

MULTI-METRIC EVALUATION OF INDOOR AIR POLLUTANTS AND HEALTH RISKS ACROSS DIFFERENT MICROENVIRONMENTS IN A UNIVERSITY CAMPUS OF DELHI, INDIA

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ABSTRACT

Indoor air quality (IAQ) has become an important environmental and public health issue, especially in densely built-up urban educational institutions where students and teachers are often confined for extended hours. In this study, the concentration level of indoor air pollutants has been assessed comprehensively across seven representative microenvironmental studies of the Delhi Technological University (DTU) campus in Delhi, India using multiple metrics. The aim of the study was to determine particulate matter (PM_{10} , $PM_{2.5}$, PM_{10}), size-resolved particle number concentrations (PNCs), carbon dioxide (CO_2) and related health risks based on Respiratory Deposition Dose (RDD) and Lung-Deposited Surface Area (LDSA).

Grimm aerosol spectrometer and HOBO CO_2 logger were used for continuous monitoring during active occupancy. The chosen microenvironments were classrooms, hostels, offices and library spaces with different levels of occupancy and with different ventilation attributes. The spatial and temporal variations of indoor pollutants, indoor-to-outdoor (I/O) relationships and the impact of ventilation systems were assessed.

The results showed high spatial variability of pollutants concentrations in various indoor environments. The quasi-ultrafine particles (qUFPs) in the particle number concentrations in all monitored microenvironments were in the highest concentration range, from $\sim 2.5 \times 10^5$ to 1.0×10^6 particles cm^{-3} . The Central Library (ME4) had the highest concentration of $PM_{2.5}$ ($\sim 145 \mu g m^{-3}$) even surpassing the WHO 24-hour Air Quality Guideline by nearly 9 times, mostly because of the high occupancy and recirculation-based HVAC operation. The highest values of lung deposited surface area (LDSA) ($\sim 118,587 \mu m^2 cm^{-3}$) and the highest qUFP particle exposure occurred in the Non-AC Hostel (ME1) which was naturally ventilated. During occupied time, high CO_2 concentration was found in the classrooms with the highest CO_2 concentration in the classroom was about 1,880 ppm indicating poor ventilation conditions in the classrooms during occupied time. Ventilation configuration, user density, and indoor activities (e.g., burning incense), which led to short-term

increases in indoor particle levels, were among the most important factors that affected indoor air pollution.

The health risk assessment showed that particle number concentration- and surface area-based metrics offered information not just from mass-based particulate measures. The results suggest that the potential exposure risk from qUFP to the respiratory tract may be underestimated in indoor environments if only PM mass concentrations are considered.

The overall findings of the study emphasize the need for implementing multi-metric IAQ assessment strategies in schools especially in highly polluted urban areas like Delhi. The results of this research can inform the design of effective ventilation, filtration and institutional policies to mitigate exposure to indoor pollutants and improve the health of occupants.

Keywords: Indoor air quality, Particle number concentration, Particulate matter, Respiratory deposition dose, Lung-deposited surface area, Technical university

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LIST OF SYMBOLS, ABBREVIATIONS AND NOMENCLATURE

ADS	Alveolar-Deposited Surface Area
AL	Alveolar Region
AQG	⁵ Air Quality Guidelines
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CFD	Computational Fluid Dynamics
CO ₂	Carbon Dioxide
DF	Deposition Fraction
DFAL	Alveolar Deposition Fraction
DTU	Delhi Technological University
HA	Head Airway Region
HEPA	¹⁹ High-Efficiency Particulate Air
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
I/O	Indoor-to-Outdoor Ratio
IQR	Interquartile Range
LDSA	Lung-Deposited Surface Area
ME	Microenvironment
ME1–ME7	Monitoring Microenvironments 1–7
MERV	Minimum Efficiency Reporting Value
NAAQS	National Ambient Air Quality Standards
NCT	National Capital Territory
NDIR	Non-Dispersive Infrared
OPC	Optical Particle Counter
PM	Particulate Matter
PM1	Particulate Matter with aerodynamic diameter $\leq 1 \mu\text{m}$

PM _{2.5}	¹⁵ Particulate Matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$
PM ₁₀	Particulate Matter with aerodynamic diameter $\leq 10 \mu\text{m}$
PNC	Particle Number Concentration
Qufp	Quasi-Ultrafine Particles
RDD	Respiratory Deposition Dose
RH	Relative Humidity
SBS	Sick Building Syndrome
TB	Tracheobronchial Region
TRAP	Traffic-Related Air Pollution
TVOCs	Total Volatile Organic Compounds
UFP	³⁵ Ultrafine Particles
VOCs	Volatile Organic Compounds
WHO	World Health Organization
$\mu\text{g m}^{-3}$	Microgram per cubic metre
$\# \text{ cm}^{-3}$	Number concentration per cubic centimetre
Mm	Micrometre
Ppm	Parts Per Million
V_t	Tidal Volume
BR	Breathing Rate
d_p	Particle Diameter
A	Significance Level
H	Hour
Min	Minute

CHAPTER 1

INTRODUCTION

1.1 General Background of the Study

Air pollution is emerging as one of the greatest ¹⁷ environmental and public health threats ¹⁷ in the world, especially ¹⁷ in rapidly urbanizing and densely populated areas. Rapid industrialization, urbanization, traffic pollution, construction, biomass burning, and energy consumption are causing serious air pollution issues in developing countries like India (Gurjar et al., 2010; Pant et al., 2015). Delhi is one of the cities in India that is often found to have very high levels of particulate pollution, particularly during winter months due to adverse meteorological conditions, traffic jams, biomass burning, industrial activities, construction dust etc.

The importance of outdoor air pollution has been widely studied, but indoor air pollution has also become a critical issue as most of the time is spent inside, in enclosed spaces like classrooms, offices, libraries, laboratories, and residential buildings, where people are exposed to air pollution (Morawska et al., 2017). Pollutants from outdoor infiltration as well as from indoor emission sources like cooking activity, incense burning, cleaning activity, smoking, occupancy movement and poor ventilation condition can be present in the indoor environment (Kulshrestha and Khare, 2011). Chronic exposure to indoor pollutants can raise the potential for respiratory exposures and negatively impact the health, comfort and productivity of the occupants.

Educational institutions are important indoor microenvironments as students and staff are indoors for long periods with different occupancy and ventilation conditions. Outdoor particulate pollutants can enter indoor areas and significantly add to the indoor pollutant burden in highly polluted urban areas like Delhi. This makes the evaluation of indoor air pollution in university environment more important than ever to understand the exposure conditions and health risks.

1.2 Indoor Particulate Matter and Its Sources

¹² Particulate matter (PM) is regarded as ⁹ one of the most important pollutants of indoor environments and human health due to its ability to penetrate into various parts of the respiratory system. ¹⁶ PM is a complex mixture of solid and liquid particles suspended in the air and is usually divided into PM₁₀,

PM_{2.5} and PM₁ fractions according to the aerodynamic diameter (Nazaroff, 2004). The transport behavior, atmospheric residence time and respiratory deposition characteristics of these particles are very different, depending on their size and physicochemical properties.

Coarse particles (PM₁₀) are primarily emitted as a result of mechanical processes including resuspension of road dust, construction activities, soil disturbances, industrial processes and dust resuspension from movement in indoor areas (Kulshrestha and Khare, 2011). The primary sources of fine and submicron particles, including PM_{2.5} and PM₁, are combustion processes including vehicular emissions, biomass burning, industrial combustion, cooking activities, incense burning, cigarette smoke and emissions from diesel generators (Moreno-Ríos et al., 2021; Sharma et al., 2025).

The infiltration of outdoor pollutants, the density of indoor occupancy, the characteristics of buildings, ventilation conditions and indoor human activities have significant effects on indoor particulate concentration (Chen and Zhao, 2011). Occupant movement, the use of chalk and paper materials, cleaning operations, and overcrowding in educational institutions can significantly contribute to the concentration of indoor particulates. There are reported increases in PM_{2.5} and PM₁₀ levels in university and classroom settings when there is insufficient ventilation and high occupancy levels (Sahu and Gurjar, 2020; Becerra et al., 2020).

Fine and ultrafine particles are regarded as being of special interest due to their long atmospheric lifetime and high respiratory penetration potential. These particles can enter deep within the alveoli and the tracheobronchial regions of the lungs and can cause oxidative stress, inflammation, lung dysfunction and cardiovascular issues (Boogaard et al., 2022; Bodor et al., 2022). Thus, monitoring of PM levels in indoor air is necessary to understand the dynamics of the pollutant and the risks of exposure to the respiratory system.

1.3 Particle Number Concentration and its properties

Conventional mass-based particulate measurements might not be sufficient to estimate the actual human exposure risk because of the low contribution of these particles to the total particulate mass and their dominant contribution to particle number concentration (PNC) (Moreno-Ríos et al., 2021). Thus, particle number concentration has become a critical parameter in understanding indoor aerosol

behavior, exposure to ultrafine particles and respiratory health risks. The particles have a high

deposition efficiency in the alveolar region, they have high surface area to volume ratio that increase their oxidative and inflammatory potential, and have small aerodynamic diameter namely, quasi-ultrafine (0.25-0.5 μ m), sub-fine (0.5-1 μ m), fine (1-2.5 μ m) and coarse (2.5-10 μ m) fractions (Nazaroff 2004; Moreno-Ríos et al. 2022).

PNC is a metric that is different from PM_{2.5} and PM₁₀, which are mass-based metrics, because it reflects the surface-area-to-volume ratio of the particle, which is much larger for ultrafine and quasi-ultrafine particles than for larger particles (Nazaroff, 2004). The particles are very reactive and can penetrate deeply into the respiratory system and transport toxic metals and organic compounds.

The main sources of the production of ultrafine and quasi-ultrafine particles are related to combustion activities such as vehicular exhaust emissions, biomass burning, industrial combustion, cooking emissions, cigarette smoke, incense burning, and diesel generator emissions (Moreno-Ríos et al., 2021; Sharma et al., 2025). In indoor settings, particle number concentrations and aerosol behaviour can also be affected by other sources of particles such as the movement of the people, cleaning activities, resuspension of settled particles, and inadequate ventilation (Morawska et al., 2017).

Previous studies have shown that outdoor aerosol infiltration, occupancy density, ventilation conditions, and indoor activities are important factors affecting the indoor particle number concentration (Chen and Zhao, 2011). Overcrowding, inadequate ventilation and close proximity of the classrooms to the traffic-influenced outdoor areas have been reported to cause elevated PNC levels in classrooms, lecture halls, libraries and hostel areas (Sahu and Gurjar, 2020). Due to their extremely small aerodynamic diameter, ultrafine particles have long atmospheric residence times and high efficiency of penetration into the respiratory system. These particles can reach deep into the alveolar part of the lungs by diffusion mechanisms and could potentially be absorbed into the systemic circulation (Kuuluvainen et al., 2016).

