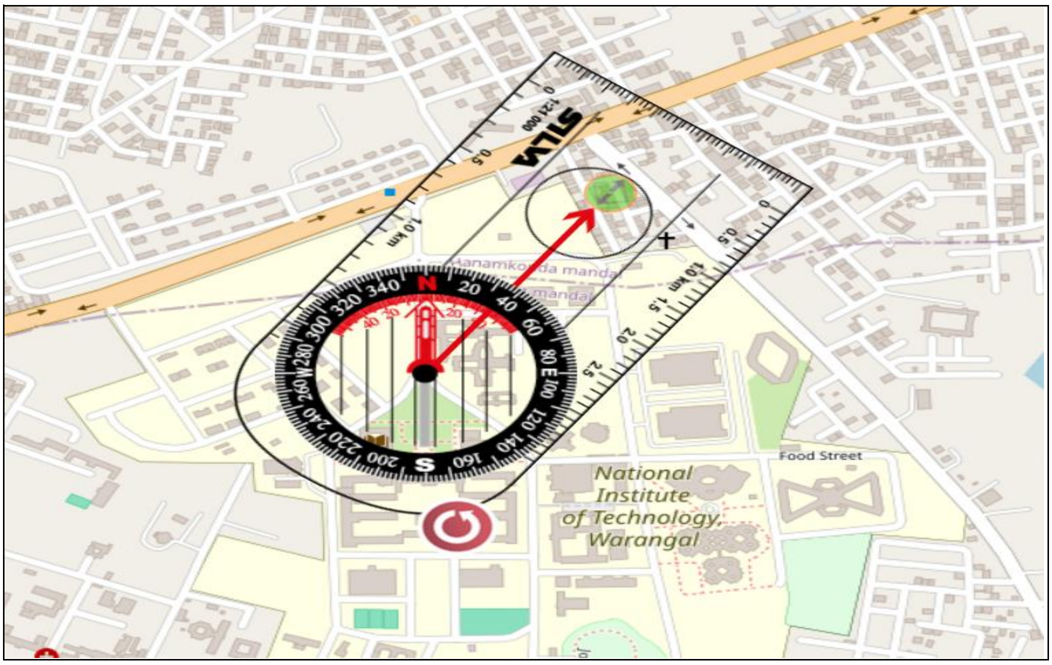


Figure 3.3a: Wind direction map during HVS sampling (February), showing dominant South-East airflow. Data sourced from weatherlink.com , 2025.

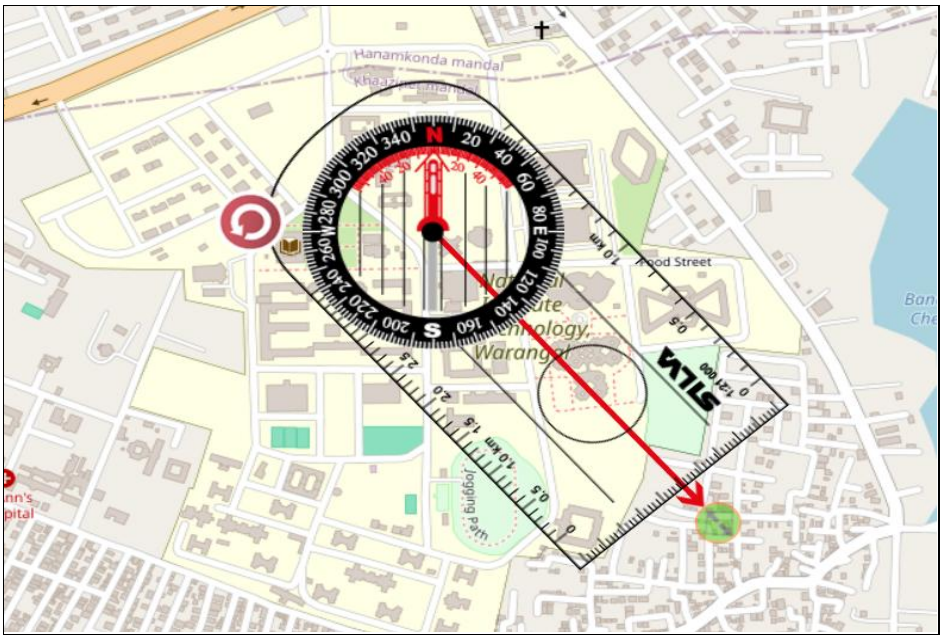


Figure 3.3b: Wind direction map during Temtop sampling (March), showing dominant South-East airflow. Data sourced from weatherlink.com , 2025.

3.4 Data Analysis Framework

The analysis focused on summarizing the pollutant concentrations and comparing them with the World Health Organization (WHO) air quality standards for $PM_{2.5}$, PM_{10}, CO_2, and HCHO (illustrated in figure 3.4) to assess the air quality levels on the NIT Warangal campus. For the Temtop M2000, air quality was monitored at each site by recording 15-minute snapshots, with measurements taken at one-minute intervals during high-occupancy periods. These one-minute data points were then averaged to provide a comprehensive representation of the air quality during these specific times. This method ensured that short-term fluctuations were captured accurately, reflecting the air conditions during peak occupancy.

For the High-Volume Sampler, the particulate mass collected during the two-hour sampling period was extrapolated to estimate the 24-hour average concentrations. This extrapolation followed standard procedures, assuming a steady-state distribution of particulates over time. By applying this proportional adjustment, the data provided a reliable estimate of daily pollutant levels, even though the sampling period was limited to just a few hours. The combination of devices allowed for a robust comparison of real-time and long-duration air quality measurements across different campus locations.

Health Parameter Guide

PM2.5	PM10	CO2(ppm)	Levels of Health Concern	HCHO(mg/m³)	Displayed Contents
0.0-12.0	0-54	0-700	Good	0-0.1	Healthy
12.1-35.4	55-154	701-1000	Moderate	>0.1	Unhealthy
35.5-55.4	155-254	1001-1500	Unhealthy for Sensitive Groups		
55.5-150.4	255-354	1501-2500	Unhealthy		
150.5-250.4	355-424	2501-5000	Very Unhealthy		
≥250.5	≥425	≥5001	Hazardous		

Figure 3.4: WHO Air Quality Guidelines for $PM_{2.5}$, PM_{10}, CO_2, and HCHO levels

This combination of real-time digital logging through the Temtop M2000 and physical sample collection via the High-Volume Sampler (HVS) facilitated both immediate air quality assessment and the possibility for more detailed chemical analysis. While the Temtop provided real-time, high-frequency data on pollutants, the HVS allowed for the collection of particulate matter over longer periods, offering deeper insights into pollutant composition. Together, these methods provided a comprehensive and balanced view of air quality, helping to understand both short-term fluctuations and long-term trends within the campus and its surrounding environment.

CHAPTER 4

RESULTS AND ANALYSIS

4.1 City vs. Campus Ambient Air Quality Trends

Ambient air quality comparisons between Balasamudram (city) and NIT Warangal (campus) revealed a consistent trend of exceeding WHO standards for AQI, $PM_{2.5}$, and PM_{10} at both locations, which underscores the significant vulnerability of the campus to the regional pollution load (Figures 4.1a–4.1c). The AQI and $PM_{2.5}$ concentrations showed a notable correlation at both sites (Figures 4.1a and 4.1b), suggesting shared pollution sources such as vehicular emissions and long-range atmospheric transport of fine particulates. Interestingly, while PM_{10} levels were consistently higher in Balasamudram (Figure 4.1c), likely due to the impact of heavy traffic, ongoing construction, and urban dust, the NIT Warangal campus demonstrated relatively lower and more stable PM_{10} concentrations. This was attributed to the campus's green cover, which helps mitigate particulate infiltration, as well as its location further removed from the direct sources of urban pollution. These findings highlight the interplay between local environmental features and the broader regional air quality challenges.

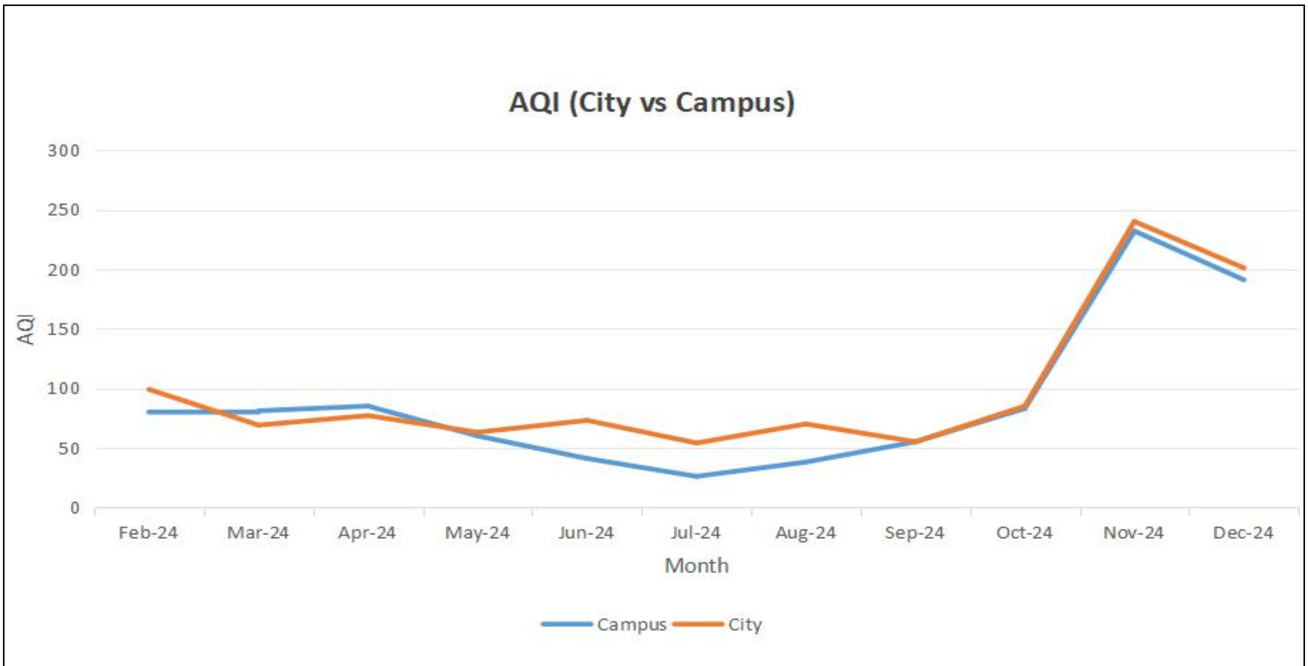


Figure 4.1a: AQI Comparison for City vs. Campus

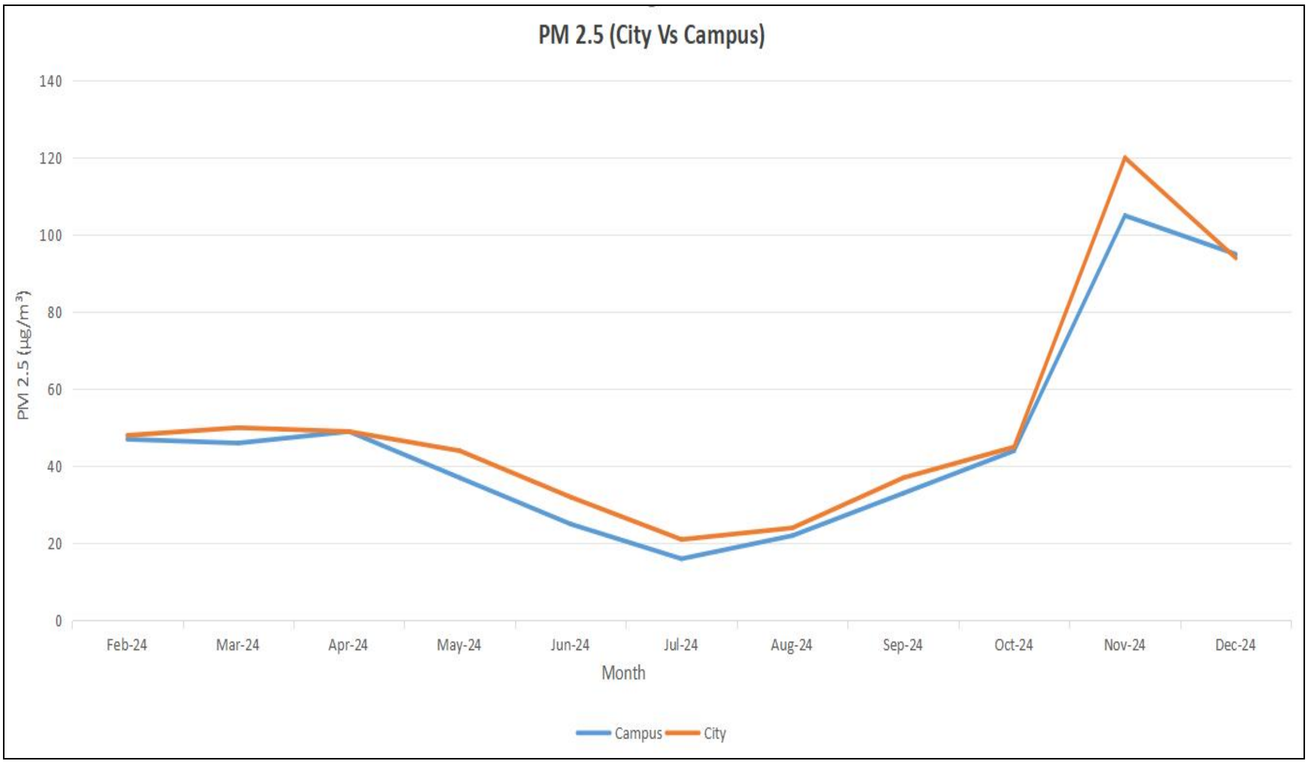


Figure 4.1b: PM2.5 Comparison for City vs. Campus

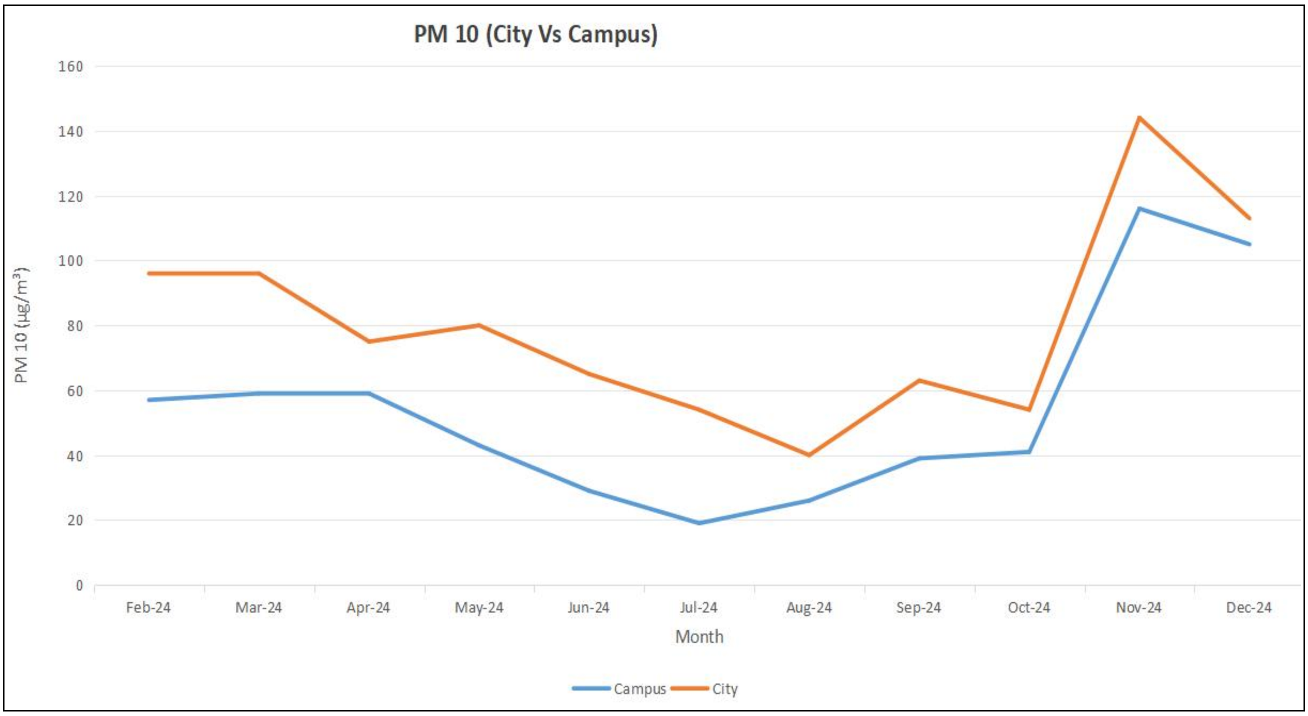


Figure 4.1c: PM10 Comparison for City vs. Campus

4.2 PM10 Infiltration During Dominant Wind Flows

During the initial phase of the study in mid-February, when the dominant wind direction was predominantly North-Eastern, a High-Volume Sampler (HVS) was strategically positioned near the main gate of the campus to measure boundary condition PM_{10} concentrations. This site was selected for its direct exposure to external vehicular emissions and the prevailing wind currents flowing in from the city perimeter, making it an ideal location to capture the impact of regional pollution entering the campus environment. The data collected from this point provided valuable insights into how external pollution sources influenced air quality within the campus boundary, establishing a baseline for further comparisons.

Air Volume Calculation:

- Q1 & Q2 = Initial & Final Airflow (m^3/min)
- t = Sampling Time (minutes)

$$V = \frac{(Q_i + Q_f) \times t}{2}$$

$$V = \frac{(1.13 + 1.13) \times 120}{2}$$

$$= 135.6\ m^3$$

Mass Concentration of Suspended Particulate Matter (SPM) Calculation:

- W1, W2 = Initial & Final Filter Weights (grams)
- V = Air Volume Sampled ($m^{3)}$

$$SPM = \frac{(W_f - W_i)}{V} \times 10^6$$

$$SPM = \frac{(2.983 - 2.981)}{135.6} \times 10^6$$

$$= 14.75\ \mu g/m^3$$

$$= 14.75 \times 12 = 177\ \mu g/m^3$$

The PM_{10} concentration derived from the HVS sampling, which was based on a two-hour active collection period and standard volumetric extrapolation, was calculated to be approximately 177 $\mu g/m^3$. This value starkly exceeded the World Health Organization's 24-hour guideline of 45 $\mu g/m^3$, underscoring the significant external particulate load present at the campus boundary during that period. The elevated concentration revealed the considerable pollution influx from regional sources, such as vehicular emissions, industrial activities, and dust, which were exacerbated by the prevailing wind patterns during the sampling period. This sharp contrast with the WHO guideline highlighted the vulnerability of the campus to external pollution, emphasizing the importance of assessing air quality in such environments.

As the study progressed into March, a shift in wind patterns toward the South-East significantly altered the pollutant dispersion dynamics within the campus. This change in wind direction had a direct impact on the distribution of particulate matter across various campus facilities. Real-time monitoring using the Temtop M2000 further revealed elevated PM_{10} concentrations in facilities aligned along the South-Eastern periphery, particularly in closed spaces such as the IFC Dining Halls and academic classrooms. These spaces, which are prone to limited air circulation due to their enclosed nature, showed notably higher indoor pollutant levels. This suggested that wind-driven infiltration, combined with restricted natural ventilation, were key contributors to the elevated PM_{10} concentrations observed in these areas.

In contrast, open facilities such as the stadium and volleyball courts exhibited comparatively lower PM_{10} concentrations, reinforcing the buffering effect of structural openness. The exposure to open air and the natural airflow through these facilities appeared to mitigate the accumulation of particulate matter, serving as a form of passive pollution control. This observation highlighted the critical role that building design, ventilation, and environmental exposure play in determining indoor air quality within institutional settings.

4.3 Facility-Wise IAQ: PM2.5, PM10, HCHO, and CO2

4.3.1 Indoor Air Quality in Closed Facilities

Indoor air quality assessments conducted across four key enclosed facilities — namely the Academic Classrooms, IFC A Dining Hall, Gymnasium, and Badminton Court — revealed clear patterns shaped by building design, occupancy density, and ventilation efficiency (Figures 4.3.1a–4.3.1d). Formaldehyde (HCHO) concentrations were generally within the World Health Organization's (WHO) recommended limit of 0.1 mg/m³, with the exception of the classroom environment, where the recorded levels exceeded the guideline (Figure 4.3.1d). This exceedance was likely driven by a combination of synthetic construction materials, furniture adhesives, and limited ventilation, particularly in areas adjacent to air-conditioned office zones where off-gassing from sealed interiors could accumulate more easily. In parallel, CO_2 levels served as an effective indicator of ventilation status and human presence, with the Gym, IFC A, and Classroom surpassing the WHO's 700 ppm benchmark (Figure 4.3.1c) — underlining issues of overcrowding and poor airflow circulation. The Badminton Court, however, consistently recorded CO_2 levels that hovered around or slightly below the limit, likely due to its semi-open architectural layout and intermittent human activity, which allowed passive air exchange. Regarding particulate matter, both $PM_{2.5}$ and PM_{10} concentrations peaked most prominently inside IFC A and the Gym (Figures 4.3.1a and 4.3.1b), where factors like dense footfall, on-site food preparation, and limited exhaust capacity contributed to the buildup of suspended particles. In contrast, the Classroom and Badminton Court demonstrated more moderate and stable particulate levels, likely a reflection of reduced indoor emission sources and occasional access to natural ventilation through doors, windows, or structural openness.