There are several studies that link exposure to high concentrations of qUFPs with oxidative stress, inflammation, asthma, cardiovascular disorders, endothelial dysfunction and neurological complications (Bodor et al., 2022; Mansor et al., 2024). Consequently, measurement of particle number concentration, in addition to conventional PM measurements, is necessary to gain a better understanding of the dynamics of indoor aerosols and their associated health risks.

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1.4 Carbon Dioxide and Ventilation Characteristics

Carbon dioxide (CO₂) is a key indoor air pollutant and is commonly used as a marker for sufficient indoor air exchange and indoor pollution due to occupancy. The main factors affecting the concentration of CO₂ in the indoor air are the human respiration, the number of people in the room, the air exchange rate and the efficiency of the ventilation system (Sarbu and Pacurar, 2015). High indoor CO₂ levels are typically a sign of poor fresh air ventilation and poor ventilation conditions in enclosed spaces.

Ventilation is one of the important factors that can control levels of indoor pollutants, thermal comfort and exposure conditions for the occupants. Depending on building infrastructure and operational requirements, indoor environments can be naturally ventilated, mechanically ventilated or air-conditioned. Poor ventilation in schools can lead to the buildup of indoor-generated pollutants and higher CO₂ levels when the building is in use (Mahyuddin and Essah, 2024).

In India, there are several educational buildings with split air-conditioning systems which are operated without adequate fresh outdoor air supply, leading to recirculation dominated indoor environment, which can potentially accumulate fine particles and gaseous pollutants over time (Wu et al., 2018). Particulate infiltration from outside to inside is a significant factor that could affect indoor air quality in naturally ventilated spaces particularly in urban areas with high outdoor particulate levels like in Delhi (Chen and Zhao, 2011).

Earlier studies have found high CO₂ levels in classrooms, offices, libraries and hostel settings when overcrowding and poor ventilation occur (Xu et al., 2022). Studies have linked high CO₂ levels in buildings to discomfort, drowsiness, decreased concentration, headaches, and decreased cognitive function among the occupants (Sarbu and Pacurar, 2015). Thus, the assessment of CO₂ concentration and ventilation characteristics is crucial to understand the accumulation and exposure situation of indoor air pollutants in university indoor environments.

1.5 Health Impacts of Indoor Air Pollution

Exposure to indoor air pollutants can lead to various health issues, including respiratory diseases, heart problems, asthma, chronic obstructive pulmonary disease (COPD), oxidative stress, lung inflammation, and decreased lung function (Boogaard et al., 2022; Bodor et al., 2022). Fine and qUFPs are especially dangerous because they can penetrate deep into the respiratory system and affect delicate lung tissues.

Previous research shows that long-term exposure to high levels of particulate matter can impact both respiratory and heart health. Fine particles like $PM_{2.5}$ and PM_{10} can reach the alveoli in the lungs, where the body's clearing processes are slower. This increases the risk of oxidative stress and inflammation (Gautam et al., 2016). PNCs can move beyond the lungs into the bloodstream and might affect both the heart and nervous systems (Moreno-Rios et al., 2021).

Indoor air pollution can also lead to symptoms of Sick Building Syndrome (SBS) such as headaches, dizziness, eye irritation, breathing difficulties, fatigue, trouble concentrating, and drowsiness among people inside (Mansor et al., 2024). Schools are particularly affected, as students and staff often spend long hours indoors under various conditions of occupancy and ventilation. Poor indoor air quality can harm academic performance, cognitive abilities, and overall health.

In heavily polluted urban areas like Delhi, outside pollutants combined with indoor emissions can greatly increase exposure risks in places like classrooms, libraries, offices, and hostels. Thus, assessing indoor air pollution and its health impacts is crucial for better indoor environmental management and to protect the health of individuals in educational settings.

1.6 Respiratory Exposure and Health-Based Metrics

Traditional assessments of particulate matter that rely only on mass concentration might not accurately reflect the real risks of respiratory exposure to ultrafine particles. Consequently, health-related aerosol exposure measures such as Respiratory Deposition Dose (RDD) and Lung-Deposited Surface Area (LDSA) have gained importance in recent years (Fatima et al., 2022; Kuuluvainen et al., 2016).

Respiratory Deposition Dose (RDD) is the number of inhaled particles that settle in different areas of the respiratory system during breathing. The International Commission on Radiological Protection (ICRP, 1994) created the Human Respiratory Tract Model to estimate how particles behave when inhaled based on their size, breathing conditions, and how efficiently they deposit. Fine and ultrafine particles are more likely to penetrate deeper into the lungs, increasing health risks.

Lung-Deposited Surface Area (LDSA) refers to the biologically active surface area of inhaled particles that settle in the lungs. It is especially important for assessing exposure to these aerosols (Geiss et al., 2016). Because ultrafine particles have very high surface-area-to-volume ratios, using LDSA for assessment gives a better understanding of their inflammatory and toxic effects compared to standard mass-based measurements.

Recent studies suggest that health-focused exposure metrics like RDD and LDSA give a fuller picture of

respiratory exposure than just measuring particulate mass (Singh et al., 2025). Therefore, combining particulate matter concentration, particle number concentration, RDD, and LDSA is essential for better assessment of indoor aerosol exposure and related health risks

1.7 Need for the study

In rapidly urbanizing cities like Delhi, where ambient pollution levels are high, indoor air pollution has emerged as a major environmental and public health problem, with the potential to reach indoor spaces and lead to human exposure. Students, faculty members and staff members spend a considerable amount of time in the classrooms, libraries, offices and hostels, making exposure to indoor air pollutants in educational institutions an important issue that needs detailed investigation.

The majority of studies in India have been carried out on conventional indicators of particulate matter like PM_{2.5} and PM₁₀. Recent scientific research has, however, indicated that particle number concentrations and smaller particle fractions such as submicron and ultrafine particles might be more harmful due to their deeper penetration into the respiratory system. Though these particles are important they are not well characterized in the university environment in India. Furthermore, few studies have measured particulate matter (PM) concentrations, particulate number concentrations (PNC), carbon dioxide (CO₂) and health-based exposure metrics like Respiratory Deposition Dose (RDD) and Lung-Deposited Surface Area (LDSA) simultaneously. The impact of various building features, occupancy and ventilation systems on indoor air pollutant concentration and health risk is also poorly understood in university campuses.

Hence, it is essential to carry out a detailed evaluation of indoor air pollution in various micro-environment of a university campus. This evaluation can help to better understand the distribution of pollutants, their exposure and potential health impacts for occupants. The results of this study will be useful in determining high-risk indoor settings and in developing strategies to minimize exposures to pollutants and to safeguard human health in educational settings.

1.8 Objectives of the study

- To monitor indoor and outdoor concentrations of particulate matter (PM₁, PM_{2.5}, and PM₁₀) across selected microenvironments within the University campus.
- To characterize size-resolved particle number concentrations (PNCs) across the selected microenvironments.
- To estimate the concentration of CO₂ across the selected microenvironments.
- To estimate health risk assessment within the University campus.

CHAPTER 2

LITERATURE REVIEW

2.1 General Overview of Indoor Air Pollution

The environment in urban India, especially in Delhi, is one of the most polluted in the world. Delhi is always among ⁶the most polluted cities in the world, and in 2023, it was reported as the third most polluted city in the world. The region has a combination of anthropogenic emissions such as vehicle exhausts, industrial emissions and construction dust, and bad meteorological conditions that trap pollutants near the surface in the post monsoon and winter season. It is important to keep track of the different sizes of particulate matter to understand the impacts on human health. Coarse particles (PM_{10}) are particles ⁴that are usually formed mechanically, such as road dust and soil resuspension, and are generally deposited in the upper respiratory tract. Fine particles ($PM_{2.5}$) are more dangerous because they can penetrate to the alveolar regions and into the systemic circulation. Sub-micron particles (PM_1) and Particle Number Concentrations (PNCs) are being studied more and more recently. Mass-based measurements such as $PM_{2.5}$ measure the mass of pollutants, while PNC measures the number of particles, including the most abundant ¹⁶ultrafine particles (UFPs) that have a very high surface-area-to-volume ratio, which enables them ¹⁶to carry toxic heavy metals and organic compounds straight to the organs. The University campus is a micro-environment where the students and staff members spend about 90% of their time indoors. These settings consist of various functional areas like lecture halls, libraries, laboratories, etc., with different pollution signatures and occupancy densities. Young adults (ages 16-21) are at a higher risk because they have increased metabolic and respiratory rates and a still-developing physiology that can exacerbate the long-term non-carcinogenic and carcinogenic effects of chronic exposure to inhalation exposures.

2.2 Particulate Matter and its Sources

Particulate matter (PM) is regarded as one of the most important pollutants in the air, which can penetrate deeply into the respiratory system and has a significant impact on human health and the environment. PM is a complex mixture of solid particles and liquid droplets suspended in the air from both natural and anthropogenic sources (Nazaroff, 2004; Ye et al., 2017). Particulate matter is usually divided into coarse particles (PM_{10}), fine particles ($PM_{2.5}$) and submicron particles (PM_1) based on aerodynamic diameter. The behaviour, atmospheric residence time, transport and deposition pathways of these particles are highly dependent on their size and physicochemical properties (Moreno-Rios et al., 2021). The sources of coarse particles (PM_{10}) are mainly mechanical activities such as construction activities, road dust resuspension, industrial activities, and soil disturbances, while fine and submicron particles are mainly emitted from combustion sources including vehicular emissions, fossil fuel combustion, biomass burning, industrial activities, cooking emissions, and smoking (Kulshrestha and Khare, 2011; Kaghazchi and Soleimani, 2023). $PM_{2.5}$ and PM_1 particles stay in the atmosphere for longer periods and have higher penetration capacity into the tracheobronchial and alveolar areas of lungs (Gautam et al., 2016; Bodor et al., 2022). The high levels of PMs in urban areas are often attributed to high levels of urbanization, traffic, industrial development, biomass burning, and unfavorable meteorology in urban regions (Gurjar et al., 2010; Pant et al., 2015). In the Indian metropolitan areas, several studies have been reported on the high levels of particulate matter (PM) exceeding the recommended limits in both indoor and outdoor environments. Kulshrestha and Khare (2011) studied indoor particulate pollution in residential buildings in Delhi and found that the traffic emissions, cooking, smoking and inadequate ventilation significantly contributed to the indoor PM levels. Likewise, Ashok et al. (2014) found significant spatial variation of $PM_{2.5}$ and PM_{10} in different indoor and outdoor microenvironment in a college campus, with higher concentration of the pollutants found near traffic influenced area. The high density of occupation, lack of ventilation and the extended time spent indoors by students and staff are some of the key vulnerabilities of educational institutions to particulate pollution (Becerra et al., 2020; Sahu and Gurjar, 2020). Sahu and Gurjar (2020) studied the indoor air quality in a technical university campus and found that the lecture halls and classrooms in the campus had very high concentration of $PM_{2.5}$ and PM_{10} because of overcrowding and inadequate ventilation.