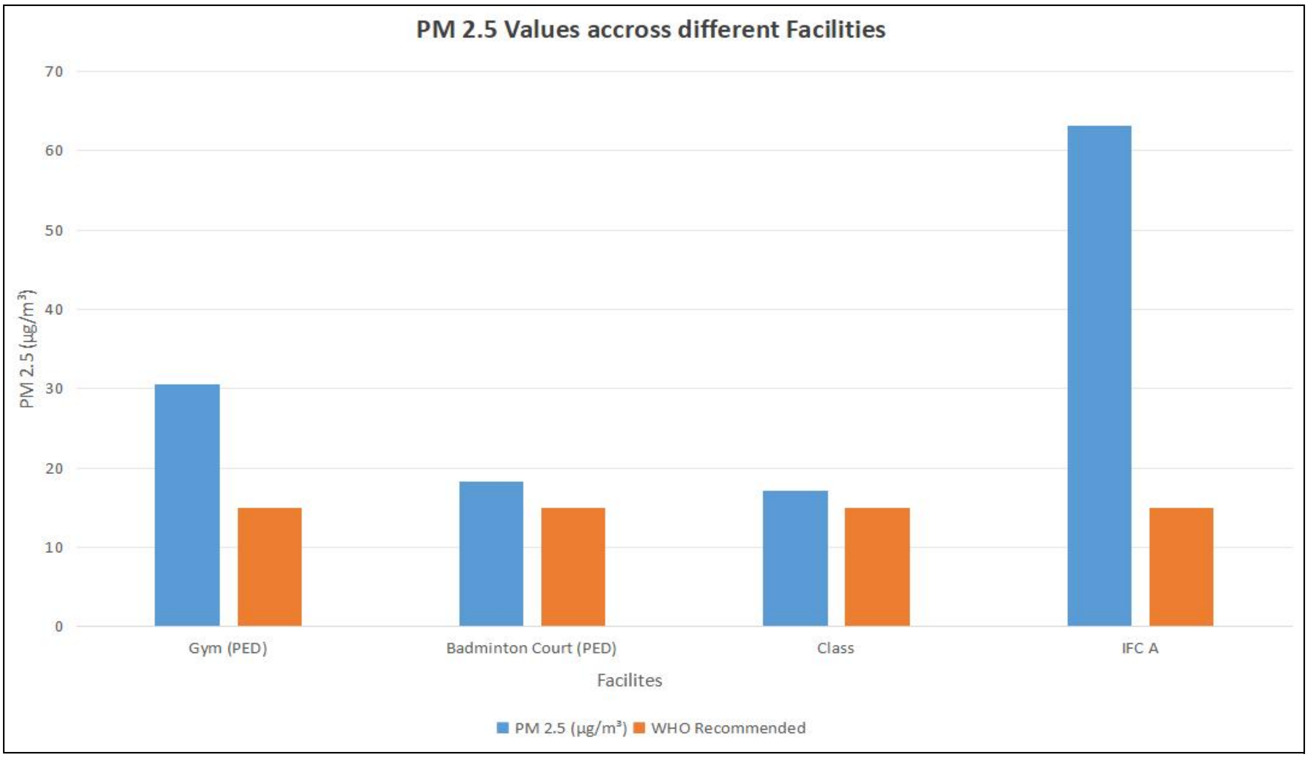


Figure 4.3.1a: PM2.5 Concentration in Closed Facilities

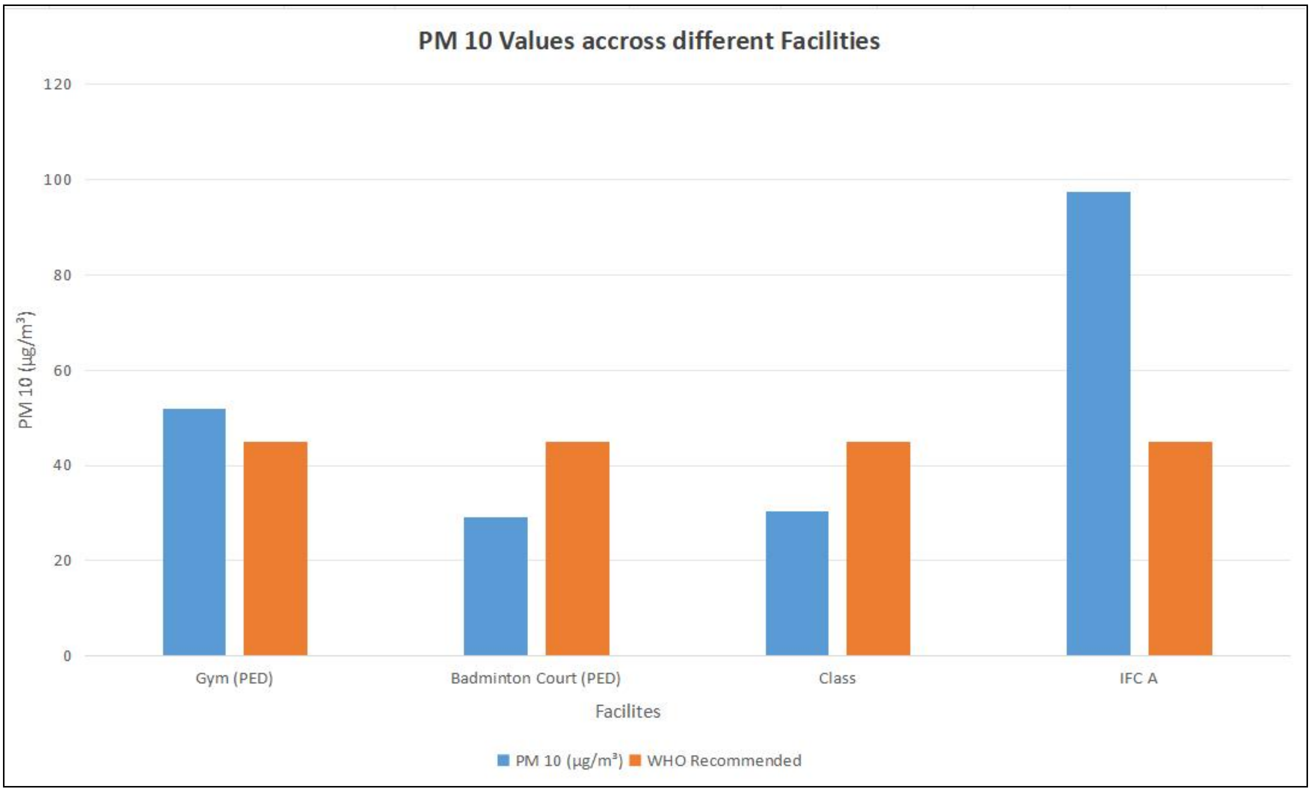


Figure 4.3.1b: PM10 Concentration in Closed Facilities

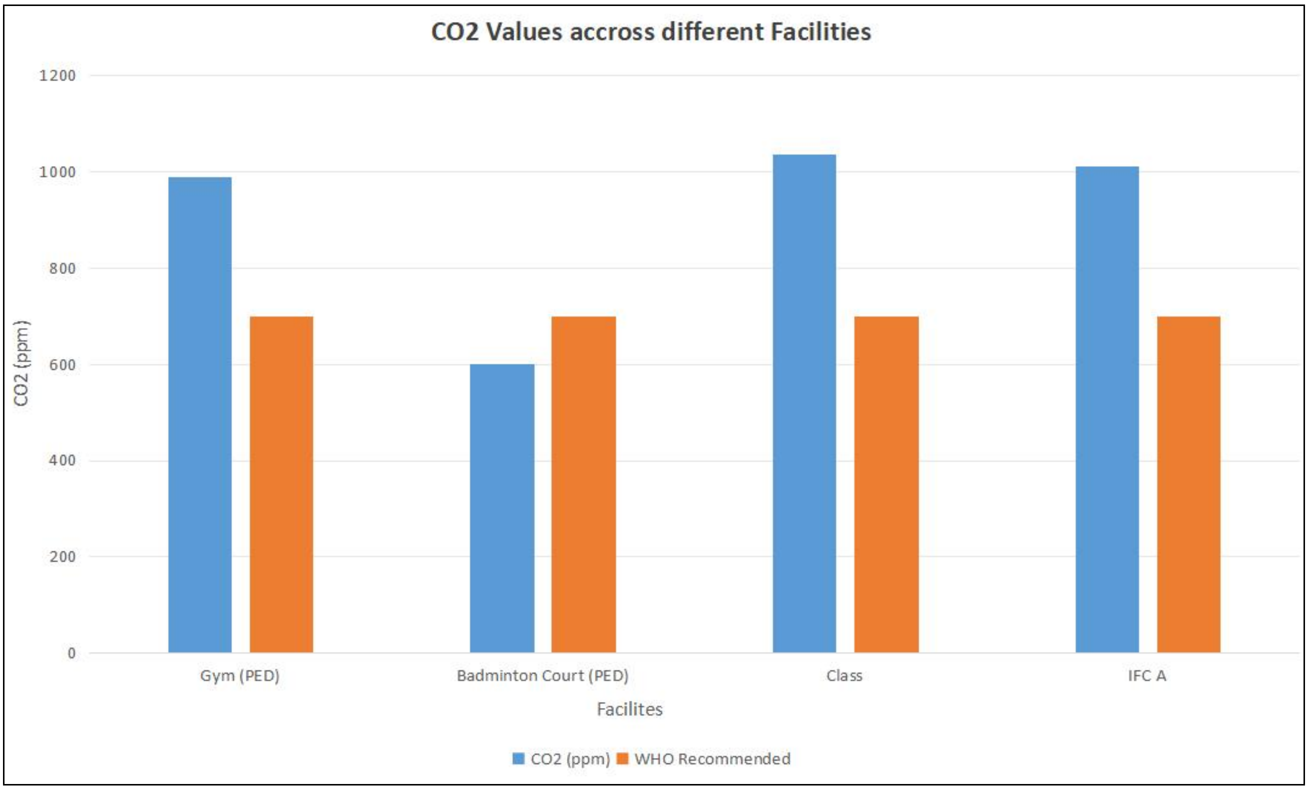


Figure 4.3.1c: CO_2 Levels in Closed Facilities

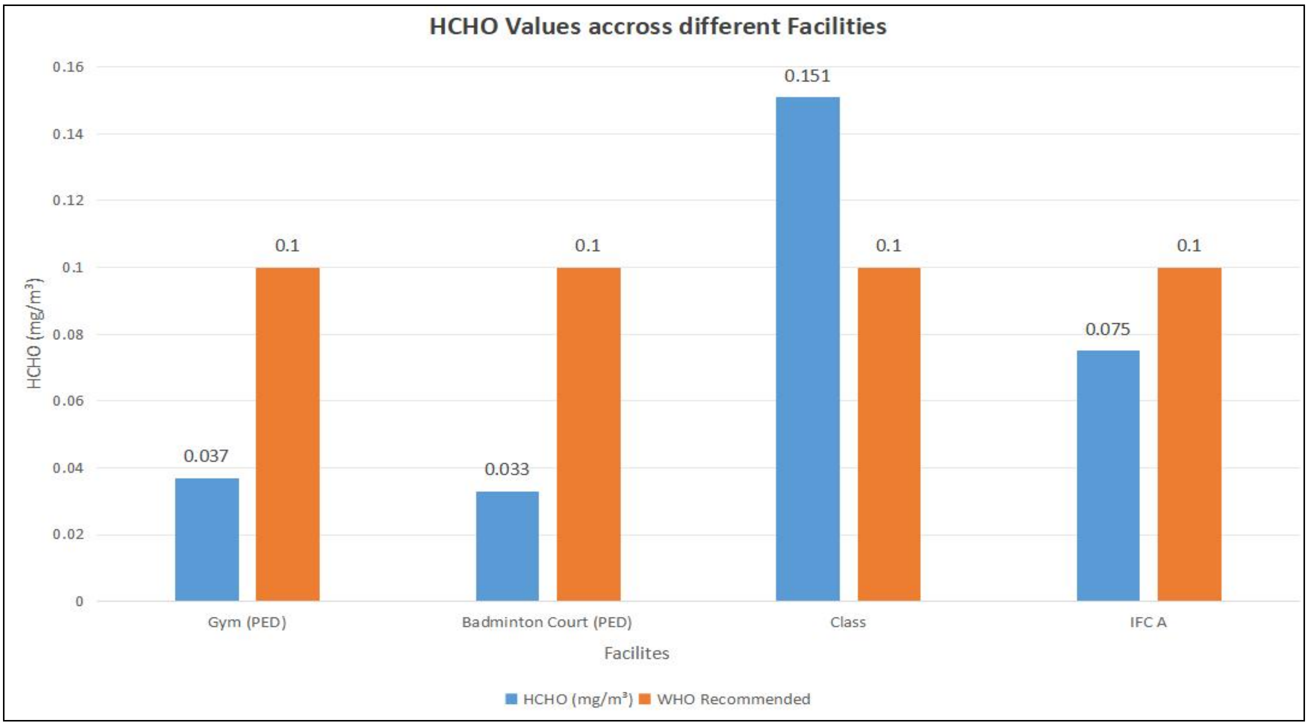


Figure 4.3.1d: HCHO Levels in Closed Facilities

4.3.2 Open Facility IAQ: PM2.5, PM10, HCHO, and CO_2

Indoor air quality assessments were conducted across four key open facilities on campus: the Volleyball Court, Main Stadium, 1K Ground, and Basketball Court. The pollutants measured included PM2.5, PM10, HCHO, and CO_2 — critical indicators of air quality and exposure risks, especially given the open-air nature of these spaces (Figures 4.3.2a–4.3.2d).

The PM2.5 concentrations across all open facilities exceeded the WHO recommended limit of 15 µg/m³ for a 24-hour average (Figure 4.3.2a). Particularly, the Main Stadium and 1K Ground recorded values nearly three times higher than the threshold, likely due to their large, open areas being exposed to higher traffic and urban pollution. In contrast, the Volleyball Court and Basketball Court showed more moderate PM2.5 levels, potentially due to the tree coverage around these areas, which could shield them from external pollution. A similar trend was observed for PM10, with the Main Stadium and 1K Ground showing values well beyond the WHO limit of 45 µg/m³ (Figure 4.3.2b). These facilities, being more exposed to external particulate pollution from vehicle emissions and dust, exhibited higher concentrations. On the other hand, the Volleyball Court and Basketball Court showed PM10 levels closer to the guideline limits, which might be attributed to their more sheltered locations.

CO_2 levels across all open facilities remained comfortably within the World Health Organization's recommended limit of 700 ppm (Figure 4.3.2c), clearly indicating that these spaces benefited from strong natural ventilation and continuous air exchange. The open architectural design of the stadium, volleyball courts, and hostel grounds allowed fresh air to circulate freely, preventing the buildup of exhaled carbon dioxide even during periods of high occupancy or sports activity. This unrestricted airflow helped maintain consistently low concentrations, despite the fluctuating number of users across different times of day.

Similarly, Formaldehyde (HCHO) concentrations were found to be well below the WHO's safety guideline of 0.1 mg/m³ in all four open-air locations (Figure 4.3.2d). The minimal presence of HCHO in these settings was expected, as the pollutant typically originates from indoor sources like adhesives, furniture materials, and cleaning agents — all of which were either absent or insignificant in these outdoor environments. The ample exposure to external air and the unrestricted dispersion of pollutants further reduced the likelihood of accumulation, ensuring that formaldehyde levels posed negligible health risks in these open campus spaces.

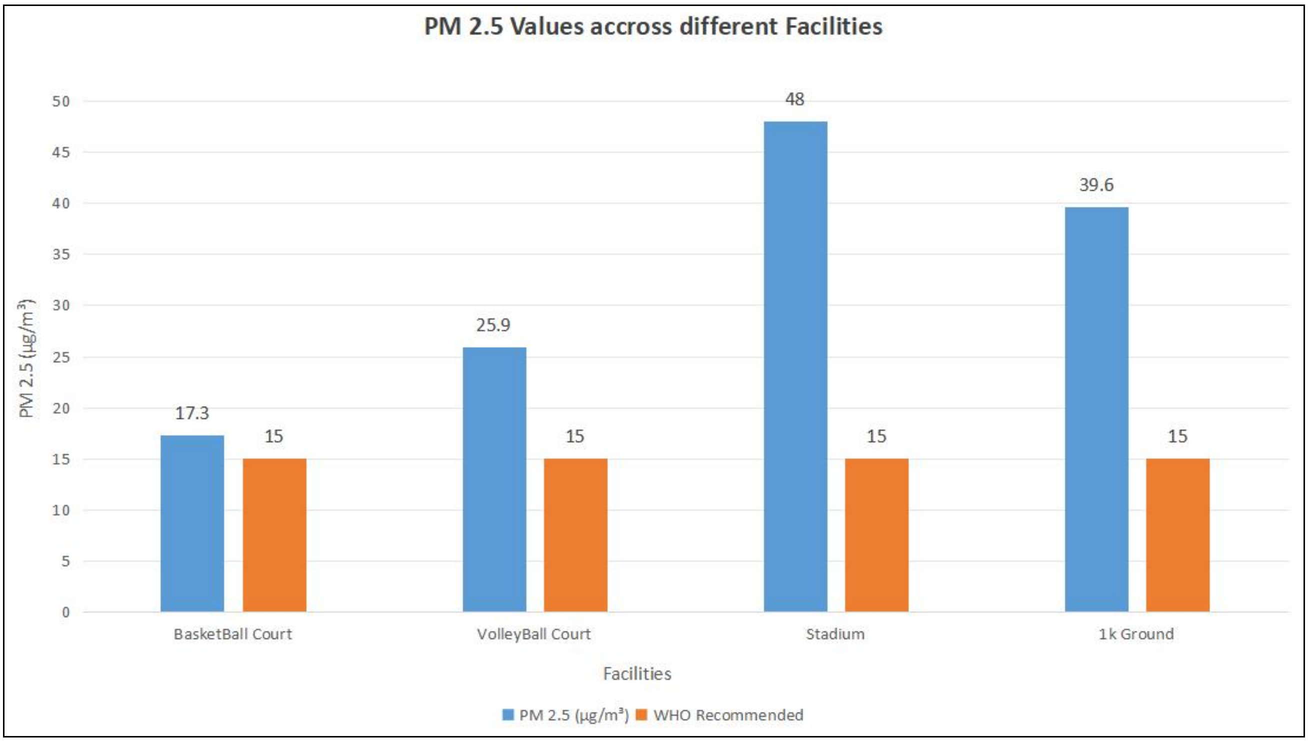


Figure 4.3.2a: **PM2.5 Concentration in Open Facilities**

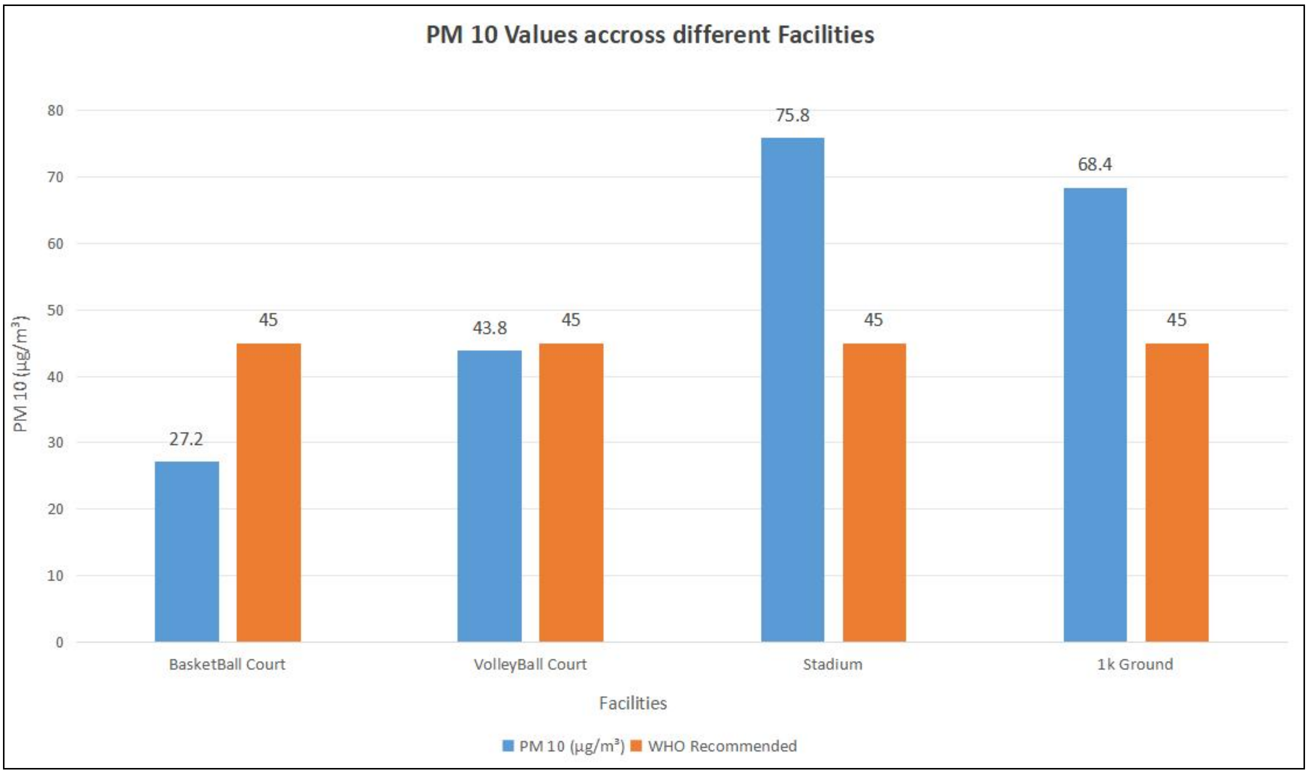


Figure 4.3.2b: **PM10 Concentration in Open Facilities**

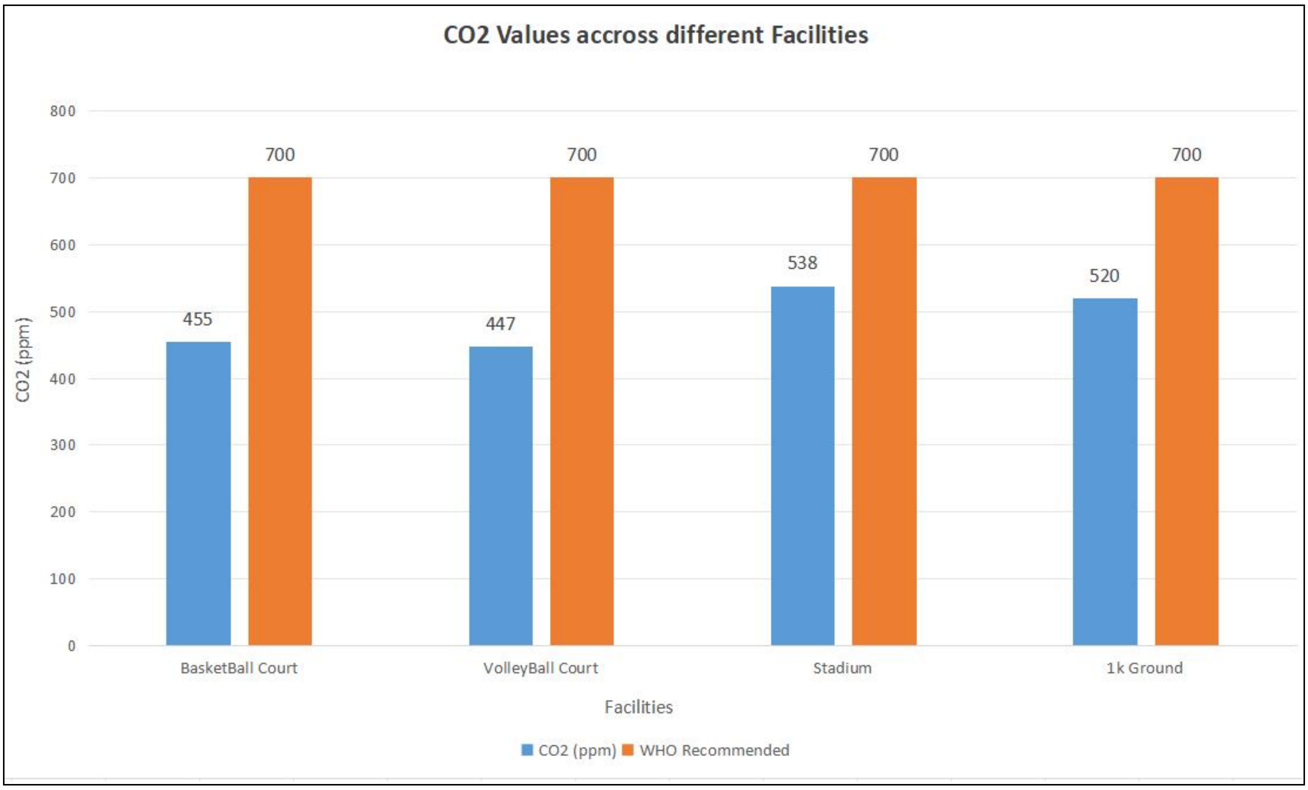


Figure 4.3.2c: **CO_2 Concentration in Open Facilities**

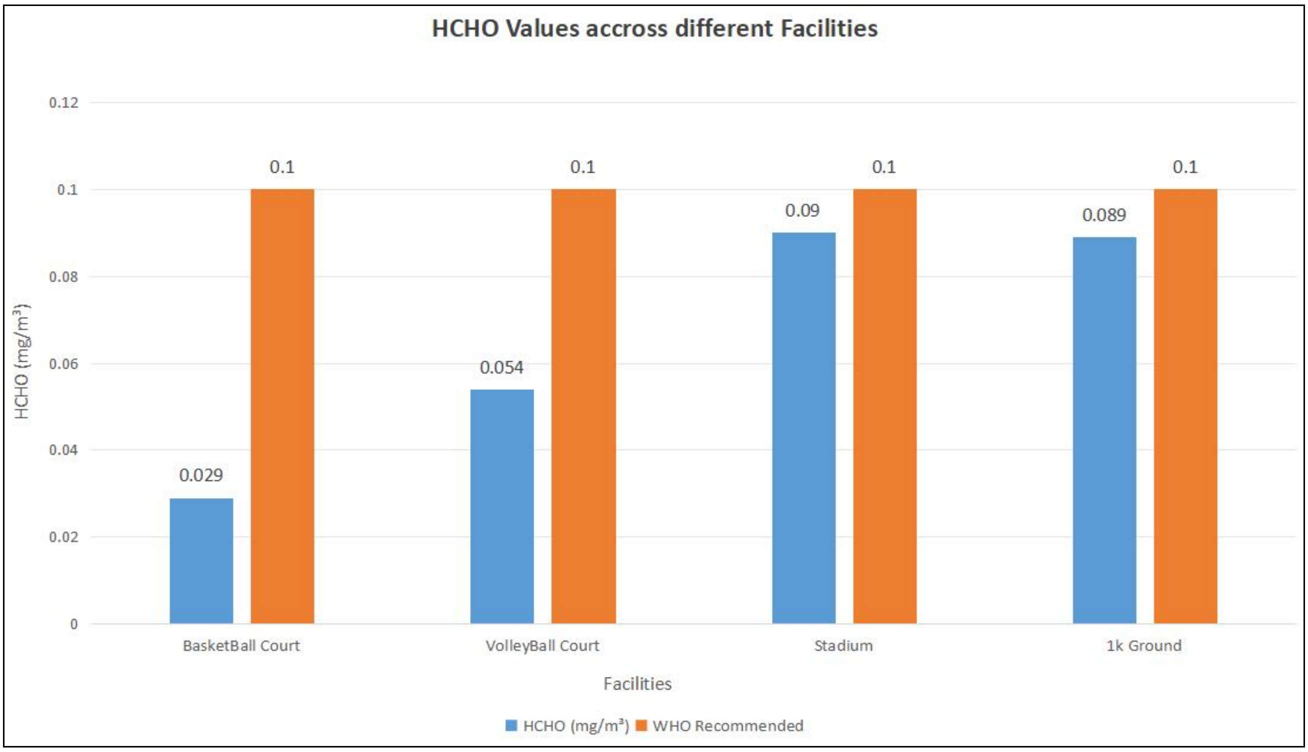


Figure 4.3.2d: **HCHO Concentration in Open Facilities**

4.4 Vertical Pollution Gradients: Floor-Wise Variability

Floor-wise air quality assessments were systematically performed at two major residential buildings within the NIT Warangal campus the 1K Hostel and the 1.8K Hostel with the aim of identifying the extent to which vertical distribution patterns influenced pollutant levels indoors. Measurements for $PM_{2.5}$, PM_{10}, HCHO, and CO_2 were taken at multiple floors in each hostel, offering insight into how architectural height, air movement, and pollutant infiltration from outdoor sources collectively shaped indoor air quality.