Becerra et al. (2020) also listed particulate matter, carbon dioxide, formaldehyde, benzene, and volatile organic compounds as primary pollutants in classroom air quality that impact student health. The effect of seasonal differences on PM levels has also been noted in several studies. Low mixing height of the atmosphere, reduced meteorological activity, and temperature inversion greatly contribute to the accumulation of PMs near the surface during the winter season (Saxena et al., 2025; Fatima et al., 2022). The authors of Fatima et al. (2022) reported significant decreases in PM_{2.5} and PM₁₀ levels during the COVID-19 lockdown period, as a result of lower vehicle traffic and industrial activity, which further supports the major anthropogenic sources in urban environments for particulate pollution. The importance of assessing the exposure risk of smaller particulate fractions, such as PM₁, has been gaining attention in recent years, as exposure risk may be underestimated when relying solely on PM_{2.5} and PM₁₀ measurements (Gautam et al., 2016; Moreno-Ríos et al., 2021). Fine and submicron particles have greater surface area/volume ratios and are able to bind toxic heavy metals, polycyclic aromatic hydrocarbons (PAHs) and organic compounds that can enhance the toxicity and inflammatory effects of the particles (Boogaard et al., 2022; Kaghazchi and Soleimani, 2023). Exposure to these particles has been linked to respiratory diseases, cardiovascular conditions, oxidative stress, neurological disorders, and impaired lung function (Bodor et al., 2022; Mansor et al., 2024). In summary, it can be concluded that previous studies have clearly shown that the levels of PM in indoor spaces are significantly affected by PM infiltration from the outdoors, the ventilation properties of the building, the number of people inside and their indoor activities (Chen and Zhao, 2011; Morawska et al., 2017). Educational institutions in highly polluted urban areas like Delhi are thus important exposure microenvironments that need detailed exposure assessment and effective mitigation measures.

2.3 Particle Number Concentration (PNC) and Size-Resolved Indoor Aerosols

Recently, particle number concentration (PNC) has attracted more scientific interest, as particulate mass concentration alone may not be a good indicator of the true human exposure risk, especially for quasi-ultrafine and submicron particles (Nazaroff, 2004; Moreno-Ríos et al., 2021). PNC account for only a small fraction of the total mass of particulate matter, but they may dominate the number concentration and have very high surface-area-to-volume ratios, and are biologically important and extremely reactive. As a result, PNC has become a significant tool to assess indoor aerosol exposure and respiratory health risks. The number of particles in the air per unit volume of air is known as

particle number concentration, which is typically reported in particles per cm³. PNC, unlike PM_{2.5} and PM₁₀, is a number-based measure and gives information on the number of particles in the size range of ultrafine and submicron particles which can have significant effects on respiratory deposition and interaction with cells but do not necessarily make a significant contribution to mass concentration (Chen and Zhao, 2011). Quasi-ultrafine and sub-fine particles are those with aerodynamic diameters of less than 1 µm but greater than 0.1 µm, while the aerodynamic diameter of the ultrafine particles is less than 0.1 µm. Previous studies have shown that combustion activities are the most important source of indoor and outdoor particle number concentrations. In urban areas, vehicular exhaust emissions, biomass burning, industrial emissions, incense burning, cooking emissions, cigarette smoke and emissions from diesel generators are important sources of qUFPs (Moreno-Ríos et al., 2021; Sharma et al., 2025). Their extremely small aerodynamic diameter (Nazaroff, 2004) results in long atmospheric residence times and the ability to reach deep into the alveolar region of the lungs by diffusion processes. Nazaroff (2004) laid the groundwork for the basic physicochemical concepts of particle transport, transformation, deposition, and resuspension in indoor environments. The study found that submicron particles are very persistent indoors and more oxidizing than coarse particles. In addition, Chen and Zhao (2011) conducted a review of the indoor-outdoor particle relationships and found that the infiltration efficiency of the building envelope is high for ultrafine particles, indicating that the contribution of outdoor combustion sources to the indoor particle exposure in urban areas is significant. There have been several studies that have specifically assessed the particle number concentration in indoor spaces. Morawska et al. (2017) reviewed the sources of airborne particulate exposure in homes, schools, offices, and institutional buildings and found that indoor sources of ultrafine particles are both outdoor infiltration and indoor human activities like cooking, cleaning, smoking, and dust resuspension. The study highlighted the strong dependence of the particle number concentration inside on ventilation conditions and the presence of people. Sharma et al. (2025) measured the indoor particle number levels in households of varying socio-economic status in Delhi, and found that the quasi-ultrafine particle (qUFPs) concentrations were very high in poorly ventilated indoor environments, especially in kitchens and high occupancy rooms. Their results showed that indoor PNC levels are significantly affected by ventilation efficiency, indoor combustion activities and infrastructure characteristics. In the same way, Moreno-Ríos et al. (2021) reviewed the behaviour, toxicity and control measures of ultrafine particles and concluded that traffic emissions and combustion processes are the main sources of the burden of ultrafine particles in urban

areas. Significant variations in particle number concentrations have also been reported in studies carried out in educational environments as a function of occupancy density and ventilation conditions. Sahu and Gurjar (2020) reported high aerosol levels in the classrooms of a university during overcrowding and poor ventilation. Becerra et al. (2020) also found indoor particulate pollution to be a critical factor that impacts the classroom environment and student health. The research indicated that the activities of occupants, outdoor infiltration and building ventilation features play a significant role in the indoor aerosol dynamics in educational institutions. The significance of assessing the size-resolved particle fractions has been increasingly recognized in recent studies, as the different particle size fractions have different deposition mechanisms, transport behavior, and health effects (Gautam et al., 2016; Moreno-Rios et al., 2021). The diffusion efficiency and alveolar deposition probability of fine and ultrafine particles are higher than that of coarse particles. The study by Gautam et al. (2016) showed that although the mass concentration of smaller particle fractions was relatively lower, they played a significant role in the deposition in the respiratory tract among school children in Delhi. The health relevance of high particle number concentration has received considerable attention, since the ultrafine particles can enter beyond the respiratory tract into systemic circulation and reach sensitive organs, such as the cardiovascular and nervous system (Boogaard et al., 2022; Bodor et al., 2022). The exposure to elevated UFP levels has been linked to oxidative stress, endothelial dysfunction, asthma, cardiovascular diseases, chronic obstructive pulmonary disease (COPD) and neurological complications (Mansor et al., 2024; Moreno-Rios et al., 2021). Although global research on particle number concentration (PNC) and on ultrafine aerosols (UFA) is growing, there is still limited research on size-resolved particle number concentration (PNC) in the university environment in India. The majority of indoor air quality studies in India still focus mainly on $PM_{2.5}$ and PM_{10} mass concentrations without accounting for the role of exposure to the very small particles and the deposition of these particles in the respiratory system. In addition, very few studies have also evaluated size-resolved particle number concentration, particulate mass, carbon dioxide, and health-based exposure measures (Respiratory Deposition Dose (RDD) and Lung-Deposited Surface Area (LDSA)) in multiple university microenvironments. Hence, the need for a more complete assessment of particle number concentration, in addition to traditional PM measurements, is crucial for better understanding of indoor aerosol dynamics, exposure characteristics and health impacts in educational institutions in high PM exposure cities like Delhi.

2.4 Ventilation Characteristics and Health Impacts of Indoor Air Pollution

Ventilation is a key determinant of indoor air quality, affecting the dilution, removal, transport and accumulation of airborne pollutants in the indoor environment. Ventilation characteristics play a significant role in the concentration of indoor air pollutants, such as PM, CO₂, bioaerosols and gaseous pollutants, in educational buildings because classrooms, libraries, offices and hostels are occupied for extended periods of time with many people present (Sarbu and Pacurar, 2015; Mahyuddin and Essah, 2024). Poor ventilation can lead to the buildup of indoor-generated pollutants, as well as the infiltration and retention of outdoor pollutants, which can have a significant impact on the health, comfort and cognitive function of the occupants. There are four types of indoor ventilation systems – natural, mechanical, hybrid and air-conditioning systems. Naturally ventilated spaces are those that use windows and doors and passive air exchange mechanisms, while mechanically ventilated spaces use fans, HVAC systems, and air filtering systems to control the air exchange and thermal comfort in the space. (Ye et al., 2017) Split air-conditioning systems are, however, widely used in several institutional buildings in India, where fresh outdoor air is not supplied and the air conditioner is used to recirculate air inside the room, which can lead to a progressive build-up of indoor-generated pollutants in the room (Sharma et al., 2025). Previous studies have shown good correlations between ventilation efficiency and indoor air pollutant levels. Sarbu and Pacurar (2015) examined the performance of the ventilation in the classrooms of university buildings and concluded that the lack of adequate ventilation rates led to a significant increase of CO₂ concentration in the interior of the classrooms, and to thermal discomfort among the students. Likewise, Wu et al. (2018) found significant differences in indoor PM_{2.5}, formaldehyde and CO₂ levels under different occupancy conditions and ventilation effectiveness. The study found that poor ventilation was one of the major factors contributing to poor indoor environmental quality. Ventilation adequacy and occupant density in indoor spaces are often estimated by measuring the concentration of carbon dioxide. High CO₂ levels inside the building are typically a sign of inadequate fresh air exchange, compared to the number of occupants (ASHRAE Standard 62.1). Mahyuddin and Essah (2024) examined the ventilation performance in the university classrooms by conducting Computational Fluid Dynamics (CFD) simulation and they found that CO₂ levels were found to be significantly higher in overcrowded classrooms with poor distribution of ventilation. The authors explained that poor ventilation conditions caused their discomfort, drowsiness and decreased concentration among the occupants in