4.4.1 1K Hostel (Kakatiya Hall of Residence):

For the 1K Hostel, the pollutant analysis revealed that concentrations of $PM_{2.5}$ and PM_{10} across all three surveyed floors Ground , 3rd, and 6th consistently exceeded the World Health Organization's recommended air quality limits of 15 µg/m³ for $PM_{2.5}$ and 45 µg/m³ for PM_{10} (Figures 4.4.1a and 4.4.1b). Among these, the Ground Floor exhibited the highest particulate concentrations, drawing attention to the influence of physical location and environmental exposure on indoor air quality. This elevated particulate load is plausibly linked to the floor's direct connection to external pathways, proximity to access roads used by vehicles, and its position near commonly trafficked pedestrian routes. Frequent opening of doors and windows, especially during peak activity hours, combined with the lack of sufficient physical barriers, likely accelerated the inward drift of suspended particulates from outdoor sources. Additionally, the ground level typically experiences reduced wind-driven ventilation compared to upper floors, and the limited vertical air mixing within enclosed residential spaces further exacerbates the stagnation and accumulation of particulate matter close to the floor level, rather than allowing dispersion upwards or outwards.

In contrast , measurements for gaseous pollutants — particularly carbon dioxide (CO_2) and formaldehyde (HCHO) offered a more stable and reassuring outlook (Figures 4.4.1c and 4.4.1d). Across all surveyed floors, the recorded concentrations of CO_2 remained comfortably within the World Health Organization's advised limit of 700 ppm, while HCHO levels stayed below the safety guideline of 0.1 mg/m³. This finding suggests that gaseous pollutants within the hostel environment were not strongly influenced by the floor level or proximity to ground-level emissions but were instead more closely linked to the efficiency of indoor ventilation systems and human occupancy patterns. The data highlights that while particulate matter is driven by outdoor infiltration and building design, gaseous pollutants like CO_2 and formaldehyde depend on indoor sources and ventilation — emphasizing the need for separate mitigation strategies.

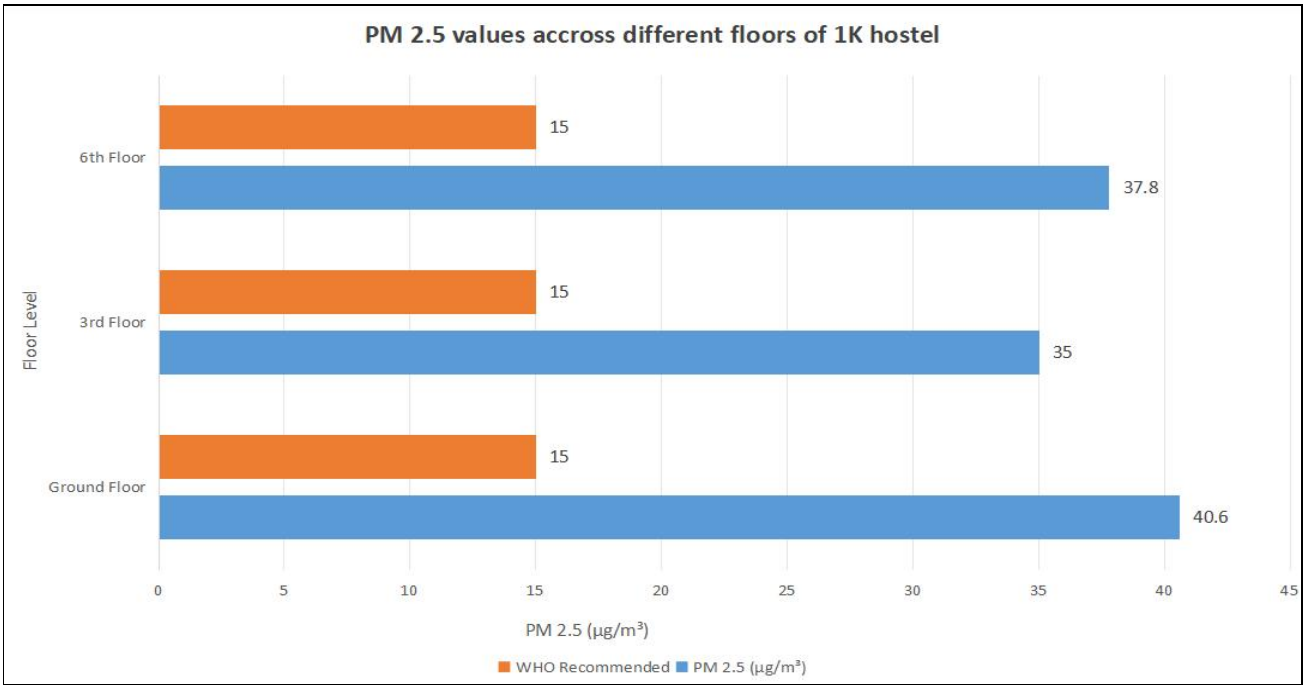


Figure 4.4.1a: Floor-wise PM2.5 concentration levels in 1K Hostel

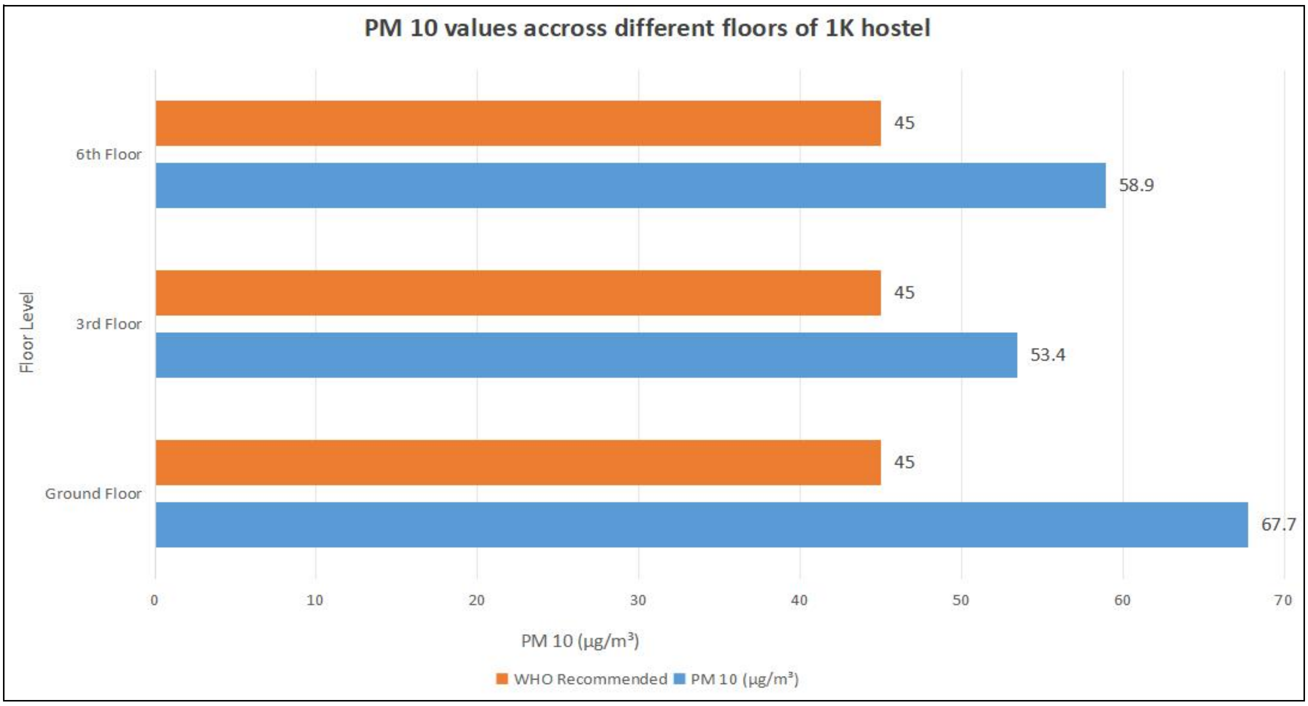


Figure 4.4.1b: Floor-wise PM10 concentration levels in 1K Hostel

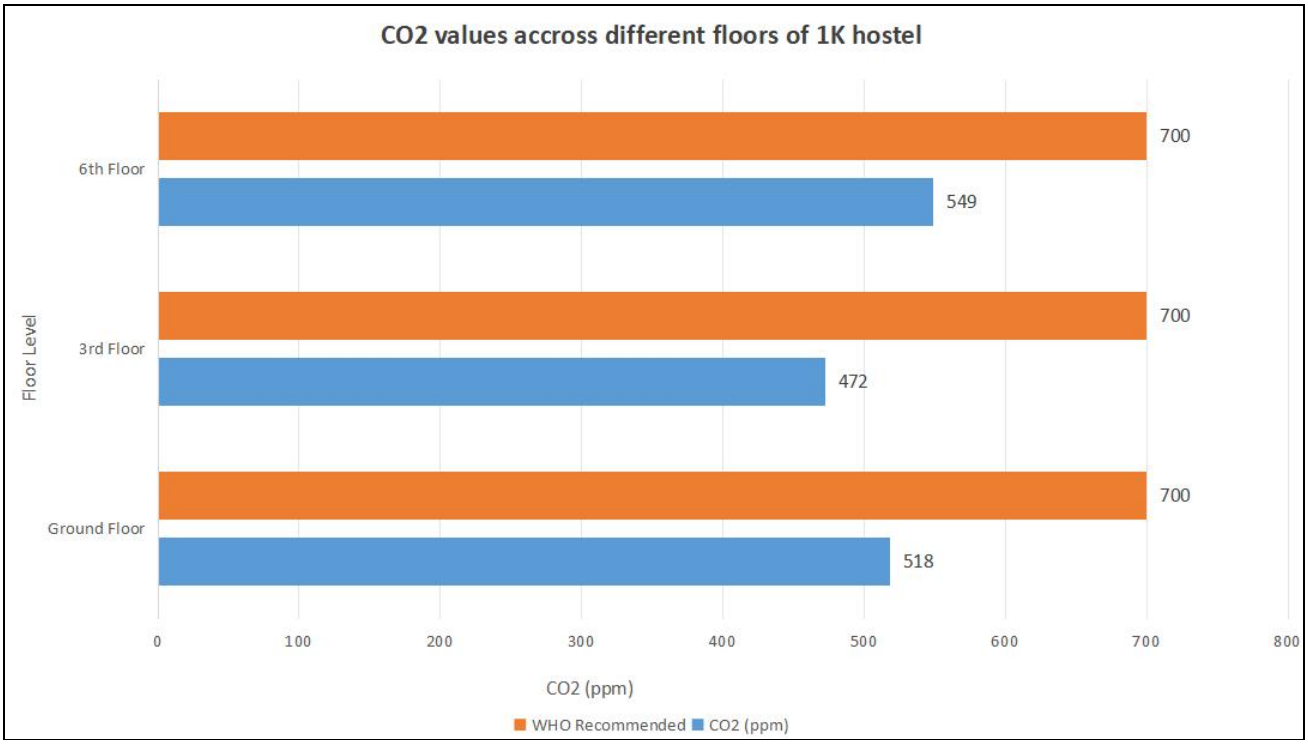


Figure 4.4.1c: Floor-wise CO_2 concentration levels in 1K Hostel

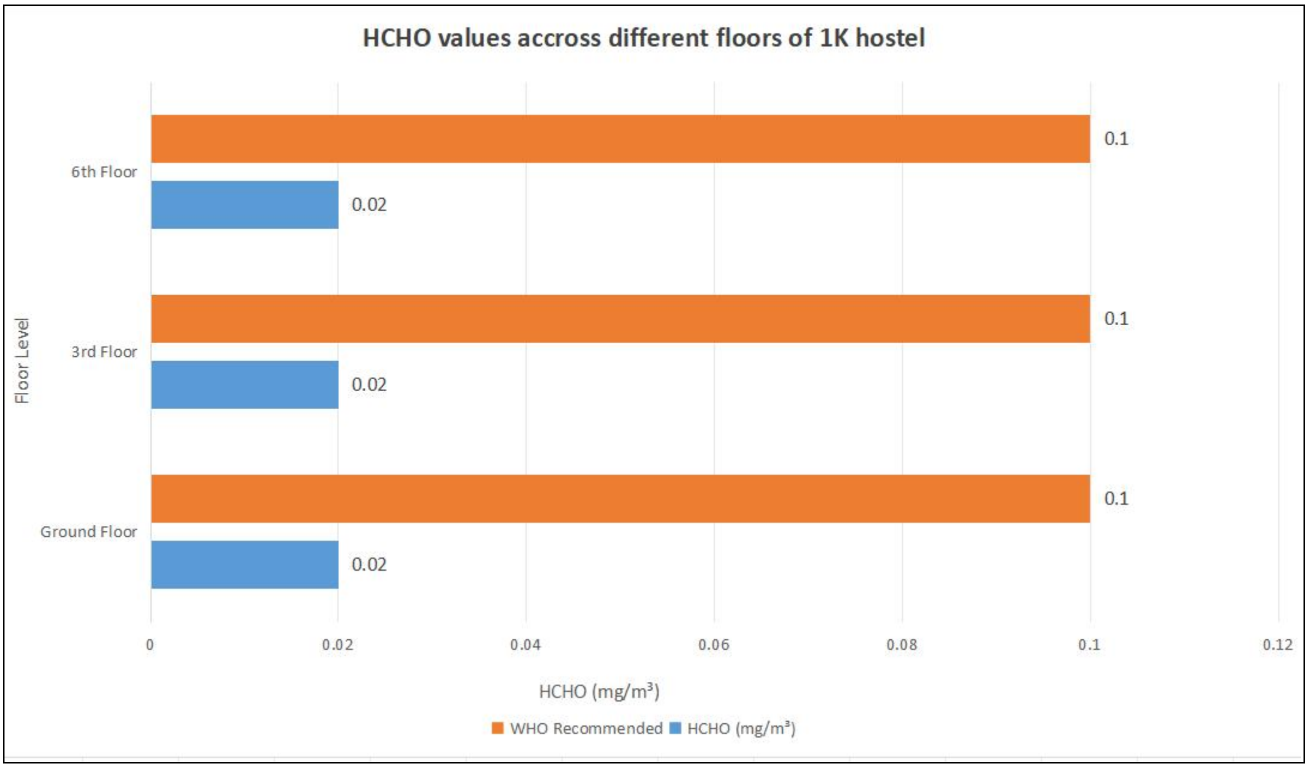


Figure 4.4.1d: Floor-wise HCHO concentration levels in 1K Hostel

4.4.2 1.8K Hostel (Ramappa Hall of Residence) :

For the 1.8K Hostel, the air quality analysis showed a distinct distribution pattern when compared to the 1K block. $PM_{2.5}$ and PM_{10} concentrations (Figure 4.4.2a and Figure 4.4.2b) were consistently recorded above the World Health Organization's recommended limits — 15 µg/m³ for $PM_{2.5}$ and 45 µg/m³ for PM_{10} — across all surveyed floors: 1st, 4th, 7th, and 9th. Unlike the 1K Hostel, where the ground floor displayed the highest values due to its close proximity to dust sources and vehicular activity, the 1.8K Hostel exhibited a gradual increase in particulate concentrations as the floor level rose, before stabilizing at the uppermost levels. This trend indicates the role of wind-driven pollutant transport and the influence of reduced physical obstructions at higher elevations, which allow airborne particulates particularly the finer $PM_{2.5}$ to accumulate more readily in upper-floor spaces.

In contrast, the measurements for gaseous pollutants such as CO_2 and HCHO (Figure 4.4.2c and Figure 4.4.2d) remained comfortably within the WHO-recommended thresholds of 700 ppm and 0.1 mg/m³, respectively, on all floors. This consistency suggests that the natural ventilation and airflow within the hostel were effective enough to prevent the buildup of these indoor-origin pollutants, regardless of floor level, even though particulate matter showed clear vertical variability.

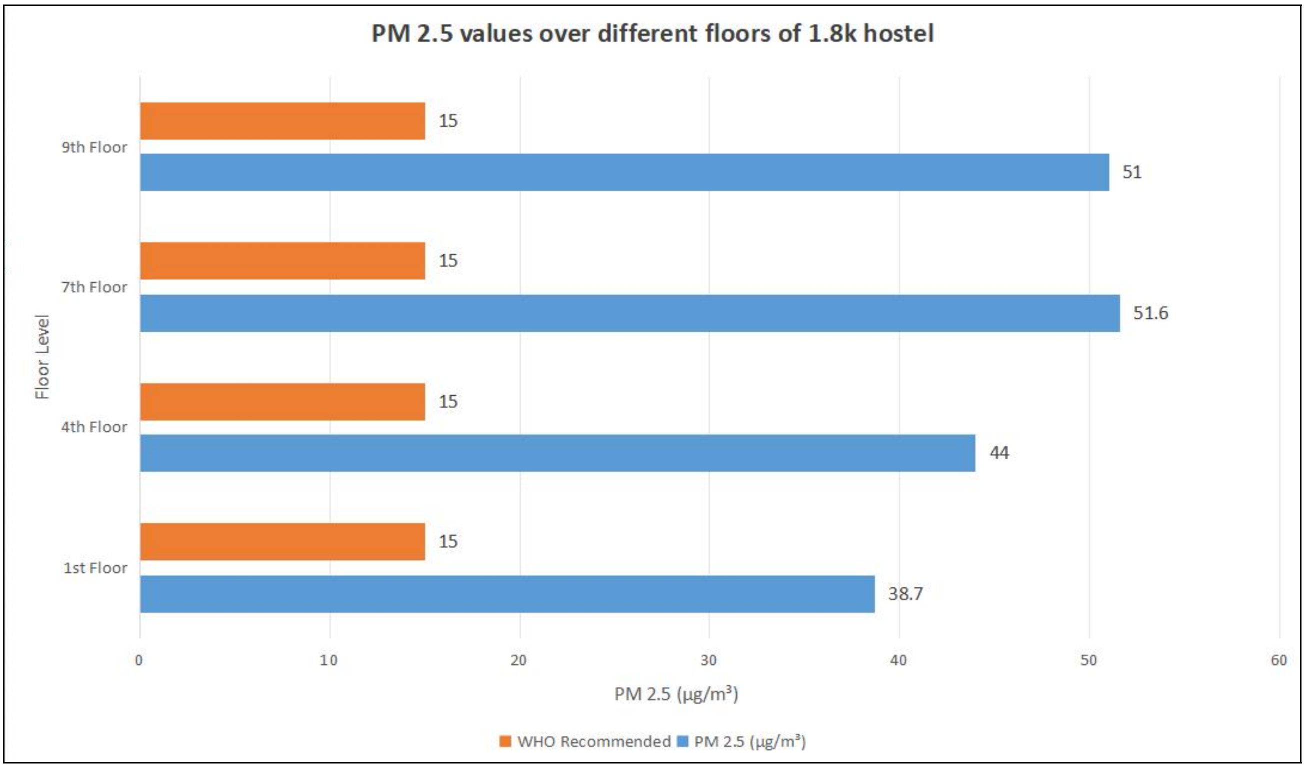


Figure 4.4.2a: Floor-wise distribution of PM2.5 concentrations at 1.8K Hostel.

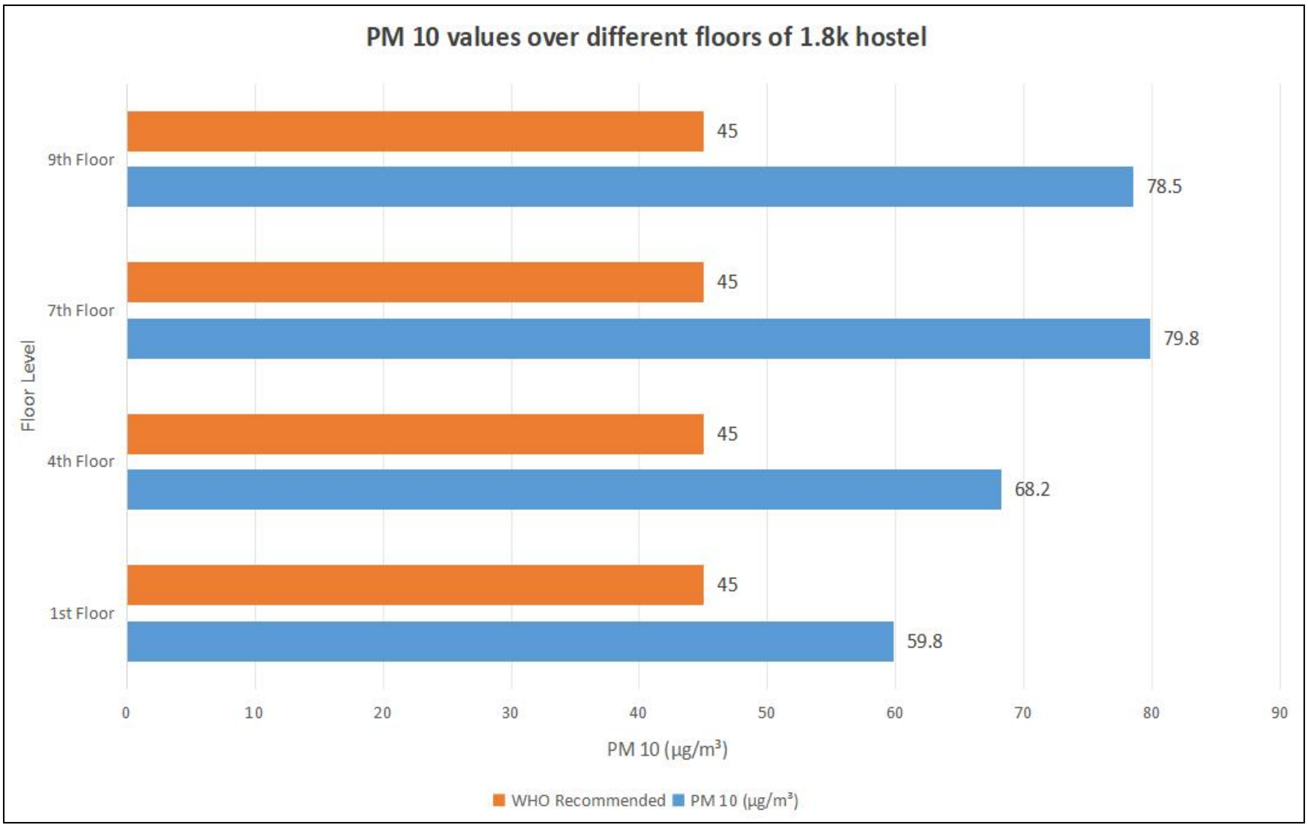


Figure 4.4.2b: Floor-wise distribution of PM10 concentrations at 1.8K Hostel.