the rooms and affected the indoor environmental quality. Several studies have been carried out in educational institutions, which have shown the role of ventilation on the accumulation of the aerosol inside and the risk of exposure. Sahu and Gurjar (2020) studied the indoor air quality in various microenvironments of a technical university campus and found that the levels of PM_{2.5} and CO₂ were high in the overcrowded lecture halls with poor ventilation. Becerra et al. (2020) also found that ventilation inefficiency, occupant density, and outdoor pollutant infiltration are key factors that lead to poor classroom air quality. The ventilation characteristics also have significant impacts on indoor ultrafine particle behaviour and particle number concentration. A study by Chen and Zhao (2011) showed that building air exchange rates and envelope properties determine the infiltration efficiency of outdoor particles into indoor spaces. Morawska et al. (2017) also found that the concentration of UFPs in indoor environments is very dependent on the type of ventilation, the activity of occupants and the way air is exchanged. Fine and ultrafine particles can be accumulated over time in buildings with recirculation-only HVAC systems, which can have poor fresh air dilution and poor filtration efficiency. Ventilation is a complex problem in urban areas like Delhi, where ambient particulate pollution is very high. Ventilation may reduce indoor generated pollutants like CO₂ but also may increase the outdoor particulate matter in indoor environment if proper filtration system is not used (Kulshrestha and Khare, 2011; Pant et al., 2015). In such highly polluted institutional settings in urban areas, optimization of ventilation strategies is a must. Indoor air pollution and inadequate ventilation have been linked to various health impacts. Mansor et al. (2024) examined the link between Sick Building Syndrome (SBS) symptoms and the office workers at a university, finding that the symptoms of SBS were strongly correlated with poor ventilation, high particulate matter concentration, headaches, dizziness, eye irritation, respiratory discomfort, fatigue, and drowsiness. In the college dormitory, elevated indoor CO₂ and VOC levels were also found to have a negative impact on the comfort of occupants and perceived indoor environmental quality by Xu et al. (2022). Poorly ventilated indoor environments have also been linked to respiratory diseases, asthma, cardiovascular disorders, lowered cognitive function, and lower academic productivity when exposed for extended periods of time (Boogaard et al., 2022; Bodor et al., 2022). Fine and ultrafine particles that are formed in the absence of proper ventilation have a high respiratory deposition potential and can cause oxidative stress, inflammation, and pulmonary dysfunction. Educational settings are especially susceptible due to the fact that students and staff are inside for extended periods of time, where they have little control over ventilation systems, and at high occupancy. Increasing attention has been paid

to the need for demand-controlled ventilation, better HVAC filtration and real-time indoor air quality monitoring to reduce risks to occupants in institutional buildings in recent studies (Ye et al., 2017; Mahyuddin and Essah, 2024).²⁹ In order to improve the indoor environmental quality and minimize the accumulation of pollutants in schools, the following strategies have been recommended: HEPA Filtration, Fresh Air Supply, Hybrid Ventilation Systems, and Occupancy-Based Airflow Management. In general, the results of previous studies have clearly demonstrated that ventilation characteristics have a fundamental role in controlling the dynamics, exposure levels and associated health risks of indoor pollutants. Thus, a thorough assessment of ventilation performance, particulate matter, particle number concentration, and CO₂ monitoring is crucial for understanding indoor exposure conditions and to implement effective ventilation mitigation measures in university settings.

2.5 Respiratory Deposition Dose (RDD) and Lung-Deposited Surface Area (LDSA) Assessment

The traditional particulate matter (PM) measurement approach that relies only on mass concentration could be inadequate for characterizing the health risks of exposure to airborne particles, especially the qUFPs and submicron particles. These health-based aerosol exposure metrics, including Respiratory Deposition Dose (RDD) and Lung-Deposited Surface Area (LDSA) are increasingly important in recent studies, as they provide a better understanding of particle deposition behaviour and respiratory exposure risks (Fatima et al., 2022; Kuuluvainen et al., 2016). The Respiratory Deposition Dose (RDD) is the amount of PM deposited in various parts of the human respiratory system during breathing. The Human Respiratory Tract Model (ICRP, 1994) was designed to predict the aerodynamic diameter dependence of particle deposition behavior in the head airway, tracheobronchial and alveolar regions as a function of breathing frequency, tidal volume and deposition efficiency. The ICRP model indicates that fine and ultrafine particles have higher penetration efficiency into the deeper alveolar region, which has diffusion dominated transport mechanisms, and therefore, higher potential respiratory health risks. The concept of RDD-based approaches has been used in several studies to assess particulate exposure in urban areas.²³ Before, during and after the COVID-19 lockdown phases in Delhi, Fatima et al. (2022) measured the respiratory deposition dose of PM_{2.5} and PM₁₀ and found significant drop in RDD during the lockdown periods because of the reduction in vehicular and industrial emissions. The study showed that the breathing rate and inhalation volume were higher during walking than sitting conditions,

leading to higher PM_{2.5} respiratory deposition dose during walking. The authors also emphasized the fact that the size of the particles, physical activity and air pollution levels all influence the deposition in the respiratory tract. The importance of long-term deposition of particles has also been shown by recent investigations in highly polluted urban areas. Singh et al. (2025) have analyzed the deposition characteristics of PM_{2.5} and PM₁₀ in Delhi during the last five years and found that the particulate levels were often found to be higher than the national standards and the World Health Organization (WHO) guidelines. The study noted that respiratory deposition doses were greater in the evening commuting period and that the smaller particulate fractions are more likely to be deposited in the alveoli and are more likely to cause health effects. The authors also noted that deposition of particulate matter in the respiratory tract may lead to respiratory irritation, acute exacerbation of asthma, airway obstruction, cardiovascular diseases, and systemic inflammation. The aerodynamic diameter of particles and the deposition mechanisms like inertial impaction, sedimentation, diffusion, interception, electrostatic interaction are significant factors in determining the deposition of particle in the respiratory system. Singh et al. (2025) have reported that the coarse particles are mainly deposited in the upper respiratory tract and tracheobronchial region while the finer and the ultrafine particles have higher penetration efficiency in the alveolar region where gas exchange takes place. Deposition in the alveolar region is especially important because the clearance mechanisms are slower and inhaled particles spend more time in contact with the lung tissue.

In recent years, Lung-Deposited Surface Area (LDSA) has become an important alternative aerosol exposure metric that provides a more useful representation of the biologically active surface area of inhaled ultrafine particles than conventional mass-based metrics do. The LDSA is the product of the surface area of the particles and their deposition efficiency in the respiratory tract, and is thus highly relevant for the assessment of toxicological and inflammatory effects related to exposure to ultrafine particles (Geiss et al., 2016; Kuuluvainen et al., 2016). Kuuluvainen et al. (2016) studied the size distributions of particulate matter in various urban areas and found that traffic-related ultrafine particles made a significant contribution to the concentrations of lung deposited surface area. The study showed that the traffic emissions had a significant impact on the concentrations of LDSA, whereas the PM_{2.5} mass concentrations were less affected, and the study also showed the importance of particle size distribution when assessing respiratory exposure risks. The authors found that both nucleation-mode and soot-mode particles played an important role in the formation of LDSA in urban areas. In addition, Geiss et al. (2016) compared the surface area concentration of particles deposited

on the lung in occupational and non-occupational settings using diffusion charger-based monitoring equipment. The study found that activities like cooking, burning incense, smoking, and industrial processes led to significant increases in LDSA, with some activities even raising the concentration of LDSA above the baseline level by several hundred times. The authors highlighted that surface area-based measurements might be more useful for assessing the potential of pulmonary inflammation than standard mass concentration measurements, especially for qUFPs. Previous toxicological studies have indicated that qUFPs have high surface area-to-volume ratios, allowing them to interact with biological tissue more than larger particles and to have a higher oxidative potential. Exposure assessment based on LDSA is therefore a better approach to the understanding of the health effects of exposure to ultrafine aerosols, since the toxicity of the particles is more often related to the reactive surface area than only to particulate mass (Kuuluvainen et al., 2016; Geiss et al., 2016). Several studies have also shown that indoor environments can have elevated respiratory exposure risk levels, but relatively low particulate mass concentrations. Fine and ultrafine particles produced by indoor activities like cooking, burning incense, smoking, cleaning, human activities and resuspension can play a significant role in the deposition in the respiratory system and lung surface exposure. Respiratory exposure to students and staff in educational settings may be further increased by prolonged exposure, poor ventilation, and infiltration of outdoor pollutants. Although there is growing interest in respiratory exposure assessment in the world through RDD and LDSA, very few studies have been conducted in India to assess PM concentration, PNC, CO₂, respiratory deposition dose and lung deposited surface area in various indoor university microenvironments. Previous studies in educational settings have largely maintained an emphasis on PM_{2.5} and PM₁₀ mass concentrations, which have been largely neglected in the effects of ultrafine particles and particle surface area on respiratory health risks.

Hence, the use of the advanced health-based aerosol exposure metrics like RDD and LDSA, in addition to the traditional method of particulate matter assessment, is necessary to get a complete picture of the behavior of the aerosol, the respiratory exposure characteristics and the health impacts in schools situated in highly polluted urban areas like Delhi.

2.6 Literature Gap

Most of the previous studies on indoor air pollution have been based on the traditional mass-based measures of PM_{2.5}, PM₁₀, etc., whereas the number concentration of particles (PNC), and advanced health-based exposure metrics, like Respiratory Deposition Dose (RDD) and Lung-Deposited Surface

Area (LDSA), have been paid relatively little attention. Most studies conducted in India have focused on outdoor air pollution or on short-term monitoring of indoor particulate matter, without considering the dynamics of the indoor aerosol and the risks of exposure to it by the respiratory system. Most of the studies performed in educational institutions have focused on particulate matter, ventilation or thermal comfort, while only a few studies have simultaneously analyzed PM, PNC, CO₂, ventilation characteristics, RDD and LDSA in various university microenvironments. Moreover, there is little information available on how occupancy patterns and ventilation systems affect exposure to UFP during high pollution levels in highly polluted urban areas like Delhi. In addition, most indoor air pollution studies still focus on mass-based exposure assessment that may underestimate the health impacts of fine and ultrafine particles. Hence, a multi-metric assessment that combines particulate matter, particle number, carbon dioxide and respiratory exposure metrics in various indoor university microenvironments is needed to gain a better understanding of the behavior of the indoor aerosol and associated health risks. The present study is designed to fill these gaps and assess PM₁, PM_{2.5}, PM₁₀, size-resolved PNC, CO₂, RDD and LDSA in various indoor microenvironments of a university campus in Delhi under different occupancy and ventilation conditions.

MATERIALS AND METHODS

3.1 Study Area and Site Description

The study was carried out in seven indoor microenvironments of Delhi Technological University (DTU) at Rohini, North-West Delhi, India (28.7499° N, 77.1177° E). DTU has an area of about 66 hectares, comprising academic, administrative, residential and recreational buildings in a well-planned institutional campus (Fig. 3.1). The campus is located in the Delhi National Capital Region, where it is surrounded by several important road corridors that contribute to high vehicular emission loading in the outdoor environment.

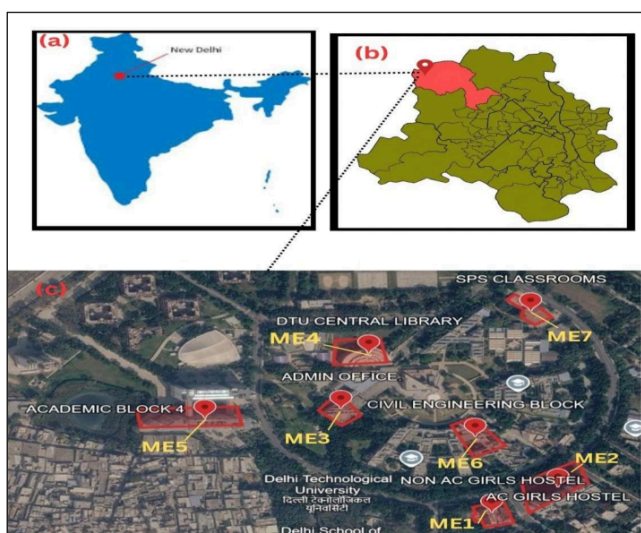


Fig 3. 1 Study area map showing location of Delhi and detailed sampling zones within DTU campus.

DTU is subject to a composite climate characterized by hot summers (maximum temperatures up to 46°C), humid monsoons (June–September), and cold winters (minimum temperatures as low as 4°C), with annual precipitation of approximately 700–800 mm.

Seven microenvironments (ME1–ME7) were chosen to represent a diverse range of built environments that students and staff encounter in their daily activities on campus. Table 3.1 provides the characteristics of each microenvironment. All sites are within the same institutional geography, which reduces inter-site variability in the outdoor pollution loading. The schematic representation of the overall monitoring framework and methodological approach adopted during the present study is illustrated in Figure 3.2.

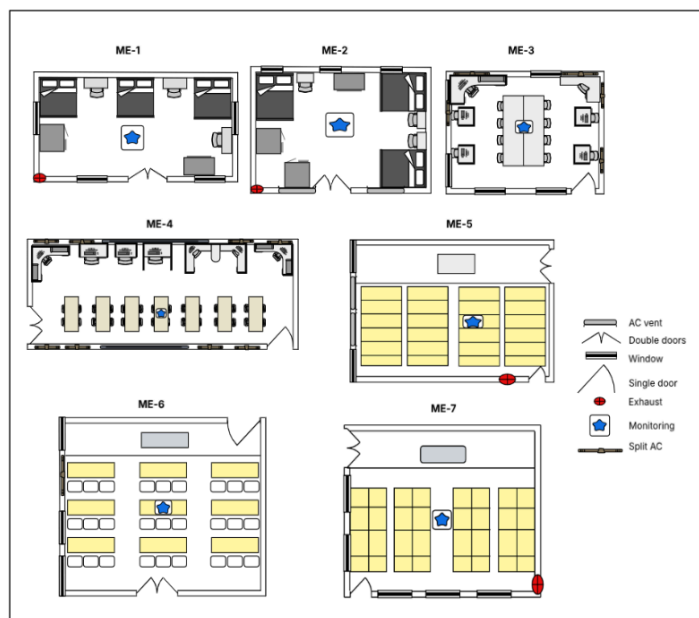


Fig 3. 2 Schematic Representation of Microenvironments (ME-1 to ME-7) with Equipment Placement.

Table 3. 1 Characteristics of indoor selected microenvironments (MEs).

ME	Description	Volume (m ³)	Occupants	Ventilation	Working Hours	Floor
ME1	Non-AC Girls Hostel	58.96	3	2 roof fans, 1 vent	24 h	Ground
ME2	AC Girls Hostel	43.25	3	2 roof fans, 3 AC vents, 1 vent	24 h	Fifth
ME3	Admin Office (Civil Engg. Block)	192.2	18–20	4 roof fans, 3 wall fans, 1 split AC, 3 window ACs	10:00–18:00	First
ME4	Central Library Reading Hall	1396.8	55–60	Centralised HVAC (12 air ducts, recirculation only)	09:00–21:00	Ground
ME5	Academic Block 4 Classroom	272.8	70–80	Central AC grill + 8 roof fans	08:00–18:00	Ground
ME6	Concrete Classroom	250.4	20–30	6 roof fans + 2 split Acs	08:00–18:00	Ground
ME7	SPS Fibre-Roof Classroom	275.4	30–40	8 roof fans + natural ventilation	08:00–18:00	Ground

3.2 Instrumentation

In this study, two main instruments were used. The particle number concentrations (PNC) and particle mass concentrations (PM₁, PM_{2.5}, PM₁₀) were determined by a portable aerosol spectrometer (Model 11-A, Grimm Aerosol Technik, Germany). The instrument is based on the principle of single-particle laser light scattering and is able to resolve particles in 31 channels of optical size ranging from 0.25 to 32µm at a fixed volumetric flow rate of 1.2 L min⁻¹. Carbon dioxide (CO₂) concentration, temperature, and relative humidity (RH) were measured simultaneously using a battery-powered HOBO MX CO₂ Logger (Onset Computer Corporation, USA). This instrument is based on non-dispersive infrared (NDIR) sensing for CO₂ (accuracy: ±50 ppm ±3% of reading; range: 0–5,000 ppm) and capacitive sensing for RH (range: 15–95%, non-condensing). The compact, battery-

powered design of the HOBO logger permitted unobtrusive deployment alongside the Grimm spectrometer in all microenvironments (Table 3.2). All the instruments were pre-calibrated as per and zero checked and span verified before the deployment of each cycle, following the quality assurance procedure used for indoor aerosol measurements (Sharma et al. 2025).

Table 3. 2 Monitoring Instruments and Specifications.

Instrument	Parameters Measured	Principle	Range	Flow Rate	Manufacturer
Grimm 11-A	PNC, PM ₁ , PM _{2.5} , PM ₁₀	Single-particle laser scattering	0.25–32 µm; 31 channels; up to 3×10^7 # L ⁻¹	1.2 L min ⁻¹	Grimm Aerosol Technik, Germany
HOBO MX CO ₂ Logger	CO ₂ , Temperature, RH	NDIR (CO ₂); capacitive RH	¹ CO ₂ : 0–5000 ppm; Temp: -20 to 70 °C; RH: 15–95%	—	Onset Computer Corporation, USA

3.3 Data Collection and Monitoring Protocol

¹ The data was collected in seven different microenvironments at Delhi Technological University. These microenvironments (MEs) include Non AC Hostel (ME1), AC Hostel (ME2), Office located at Administrative building (ME3), Reading Hall at central library (ME4), Fully ventilated academic block classroom (ME5), Concrete Classroom (ME6) and Fibre-Roof Classroom (ME7); these are the key indoor spaces, where students and staff spend substantial proportions of their daily life, and therefore making realistic assessment of individual exposure pathways. Continuous 12-hour measurements were conducted at 1-minute intervals in each indoor microenvironment during the daytime active-occupancy period: 08:00–20:00 hours. This specific duration (12hrs) was selected to represent the entire active-occupancy period when students and staff are present, as well as the peak-exposure conditions that occur during active occupancy and the related emission and ventilation deficits. To obtain similar indoor-outdoor profiles, measurements were taken at the same locations on the next alternate day under similar meteorological conditions.

¹ The measurements of indoor and outdoor could not be done simultaneously due to the availability of a single monitoring instrument, which restricted parallel data collection; however, measurements were carried out within the same week and under similar weather conditions, which minimized

external variability. Prior permission was obtained from the university authorities and hostel residents before carrying out indoor monitoring activities. The monitoring took place while the spaces were occupied, and no personal identity, medical information, or sensitive data was collected from the participants. The study focused only on monitoring indoor air pollutants and did not disrupt the usual activities of the residents. Informed verbal consent was obtained from the hostel residents before monitoring, following standard practices for studies related to human exposure to environmental factors. The instrument was placed 1.2-1.5 m above the floor, avoiding contact with any walls, doors, or direct air outlets like AC vents and fans. Representative photographs illustrating the deployment of monitoring instruments across different indoor microenvironments and sampling locations are presented in Figure 3.3.

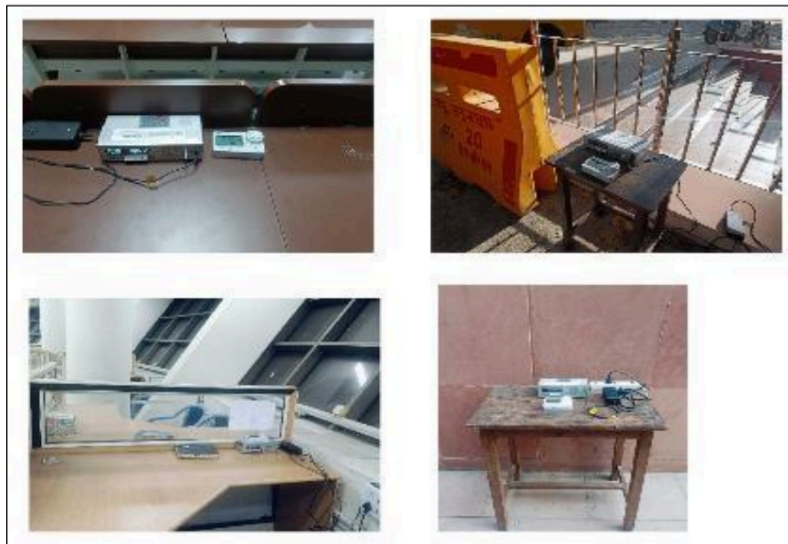


Fig 3. 3 Representative Photographs of Monitoring Equipments Deployed at Sampling Sites.

3.4 Data Processing and Statistical Analysis

A multi-stage statistical framework was used to ensure integrity of the results. Data normality was

first evaluated by the Shapiro-Wilk test. Dataset showed significant deviations from a normal distribution ($p < 0.05$) and therefore non-parametric methods were used for subsequent analyses. Outlier identification and removal were done using Tukey's Interquartile Range (IQR) method, with the criterion of $1.5 \times \text{IQR}$ was used. Kruskal-Wallis tests at significance level $\alpha = 0.05$ evaluated statistically significant spatial differences in pollutant concentrations among the seven microenvironments. Data processing and statistical analyses were performed in Python, boxplot visualization and diurnal trend analysis were performed in OriginPro 2024.

CO₂ data for ME1 and ME2 were not included in any CO₂ analyses because post-monitoring inspection revealed that these sensors recorded CO₂ levels well below the atmospheric CO₂ levels of 420 ppm during the monitoring periods, which is physically impossible and indicates the glitch in the data. Data from all other CO₂ stations (ME3 - ME7) have passed quality control.

3.5 Respiratory Deposition Dose (RDD) Calculation

The Respiratory Deposited Dose (RDD) was estimated in order to measure the amount of particulate matter deposited in various respiratory system regions of the human body. The calculations were carried out using deposition fractions derived from the Human Respiratory Tract Model proposed by the International Commission on Radiological Protection (ICRP, 1994), which has been widely adopted in respiratory exposure and particulate deposition assessment studies (Das et al., 2023; Singh et al., 2025).