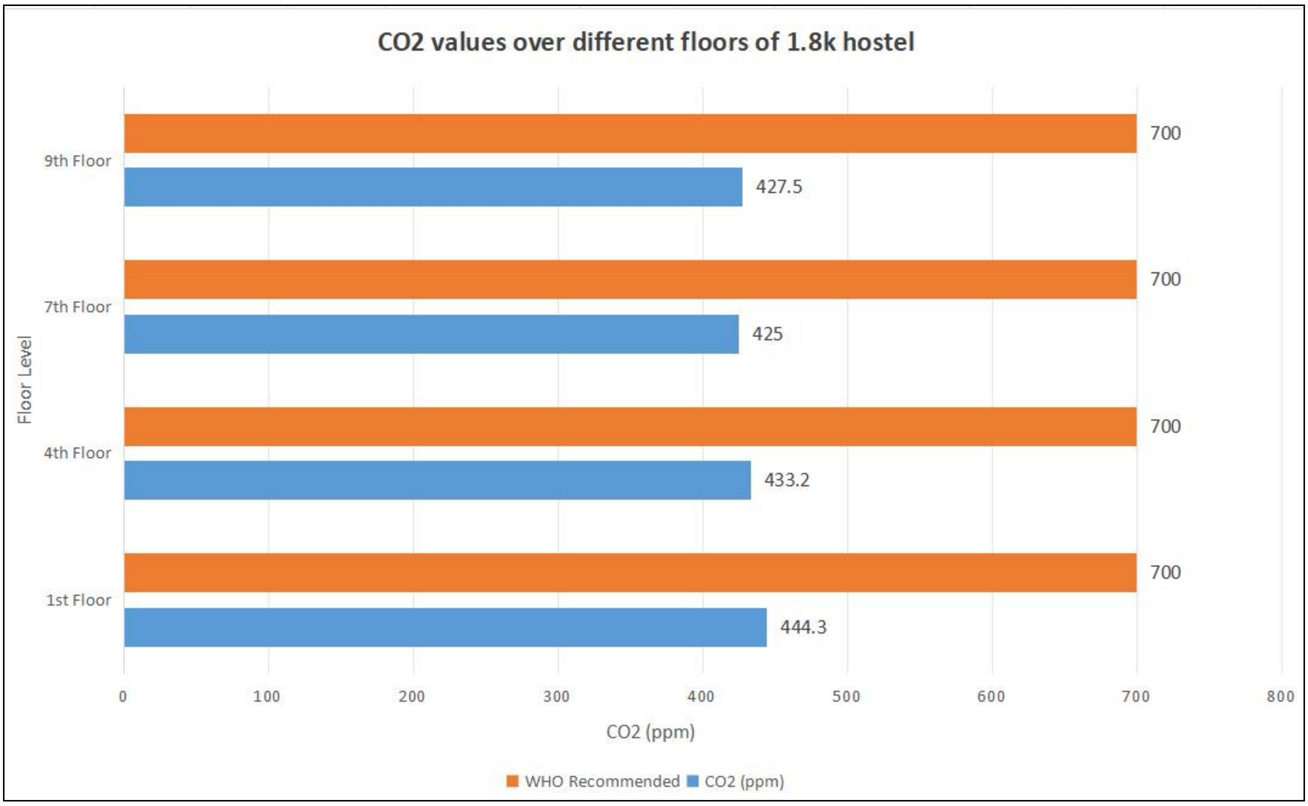


Figure 4.4.2c: Floor-wise CO_2 concentration levels in 1.8K Hostel

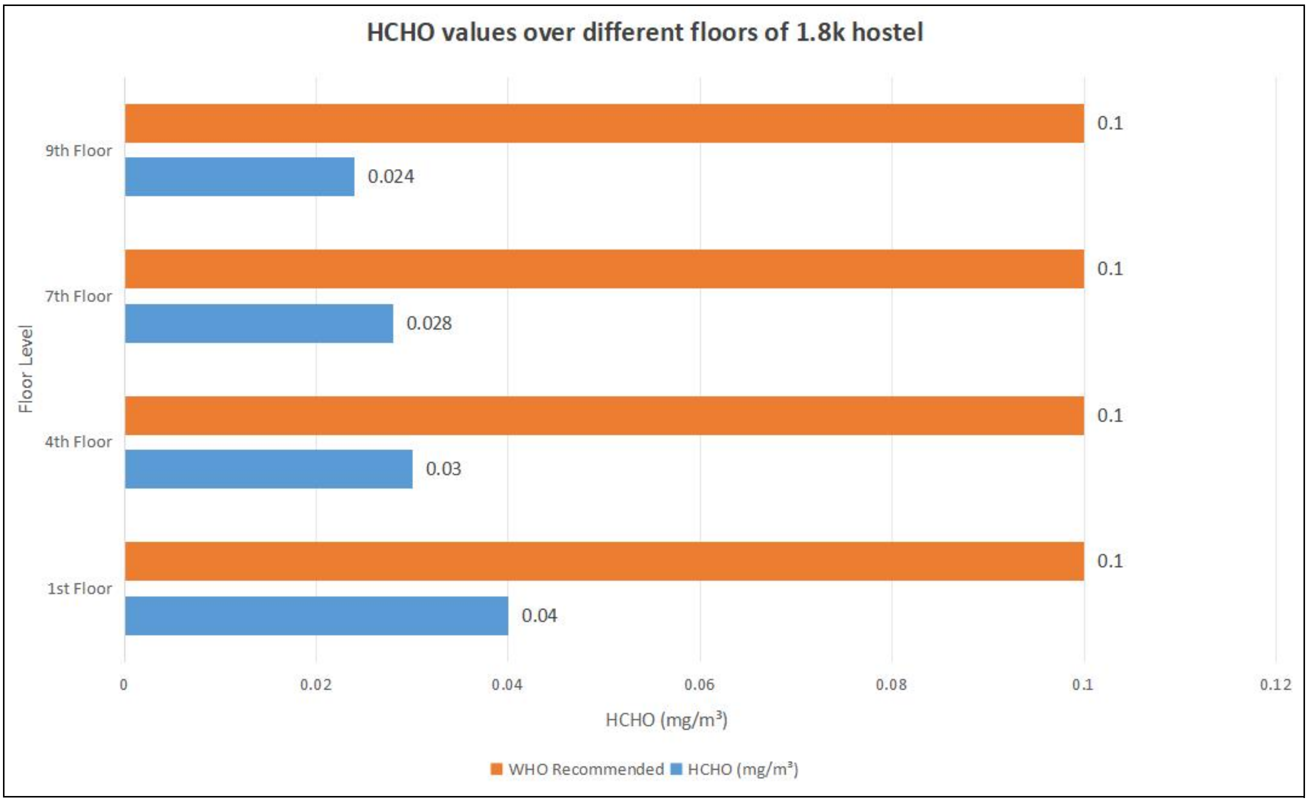
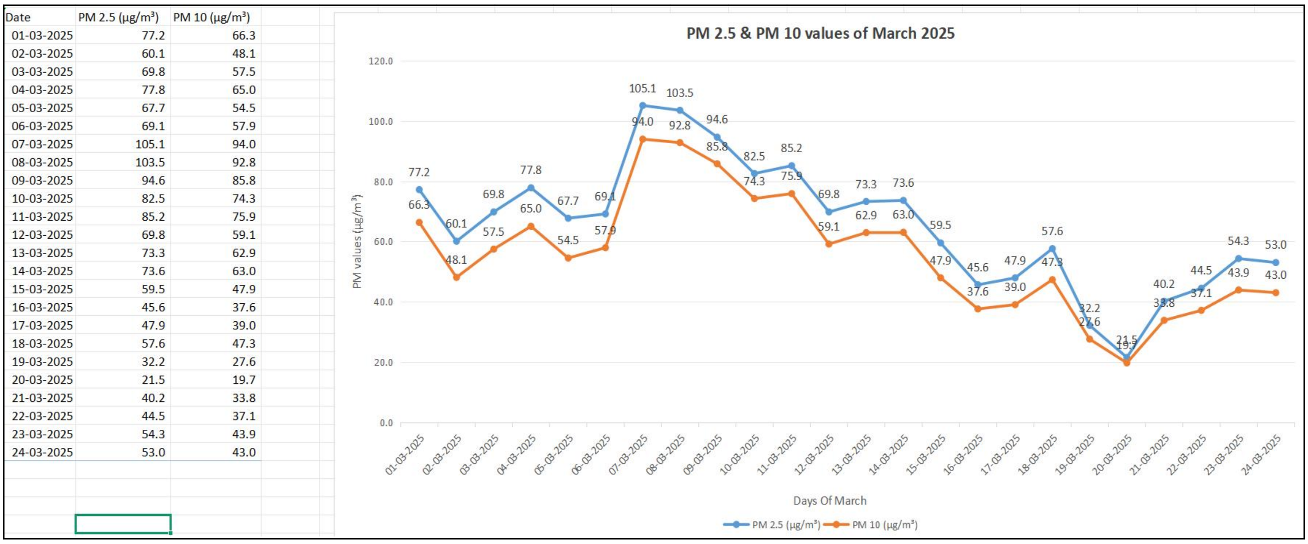


Figure 4.4.2d: Floor-wise HCHO concentration levels in 1.8K Hostel

4.5 Seasonal Shifts and Spatial Correlations

The month of March 2025 exhibited notable variability in $PM_{2.5}$ and PM_{10} concentrations across the NIT Warangal campus, as evidenced by the recorded dataset (Figure 4.5). These fluctuations were especially pronounced and reflected the transitional nature of the season, where the prevailing wind patterns gradually shifted from the typical northeasterly flow of late winter to the emerging southeasterly currents associated with the onset of summer. This shift not only altered the direction of pollutant inflow but also affected dispersion dynamics and pollutant accumulation across both outdoor and indoor campus environments.

Such transitional months are often marked by unstable weather conditions, shifting temperatures, and irregular wind speeds, all of which contribute to short-term spikes and dips in pollutant levels. This behavior aligned with our February HVS boundary condition measurements, where winds were predominantly northeasterly, exposing the campus to particulate inflow from urban sources near the perimeter. However, by mid to late March, southeasterly winds became more dominant, redirecting pollutant movement across the campus and influencing concentrations, particularly in facilities positioned along the southeast boundary. To ensure the reliability and representativeness of the air quality data, Temtop measurements were not restricted to isolated snapshots but were distributed across a span of 2–3 weeks. This approach minimized the risk of skewed results from unusually clean or polluted days and provided a more balanced and accurate assessment of ambient air quality during this season of atmospheric transition.



Date	PM 2.5 (µg/m³)	PM 10 (µg/m³)
01-03-2025	77.2	66.3
02-03-2025	60.1	48.1
03-03-2025	69.8	57.5
04-03-2025	77.8	65.0
05-03-2025	67.7	54.5
06-03-2025	69.1	57.9
07-03-2025	105.1	94.0
08-03-2025	103.5	92.8
09-03-2025	94.6	85.8
10-03-2025	82.5	74.3
11-03-2025	85.2	75.9
12-03-2025	69.8	59.1
13-03-2025	73.3	62.9
14-03-2025	73.6	63.0
15-03-2025	59.5	47.9
16-03-2025	45.6	37.6
17-03-2025	47.9	39.0
18-03-2025	57.6	47.3
19-03-2025	32.2	27.6
20-03-2025	21.5	19.7
21-03-2025	40.2	33.8
22-03-2025	44.5	37.1
23-03-2025	54.3	43.9
24-03-2025	53.0	43.0

Figure 4.5: Monthly variation of PM2.5 and PM10 across NIT Warangal during March 2025

CHAPTER 5

DISCUSSION AND CONCLUSIONS

The findings of this study underscore the pervasive presence of air pollution throughout various microenvironments on the NIT Warangal campus. This pollution is influenced by a range of factors that interact in complex ways. Spatially, certain areas of the campus, such as open facilities and closed buildings, experience different levels of pollution exposure due to their location and the surrounding environment. Seasonally, changes in wind patterns during the year — such as the shift from northeastern winds in winter to southeastern winds in spring — play a significant role in transporting pollutants into the campus from surrounding urban areas.

The study also reveals how architectural and design features within the campus buildings contribute to exposure patterns. For instance, closed spaces with poor ventilation systems, such as classrooms and dining halls, trap pollutants like CO_2 and particulate matter, leading to elevated indoor concentrations. Meanwhile, open facilities benefit from better natural ventilation, keeping pollutant levels relatively lower. Furthermore, the presence of high foot traffic, limited air exchange, and structural factors like building height also contribute to variations in air quality across the campus.

Overall, the findings make it clear that the air quality on educational campuses is shaped by a combination of external factors (such as the influx of pollution from nearby urban areas) and internal factors (including the design, ventilation, and use of campus buildings). These interconnected influences must be taken into account when developing strategies for improving air quality and reducing exposure risks.

5.1 Wind Direction as a Driver of Indoor Pollution

Wind direction played a pivotal role in shaping both outdoor and indoor pollution levels on the NIT Warangal campus, serving as a significant environmental variable influencing pollutant dispersion. Field observations and data from the High Volume Sampler (HVS) deployed in mid-February revealed a strong correlation between wind patterns and air quality. Throughout February, the campus experienced predominantly northeasterly winds, which likely transported particulate matter from nearby semi-urban areas located on the outskirts of Warangal. This influx of pollutants was especially evident at boundary locations and contributed to elevated pollution levels.

As the study progressed into mid to late March, a noticeable shift in wind direction occurred, with southeasterly winds becoming more dominant. This transition marked the seasonal shift from winter to pre-summer conditions, altering atmospheric dynamics and influencing the movement of airborne particulates. The change in wind direction had a notable effect on the redistribution of pollutants, with southeastern-facing areas of the campus experiencing higher pollutant concentrations.

This seasonal shift in wind patterns, combined with temperature fluctuations and changes in atmospheric stability, underscores the need for air quality monitoring strategies that capture temporal variability as show in AirLink dashboard (Figure 5.1). Relying solely on short-term measurements would overlook the larger, long-term impact of prevailing winds on pollutant movement and indoor air quality. Additionally, these findings highlight the importance of architectural design, such as building orientation, window placement, and landscaping, in mitigating the effects of wind-driven pollution. Properly designed campuses can use these elements as passive strategies to reduce the impact of external pollution sources on indoor air quality.