The RDD was calculated using the following expression:

$$RDD (\mu g \text{ min}^{-1}) = C \times V_T \times BR \times DF_{\text{region}}$$

where:

- C = mean indoor particulate matter concentration ($\mu g \text{ m}^{-3}$)
- V_t = tidal volume ($\text{m}^3 \text{ breath}^{-1}$)
- BR = breathing frequency (breaths min^{-1})
- DF_{region} = deposition fraction for the selected respiratory region

The deposition fractions considered in the analysis corresponded to the head airway (HA), tracheobronchial (TB), and alveolar (AL) regions of the respiratory tract.

Adult physiological parameters adopted in the study were:

- **Sitting activity:** $V_t = 0.000625 \text{ m}^3 \text{ breath}^{-1}$, $BR = 12 \text{ breaths min}^{-1}$
- **Light activity:** $V_t = 0.001250 \text{ m}^3 \text{ breath}^{-1}$, $BR = 20 \text{ breaths min}^{-1}$

RDD calculations were performed separately for PM_{10} , $PM_{2.5}$, and PM_{10} under both activity conditions for all seven microenvironments. The deposition fraction parameters adopted for the estimation of Respiratory Deposition Dose (RDD) for different particulate size fractions are summarized in Table 3.3.

Table 3.3 Deposition fraction parameters adopted for PM_{10} , $PM_{2.5}$, and PM_{10} Respiratory Deposited Dose (RDD) estimation.

PM Fraction	Aerodynamic particle diameter, dp (μm)	DF – Head Airway (HA)	DF – Tracheobronchial Region (TB)	DF – Alveolar Region (AL)	DF – Total Deposition Fraction	Primary Deposition Mechanism
PM_{10}	1	0.2851	0.0272	0.1217	0.434	Alveolar diffusion dominant
$PM_{2.5}$	2.5	0.6876	0.0607	0.1077	0.856	Head airway impaction Dominant
PM_{10}	10	0.8114	0.0152	0.0193	0.8459	Inertial impaction in nasal cavity

3.6 Lung-Deposited Surface Area (LDSA) Calculation

Lung-Deposited Surface Area (LDSA) was estimated to evaluate the total particle surface area depositing in the alveolar region of the lungs. Unlike mass-based measures, LDSA offers a measure of potential exposure to particle concentrations that depends on the area available for interaction with the lung tissue. LDSA was calculated across all four size fractions to yield total LDSA (Source: Adapted from ICRP, 1994). The input parameters and deposition characteristics adopted for Lung-Deposited Surface Area (LDSA) estimation are presented in Table 3.4.

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Lung-Deposited Surface Area (LDSA) was calculated as:

$$LDSA (\mu m^2 cm^{-3}) = \sum_i [\pi \times d_i^2 \times N_i \times DF_{AL}(d_i)]$$

where:

- d_i = midpoint aerodynamic diameter of size fraction i (μm)
- N_i = mean particle number concentration for size fraction i ($\# cm^{-3}$)
- $DF_{AL}(d_i)$ = alveolar deposition fraction corresponding to particle diameter d_i

Table 3. 4 Input parameters and deposition characteristics used for Lung-Deposited Surface Area (LDSA) estimation.

Size Fraction	Particle Size Range (μm)	Midpoint Diameter, d_p (μm)	Alveolar Deposition Fraction, DF_{AL}	Surface Area ($\pi d_p^2 N$)	Dominant Deposition Mechanism
qUFP	0.25–0.50 μm	0.35	0.0629	$\pi \times (0.35)^2 \times N_{qUFP}$	Brownian diffusion dominant
Subfine	0.50–1.00 μm	0.75	0.1078	$\pi \times (0.75)^2 \times N_{subfine}$	Mixed diffusion+impaction
Fine	1.00–2.5 μm	1.75	0.1242	$\pi \times (1.75)^2 \times N_{fine}$	Inertial impaction dominant
Coarse	2.5–10.0 μm	5	0.0575	$\pi \times (5.00)^2 \times N_{coarse}$	Gravitational settling

3.7 Limitations

- Due to the availability of only a single set of reference instruments, indoor and outdoor measurements could not be conducted simultaneously.
- Monitoring was done for 12 hours during occupied periods and therefore did not capture variations that may occur outside the monitoring timeframe.
- Reliable CO₂ data could not be obtained for ME1 and ME2 due to technical glitch.

CHAPTER 4

RESULTS and DISCUSSIONS

4.1 Statistical Overview

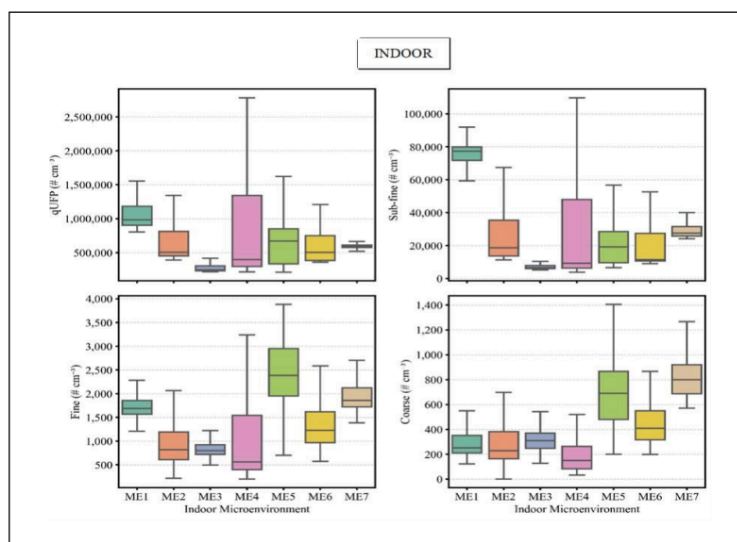
1 Kruskal–Wallis tests confirmed statistically significant spatial differences ($p < 0.05$) for all measured parameters across the seven measured microenvironments, thus supporting the hypothesis that the indoor pollutant regime is determined by the building design, the occupancy density, the type of ventilation and the activity of the indoor sources. The effect sizes (as assessed by the Kruskal–Wallis H statistic) were largest for $PM_{2.5}$ and qUFP, reflecting the high sensitivity of fine and submicron particles to both indoor source activity and ventilation design.

4.2 Spatial Variability of Particle Number Concentration

Quasi-ultrafine particles (qUFP) were the dominant size fraction for all seven microenvironments, with median concentrations ranging from 2.5×10^5 particles cm^{-3} in ME3 (Admin Office) to 1.0×10^6 particles cm^{-3} in ME1 (Non-AC Hostel) and a consistent dominance hierarchy qUFP > subfine > fine > coarse was observed across all sites. The size ordering, confirmed in both spatial and temporal analyses, is consistent with the physicochemical properties of urban aerosol with a strong contribution from combustion-derived nucleation-mode particles from traffic and solid-fuel burning. The descriptive statistical summary of indoor and outdoor PNCs across the monitored university microenvironments is presented in Table 4.1.

ME1 (Non-AC Hostel) recorded the highest indoor qUFP median ($\sim 1.0 \times 10^6$ particles cm^{-3}), attributable to continuous long hours residential occupancy without mechanical air filtration, the hostel's location which may increase outdoor air exchange compared to other spaces, and the proximity of the campus to arterial road corridors that sustain elevated outdoor ultrafine burdens throughout the day. ME4 (Central Library) had the largest inter-quartile range (IQR) for qUFP (around $0.35\text{--}1.3 \times 10^6$ particles cm^{-3}) due to the particle recirculation that occurred when the library was used by large groups of students for reading. These particles could not be efficiently removed

by a recirculation-only centralised HVAC system. ME2 (AC Hostel) had moderate background qUFP ($\sim 5.0 \times 10^5$ particles cm^{-3}) with extreme episodic event ($\sim 2.4 \times 10^6$ particles cm^{-3}) that matched an incense-burning event that was documented in the diurnal analysis. ME3 (Admin Office) and ME5 (Academic Block Classroom) recorded the lowest median qUFP, consistent with good mechanical ventilation supply and lower steady-state occupancy in ME3. The spatial variation of indoor particle number concentration fractions across the selected university microenvironments is illustrated in Figure 4.1.



1 Fig 4. 1 Spatial variation of qUFP, subfine, fine and coarse fractions across selected indoor microenvironments.

In all microenvironments, the outdoor qUFP was higher than the indoor qUFP (range: 5.0×10^5 to $>2.0 \times 10^6$ particles cm^{-3}), indicating that vehicular combustion emissions are the major source in the DTU campus environment. It is important to note that the indoor qUFP is always lower than the outdoor qUFP, indicating that the building envelope does attenuate the infiltration of emissions from the outdoors, but not entirely and source-specific.

Sub-fine PNC were found to be in the range of about 5,000 and 70,000 particles cm^{-3} indoors. ME1 recorded the highest sub-fine median ($\sim 70,000$ particles cm^{-3}) and ME3 the lowest ($\sim 6,000$ particles cm^{-3}). Fine particle indoor medians were significantly lower than qUFP, ranging from approximately 650 to 2,500 particles cm^{-3} , with ME5 and ME7 (classrooms with higher foot-traffic activity) recording the highest fine medians. The coarse median ranged from around 150 to 830 particles cm^{-3} indoors, with ME7 (Fibre-Roof Classroom) having the highest coarse median, which may be due to the use of fibrous construction materials and resuspension caused by foot traffic. The spatial distribution of outdoor particle number concentration fractions measured across the monitored microenvironments is illustrated in Figure 4.2.

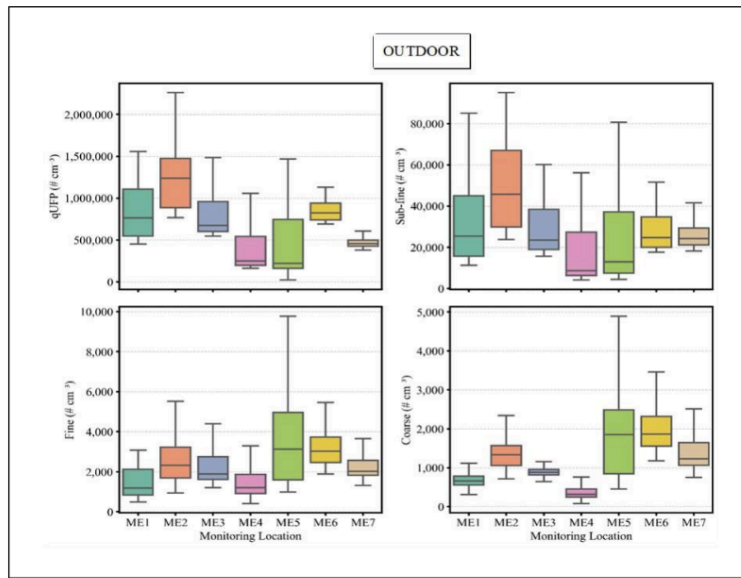


Fig 4. 2 Spatial variation of outdoor qUFP, subfine, fine and coarse fractions across selected microenvironments.

Table 4. 1 Statistical summary of indoor and outdoor PNCs (particles/m³) across monitored university microenvironments.

Microenvironments (MEs)	Parameter	Mean $\pm$ SD	Median	IQR	Min	Max
ME1: Non-AC Hostel (Indoor)	qUFP	1,060,085 $\pm$ 204,713	982,293	279,493	805,378	1,552,862
ME1: Non-AC Hostel (Indoor)	subfine	76,548 $\pm$ 9,989	77,408	8,235	53,658	100,073
ME1: Non-AC Hostel (Indoor)	fine	1,732 $\pm$ 244	1,689	289	1,206	2,471
ME1: Non-AC Hostel (Indoor)	coarse	290 $\pm$ 114	252	142	123	840
ME1: Non-AC Hostel (Outdoor)	qUFP	855,979 $\pm$ 333,115	764,279	560,118	453,134	1,555,852
ME1: Non-AC Hostel (Outdoor)	subfine	32,808 $\pm$ 21,027	25,419	29,200	11,323	84,977
ME1: Non-AC Hostel (Outdoor)	fine	1,459 $\pm$ 704	1,183	1,280	494	3,085
ME1: Non-AC Hostel (Outdoor)	coarse	791 $\pm$ 407	659	231	309	2,170
ME2: AC Hostel (Indoor)	qUFP	1,524,663 $\pm$ 332,190	1,435,892	476,998	917,612	2,762,274
ME2: AC Hostel (Indoor)	subfine	114,054 $\pm$ 25,223	109,474	30,378	77,828	205,672
ME2: AC Hostel (Indoor)	fine	1,770 $\pm$ 246	1,742	322	890	2,790
ME2: AC Hostel (Indoor)	coarse	309 $\pm$ 114	271	100	138	1,031
ME2: AC Hostel (Outdoor)	qUFP	575,723 $\pm$ 234,723	524,115	310,559	236,689	1,960,396
ME2: AC Hostel (Outdoor)	subfine	46,501 $\pm$ 28,417	39,012	47,223	23,229	192,069
ME2: AC Hostel (Outdoor)	fine	1,638 $\pm$ 665	1,526	1,142	532	4,771
ME2: AC Hostel (Outdoor)	coarse	682 $\pm$ 380	521	459	254	1,837
ME3: Admin Office (Indoor)	qUFP	1,325,318 $\pm$ 287,467	1,272,345	303,470	686,840	2,342,678
ME3: Admin Office (Indoor)	subfine	88,587 $\pm$ 28,778	84,230	27,913	46,800	227,568
ME3: Admin Office (Indoor)	fine	1,623 $\pm$ 255	1,584	377	613	3,812
ME3: Admin Office (Indoor)	coarse	296 $\pm$ 141	244	143	107	1,042
ME3: Admin Office (Outdoor)	qUFP	866,709 $\pm$ 345,625	758,905	563,915	387,948	2,569,791
ME3: Admin Office (Outdoor)	subfine	43,372 $\pm$ 24,620	39,221	32,579	14,322	147,513
ME3: Admin Office (Outdoor)	fine	1,283 $\pm$ 632	1,118	1,100	489	4,003
ME3: Admin Office (Outdoor)	coarse	528 $\pm$ 373	334	779	93	2,679

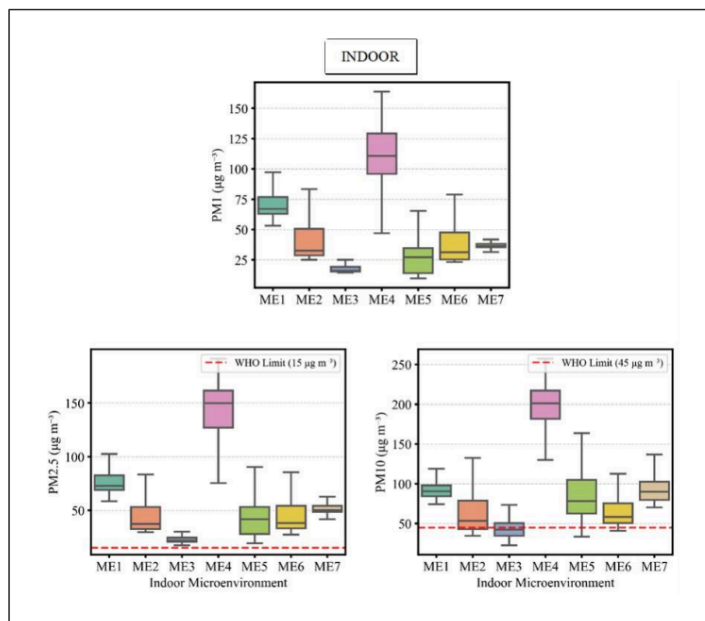
ME4: Library (Indoor)	qUFP	980,564 ± 230,296	909,825	407,495	479,213	2,241,248
ME4: Library (Indoor)	subfine	53,500 ± 14,916	52,716	12,742	25,119	104,728
ME4: Library (Indoor)	fine	1,595 ± 300	1,568	393	1,025	3,235
ME4: Library (Indoor)	coarse	239 ± 96	212	112	105	1,064
ME4: Library (Outdoor)	qUFP	791,761 ± 276,150	710,338	499,762	381,543	2,073,389
ME4: Library (Outdoor)	subfine	63,768 ± 20,677	60,957	26,888	27,370	146,444
ME4: Library (Outdoor)	fine	1,347 ± 621	1,218	1,029	363	5,080
ME4: Library (Outdoor)	coarse	594 ± 466	338	1,208	122	4,205
ME5: AB-4 (well ventilated) Classroom (Indoor)	qUFP	2,100,496 ± 557,561	1,990,481	1,186,214	507,683	8,295,248
ME5: AB-4 (well ventilated) Classroom (Indoor)	subfine	159,540 ± 36,653	155,420	44,215	79,204	305,680
ME5: AB-4 (well ventilated) Classroom (Indoor)	fine	1,904 ± 271	1,854	476	935	3,759
ME5: AB-4 (well ventilated) Classroom (Indoor)	coarse	279 ± 119	254	139	60	1,047
ME5: AB-4 (Outdoor)	qUFP	719,578 ± 398,874	475,331	678,071	385,118	4,544,069
ME5: AB-4 (Outdoor)	subfine	41,423 ± 20,935	37,123	36,693	11,489	159,792
ME5: AB-4 (Outdoor)	fine	1,807 ± 585	1,610	964	395	5,407
ME5: AB-4 (Outdoor)	coarse	978 ± 565	677	1,695	205	5,447
ME6: TW3 (concrete) Class (Indoor)	qUFP	2,371,609 ± 545,499	2,314,543	1,167,910	666,540	8,780,479
ME6: TW3 (concrete) Class (Indoor)	subfine	172,024 ± 41,296	169,635	49,891	82,721	391,280
ME6: TW3 (concrete) Class (Indoor)	fine	2,056 ± 369	2,020	632	957	4,428
ME6: TW3 (concrete) Class (Indoor)	coarse	181 ± 98	157	131	70	1,086
ME6: TW3 (Outdoor)	qUFP	743,197 ± 465,058	621,671	540,103	315,948	3,295,935
ME6: TW3 (Outdoor)	subfine	55,597 ± 37,679	44,084	54,700	21,458	319,164
ME6: TW3 (Outdoor)	fine	2,234 ± 654	2,157	1,163	912	4,667
ME6: TW3 (Outdoor)	coarse	1,042 ± 875	462	1,440	45	8,541
ME7: SPS (Fiber Roof) (Indoor)	qUFP	1,446,183 ± 447,647	1,396,078	733,771	729,411	6,336,429
ME7: SPS (Fiber Roof) (Indoor)	subfine	82,279 ± 23,596	80,171	32,302	42,860	310,300
ME7: SPS (Fiber Roof) (Indoor)	fine	1,887 ± 335	1,878	451	1,030	3,300

ME7: SPS (Fiber Roof) (Indoor)	coarse	136 ± 91	118	108	54	830
ME7: SPS (Outdoor)	qUFP	1,031,434 ± 276,496	978,899	529,710	702,082	4,690,021
ME7: SPS (Outdoor)	subfine	64,853 ± 22,689	62,110	26,733	31,292	303,387
ME7: SPS (Outdoor)	fine	1,534 ± 389	1,506	556	868	3,133
ME7: SPS (Outdoor)	coarse	496 ± 343	319	558	72	3,232

4.1 Spatial Variability of PM Concentrations

Indoor PM₁ ranged from 15 to 160 µg m⁻³ across selected microenvironments. ME4 (Central Library) recorded the highest PM₁ median (~115 µg m⁻³; IQR ~95–130 µg m⁻³), indicating continuous accumulation of fine particles attributable to the combination of high occupant load (55–60 persons), a large repository of paper and archival materials that serve as a persistent source of cellulose-based dust resuspended by HVAC airflows, and the recirculation-only HVAC design that progressively concentrates fine PM over the 12-hour operating day with no outdoor air dilution. ME1 had the second-highest PM₁ median (~67 µg m⁻³). ME3 recorded the lowest PM₁ (~15 µg m⁻³), consistent with its low occupancy and good mechanical air exchange. The spatial variation of indoor PM₁, PM_{2.5}, and PM₁₀ concentrations across the selected university microenvironments is presented in Figure 4.3.

Indoor PM_{2.5} ranged from approximately 18 to 190 µg m⁻³. ME4 had the highest PM_{2.5} median (~145 µg m⁻³), approximately 9.7 times the WHO 2021 24-hour AQG value of 15 µg m⁻³ and 2.4 times India's NAAQS 24-hour standard of 60 µg m⁻³. Although the monitoring was conducted for a 12- hour daytime period rather than over a full 24-hour cycle, the consistently elevated concentrations observed during occupied hours strongly suggest the likelihood of exceedance of the prescribed 24- hour standards.



1 Fig 4. 3 Spatial variation of PM₁, PM_{2.5} and PM₁₀ across selected indoor microenvironments.

Such high PM_{2.5} levels indicate a potential inhalation risk for the regular occupants of this indoor environment. Similarly, ME1 also showed elevated PM_{2.5} levels, with a median concentration of approximately 72 µg m⁻³, exceeding the WHO AQG and NAAQS limits by about 4.8 and 1.2 times, respectively, during the monitoring period. The spatial distribution of outdoor PM fractions measured across the monitored microenvironments is illustrated in Figure 4.4.