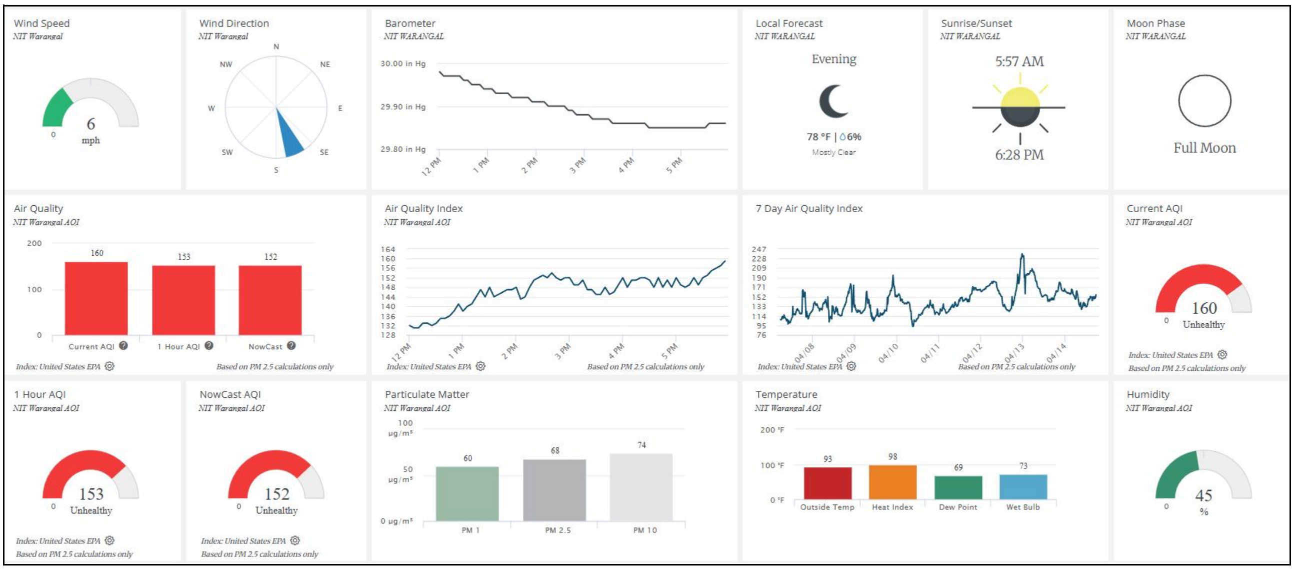


Figure 5.1: AirLink dashboard snapshot showing wind direction and pollutant variations at NIT Warangal. Sourced from weatherlink.com

5.2 Bridging Ambient Standards and Indoor Air Quality

The data collected across various campus facilities consistently indicated that WHO's ambient air quality thresholds for PM2.5, PM10, and CO_2 were often exceeded, particularly in indoor spaces such as IFC A (Dining Hall), the Gymnasium, and classrooms. This highlights a significant discrepancy between the ambient air quality standards typically designed for outdoor environments and the challenges posed by indoor air pollution, especially in high-occupancy spaces with insufficient ventilation systems. The elevated pollutant levels observed within these facilities underline the difficulty in maintaining safe air quality in closed environments, where factors such as building design, occupant behavior, and ventilation can contribute to indoor air quality degradation.

Though the WHO has established indoor exposure limits for certain pollutants, the campus data suggest that indoor environments frequently mirror the outdoor pollution load, but with the potential for certain pollutants to accumulate at even higher concentrations depending on the ventilation conditions and human activity. For example, particulate matter, which was often carried into the campus from external sources such as dust-laden winds and vehicular emissions, tended to accumulate in indoor environments with poor ventilation, such as rooms with sealed windows and walls. The lack of mechanical air exchange in these spaces resulted in particulate matter remaining trapped, leading to higher concentrations than would be expected from outdoor air quality alone.

Elevated CO_2 levels, on the other hand, were predominantly linked to occupancy density and inadequate air circulation. In spaces such as the Gymnasium and Dining Hall, where large groups of people congregated, CO_2 levels frequently exceeded WHO guidelines due to the high number of occupants and the lack of effective ventilation systems to facilitate the exchange of stale indoor air. This emphasizes how human behavior such as the number of individuals present and their activities combined with building design, directly impacts the air quality in indoor spaces.

The case of formaldehyde (HCHO) provided further insight into the complexities of indoor air quality. Despite high levels of particulate pollution, formaldehyde concentrations often remained within safe limits across most spaces. However, the classroom stood out as an exception, with formaldehyde levels exceeding recommended thresholds. This was likely due to off-gassing from synthetic materials, adhesives in furniture, and the presence of construction materials used in building the space. In contrast to particulate pollution, which largely originates from outdoor sources, the elevated formaldehyde concentration was a product of internal factors, further emphasizing the need for comprehensive air quality management that accounts for both external pollutants and indoor emissions.

5.3 Institutional Mitigation Strategies and Key Findings

The findings of this study strongly emphasize the need for educational institutions like NIT Warangal to adopt a more structured, proactive approach to indoor air quality management. Given the consistently elevated levels of pollutants such as PM2.5, PM10, and CO_2 within campus facilities, especially in high-traffic areas like classrooms, dining halls, and gyms, it's clear that improvements to the mechanical ventilation systems are essential. Upgrading and optimizing ventilation infrastructure is likely the most effective short-term solution to mitigate both particulate matter and CO_2 buildup. By enhancing air circulation and introducing better filtration systems, these spaces can see significant improvements in air quality, thereby reducing the health risks associated with poor indoor air quality.

In addition to improving mechanical ventilation, incorporating real-time monitoring for CO_2 and particulate matter can provide valuable data for dynamic adjustments to ventilation systems. These adjustments could be made in response to fluctuations in occupancy levels and pollutant concentrations, ensuring that air quality is maintained at optimal levels. Real-time data could also enable a more personalized and responsive approach, enhancing comfort and health safety for students and staff by adjusting ventilation rates based on real-time air quality assessments.

Another crucial strategy highlighted by the findings is the incorporation of green infrastructure on campus. The strategic planting of trees, hedges, and other vegetation can act as a natural barrier, reducing the intrusion of dust and airborne particulates, particularly in ground-floor hostel rooms and nearby open spaces like sports facilities. Green spaces not only improve the aesthetic appeal of the campus but also provide significant environmental benefits by naturally filtering out pollutants from the air, providing a dual advantage for the health and well-being of the campus community.

Periodic air quality audits using devices like the Temtop or equivalent air monitoring sensors should be institutionalized as part of routine campus operations. These audits would provide critical insights into pollutant levels, enabling the campus authorities to track and manage pollution exposure, especially during transitional months where atmospheric conditions can fluctuate significantly. Implementing regular air quality assessments can ensure that corrective actions are taken promptly, preventing long-term exposure to harmful pollutants.

Finally, the study underscores the importance of using data-driven decision-making to guide spatial planning and the allocation of resources. By integrating air quality data into the evaluation of facility usage patterns, campus authorities can identify areas that are most at risk of poor air quality based on both the severity of pollutant concentrations and the length of exposure. This approach ensures that interventions are focused on the most problematic areas, optimizing resources and effectively protecting the health of those who spend significant time in these spaces. This combination of strategic infrastructure improvements, real-time monitoring, green infrastructure, and data-driven spatial planning will contribute to creating a healthier, more sustainable campus environment for all.

5.4 Policy Advocacy and Future Research Directions

The evidence presented underscores the critical need to update policy perspectives on indoor air quality, particularly within academic and public institutional settings in India. While national ambient air quality standards (NAAQS) provide a foundation for regulatory monitoring of outdoor air quality, indoor environments — where individuals spend the majority of their time — remain significantly under-regulated and under-studied. Addressing this gap will require a combination of legislative action, institutional accountability, and a shift in how we view air quality in enclosed spaces.

This study clearly demonstrates that indoor air quality (IAQ) should not be treated as an isolated technical issue but must be integrated into public health considerations and sustainable campus design. National guidelines should emphasize the routine monitoring of IAQ in schools, universities, and hostels, along with the establishment of clear ventilation benchmarks and maintenance schedules for both mechanical and natural systems. Such measures will not only improve air quality but also contribute to a healthier and more sustainable living and learning environment for students and staff alike.

Future research should aim to expand both the spatial and temporal scope of this study. Longitudinal studies capture seasonal extremes and the behavior of pollutants over different weather cycles would provide deeper insights into how indoor air quality fluctuates in academic environments. Additionally, the inclusion of pollutants such as Volatile Organic Compounds (VOCs), nitrogen dioxide (NO_2), and ozone (O_3) would enrich our understanding of indoor air risks and their potential health impacts. This expanded research focus will be crucial in developing comprehensive strategies to mitigate indoor air pollution and safeguard public health in academic and institutional settings.

APPENDIX I

Temtop Air Quality Monitor (Model: M2000) Specifications

The Temtop M2000 Air Quality Monitor is a portable, laser-based particle counter combined with a gas sensor suite designed for indoor air quality assessment. It is widely used for real-time measurement of particulate matter and gaseous pollutants, particularly in resource-limited settings where a balance between accuracy and portability is essential. The core specifications are outlined below:

Model	M2000 Series
Dimensions	223.5x73.5x37.5mm / 8.8x2.8x1.4
Battery capacity	3000mAh
Battery life	6-8h
Input	DC 5V/1A
Display	TFT color screen
Weight	228g @M2000/M2000 2nd 221g @M2000C/M2000C 2nd
Operation environment	Temperature range: 0-50°C(32-122°F) Humidity range: 0-90% RH Atrnospheric pressure condition: 1atm
Temperature	Measuring range: 0-50°C(32-122°F) Resolution: 0.1°C Accuracy: ±1°C
Humidity	Measuring range: 0-99.9% RH Resolution: 0.1% RH Accuracy: ±5% RH
PM2.5	Sensor: Laser PM sensor Measuring range: 0-999 μg/m³ Resolution: 0.1 μg/m³ Accuracy: ±10 μg/m³(0-100 μg/m³) ±10%(100-500 μg/m³)
PM10	Sensor: Laser PM sensor Measuring range: 0-999 μg/m³ Resolution: 0.1 μg/m³ Accuracy: ±15 μg/m³(0-100 μg/m³) ±15%(100-500 μg/m³)
Carbon dioxide (CO_2)	Sensor: Non-Dispersive Infrared (NDIR)CO_2 sensor Measuring range: 0-5000 ppm Resolution: 1 ppm Accuracy: ±5% ±50 ppm(400~5000ppm)
HCHO*	Sensor: Electrochemical HCHO sensor Measurement range:0-2 mg/m³ Resolution: 0.001 mg/m³

REFERENCES

- Asrani, S., & Shah, D. (2024). *Review on indoor air quality in Indian buildings*. Retrieved from https://www.researchgate.net/publication/352894464_Review_on_indoor_air_quality_in_Indian buildings
- Datta, A., Suresh, R., Gupta, A., Singh, D., & Kulshrestha, P. (2017). Indoor air quality of non-residential urban buildings in Delhi. *International Journal of Sustainable Built Environment, 6*, 412–420.
- Instrumex India. (2021). *High-Volume PM_{10} Sampler (Model IPM-115 BL/NL)*. Retrieved from https://instrumexindia.com/high-volume-pm10-sampler.html
- Sahu, R., Dixit, K. K., Mishra, S., Kumar, P., Shukla, A. K., Sutaria, R., Tiwari, S., & Tripathi, S. N. (2020). Validation of low-cost sensors in measuring real-time PM_{10} concentrations at two sites in Delhi National Capital Region. *Sensors, 20*(5), 1347. https://doi.org/10.3390/s20051347
- Shree, V., Marwaha, B. M., & Awasthi, P. (2019). Indoor air quality investigation at primary classrooms in Hamirpur, Himachal Pradesh, India. *Hydro Nepal, 24*, 45–48.
- Singh, P., Arora, R., & Goyal, R. (2017). Indoor air quality assessment in selected schools of Delhi-NCR, India. *International Journal of Applied Home Science, 4*(5–6), 389–394.
- Temtopus. (2024). *Temtop M2000 2nd-Generation Portable Air Quality Monitor for $PM_{2.5}$, PM_{10}, CO_2, and HCHO*. Retrieved from https://temtopus.com/products/temtop-m2000-2nd-generation-air-quality-monitor-for-pm2-5-pm10-particles-co2-hcho-temperature-humidity-settable-audio-alarm-data-export-recording-curve-easy-calibration
- The Union. (2021). *Progress on indoor air quality regulation in India*. Retrieved from https://theunion.org/news/progress-on-indoor-air-quality-regulation-in-india
- Vijay, N., & Sarasamma, J. D. (2024). A critical review on the indoor air quality status of schools in India. *Current World Environment, 19*(3). https://doi.org/10.12944/CWE.19.3.3