1 PM₁₀ ranged from approximately 35–260 µg m⁻³, peaking in ME4 (~200 µg m⁻³). The hierarchy of PM₁₀ > PM_{2.5} > PM₁ is consistent in all microenvironments, as expected, given that larger particles will settle out more quickly. Outdoor PM_{2.5} ranged from ~40–170 µg m⁻³ with occasional peaks exceeding 300 µg m⁻³, confirming the heavily polluted ambient background that constitutes the outdoor boundary condition for indoor infiltration at DTU. The descriptive statistical summary of

indoor and outdoor PM_{10} , $PM_{2.5}$, and PM_{10} concentrations across the monitored university microenvironments is presented in Table 4.2.

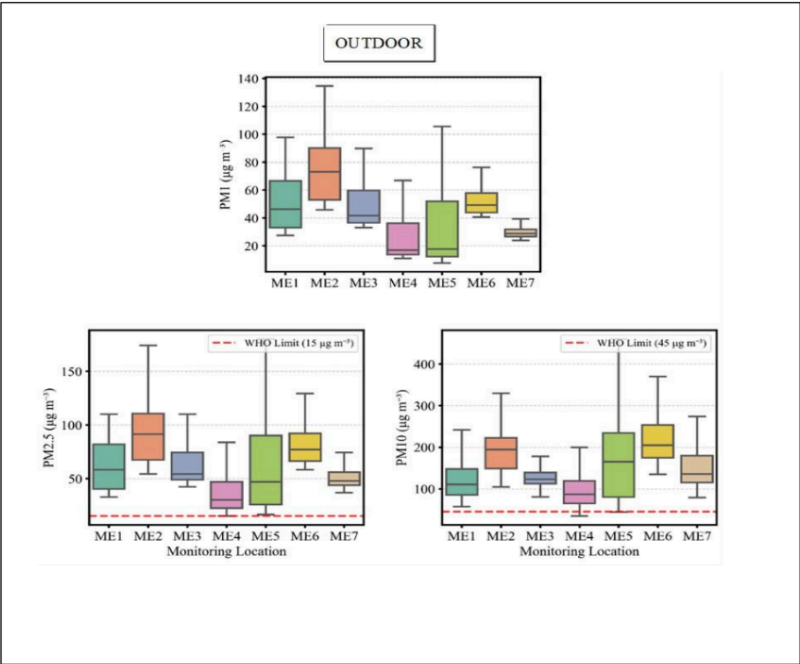


Fig 4. 4 Spatial variations of outdoor PM_1 , $PM_{2.5}$ and PM_{10} across selected microenvironments.

Table 4. 2 Statistical summary of indoor and outdoor PM₁, PM_{2.5}, and PM₁₀ concentrations ($\mu\text{g m}^{-3}$) across monitored university microenvironments.

Microenvironment (MEs)	Parameter	Mean $\pm$ SD	Median	IQR	Min	Max
ME1: Non-AC Hostel (Indoor)	PM ₁	70.8 $\pm$ 11.8	67.0	13.7	53.2	99.5
ME1: Non-AC Hostel (Indoor)	PM _{2.5}	76.8 $\pm$ 11.5	72.9	13.4	58.4	105.6
ME1: Non-AC Hostel (Indoor)	PM ₁₀	92.4 $\pm$ 12.9	90.7	13.9	74.4	241.8
ME1: Non-AC Hostel (Outdoor)	PM ₁	52.1 $\pm$ 20.8	46.2	33.5	27.4	97.8
ME1: Non-AC Hostel (Outdoor)	PM _{2.5}	62.2 $\pm$ 22.8	58.2	41.6	32.7	110.1
ME1: Non-AC Hostel (Outdoor)	PM ₁₀	81.8 $\pm$ 25.2	76.3	47.4	57.1	317.5
ME2: AC Hostel (Indoor)	PM ₁	85.4 $\pm$ 18.8	83.4	21.4	51.9	160.4
ME2: AC Hostel (Indoor)	PM _{2.5}	122.2 $\pm$ 30.5	117.4	45.7	75.0	296.0
ME2: AC Hostel (Indoor)	PM ₁₀	145.9 $\pm$ 40.2	139.8	60.2	92.5	406.8
ME2: AC Hostel (Outdoor)	PM ₁	44.7 $\pm$ 19.4	41.9	25.5	20.0	98.6
ME2: AC Hostel (Outdoor)	PM _{2.5}	75.3 $\pm$ 24.5	72.5	34.5	47.4	174.4
ME2: AC Hostel (Outdoor)	PM ₁₀	116.4 $\pm$ 36.8	109.1	63.8	71.6	367.6
ME3: Admin Building Office (Indoor)	PM ₁	111.8 $\pm$ 28.4	109.2	36.8	61.3	322.9
ME3: Admin Building Office (Indoor)	PM _{2.5}	142.3 $\pm$ 32.2	139.3	38.0	93.6	362.8
ME3: Admin Building Office (Indoor)	PM ₁₀	194.5 $\pm$ 32.4	194.3	43.3	125.4	297.0
ME3: Admin Building Office (Outdoor)	PM ₁	26.1 $\pm$ 12.3	24.9	14.6	11.9	62.6
ME3: Admin Building Office (Outdoor)	PM _{2.5}	52.4 $\pm$ 22.2	50.2	20.8	23.6	157.0
ME3: Admin Building Office (Outdoor)	PM ₁₀	90.8 $\pm$ 21.6	88.5	31.9	43.2	218.0
ME4: Library (Indoor)	PM ₁	100.8 $\pm$ 18.0	99.6	21.4	67.4	164.4
ME4: Library (Indoor)	PM _{2.5}	143.0 $\pm$ 29.9	141.2	42.6	97.3	388.2

ME4: Library (Indoor)	PM ₁₀	201.0 ± 35.1	198.0	53.5	135.3	393.2
ME4: Library (Outdoor)	PM ₁	45.7 ± 17.7	44.2	23.3	20.7	104.3
ME4: Library (Outdoor)	PM _{2.5}	47.4 ± 21.2	45.3	20.0	21.8	127.5
ME4: Library (Outdoor)	PM ₁₀	98.2 ± 27.8	95.1	35.8	43.0	314.7
ME5: AB-4 (well ventilated) Classroom (Indoor)	PM ₁	138.9 ± 37.2	137.5	42.5	77.3	286.4
ME5: AB-4 (well ventilated) Classroom (Indoor)	PM _{2.5}	155.3 ± 37.5	152.8	42.8	102.5	306.0
ME5: AB-4 (well ventilated) Classroom (Indoor)	PM ₁₀	192.7 ± 43.1	188.9	47.4	134.7	429.8
ME5: AB-4 (Outdoor)	PM ₁	41.2 ± 14.9	40.3	21.1	18.9	87.6
ME5: AB-4 (Outdoor)	PM _{2.5}	80.3 ± 25.4	76.8	35.3	44.6	179.2
ME5: AB-4 (Outdoor)	PM ₁₀	97.4 ± 28.7	92.6	44.8	51.6	270.3
ME6: TW3 (concrete) Class (Indoor)	PM ₁	134.2 ± 39.5	131.7	53.6	64.6	324.3
ME6: TW3 (concrete) Class (Indoor)	PM _{2.5}	142.4 ± 39.6	139.4	53.3	91.2	347.6
ME6: TW3 (concrete) Class (Indoor)	PM ₁₀	185.3 ± 43.3	182.0	56.9	127.5	370.4
ME6: TW3 (Outdoor)	PM ₁	23.6 ± 10.5	22.4	13.6	8.8	64.3
ME6: TW3 (Outdoor)	PM _{2.5}	52.0 ± 23.6	49.1	25.7	19.5	137.9
ME6: TW3 (Outdoor)	PM ₁₀	96.3 ± 28.1	93.0	38.2	45.2	314.7
ME7: SPS (Fiber Roof) (Indoor)	PM ₁	66.4 ± 22.2	63.3	27.7	25.8	224.5
ME7: SPS (Fiber Roof) (Indoor)	PM _{2.5}	87.1 ± 23.6	84.7	26.9	54.3	246.4
ME7: SPS (Fiber Roof) (Indoor)	PM ₁₀	113.0 ± 25.2	111.5	30.5	75.4	220.9
ME7: SPS (Outdoor)	PM ₁	26.7 ± 9.4	25.6	13.9	12.8	76.6
ME7: SPS (Outdoor)	PM _{2.5}	52.5 ± 17.6	51.0	24.3	27.4	147.7
ME7: SPS (Outdoor)	PM ₁₀	91.1 ± 30.0	87.2	50.2	34.6	284.3

4.2 Spatial Variability of CO₂

The data for continuous CO₂ monitoring for ME1 (Indoor/Outdoor), ME2 (Indoor/Outdoor), and ME4 (Outdoor) were explicitly excluded from this analysis. Data validation after the campaign

showed a significant drift in sensor calibration at these locations during the monitoring period, leading to the measurement of values that were physically impossible, well below the natural atmospheric background level of ~420 ppm. All data from sensor deployments with known issues (including failures of the sensors to function correctly) were discarded from the data for the purposes of spatial analysis, except for the following deployments: Indoor ME3–ME7; Outdoor ME3, ME5, ME6, ME7.

The indoor CO₂ spatial distribution in the assessed university microenvironments is shown in Figure 4.5. These concentration levels are a very good indicator of the building's ventilation adequacy and the number of occupants and are primarily used for human respiration as the main source of CO₂ in a building. ASHRAE 62.1 standard principles recommend maintaining CO₂ levels below a 1000 ppm threshold to prevent cognitive fatigue and obtain acceptable indoor air quality for students.

The highest CO₂ concentration was obtained in the AB-4 (ME5) well-ventilated classroom with the mean CO₂ concentration reaching 1,018 ppm, with peak transient exposures reaching nearly 1,880 ppm. This is a common and significant over-achievement of the 1000 ppm proxy which suggests that air exchange may be insufficient because of the high occupancy of the building during lectures. Likewise, the mean and peak CO₂ levels in ME6 (concrete classroom) were elevated at ~850 ppm, respectively 1250 ppm.

By contrast, the indoor CO₂ levels in ME7 (SPS fibre-roof classroom) were significantly lower (mean ~576 ppm). The fibre roof's highly permeable, semi-open architecture allows for quick and easy passive ventilation to the outdoor air which is the cause of this enhanced IAQ in comparison to the significantly enclosed concrete classrooms where a respiratory build-up of CO₂ can be noted. The CO₂ levels in ME3 (Admin Building) and ME4 (Library) were kept at acceptable levels, typically lower than 1,000 ppm.

The ambient CO₂ level for all the valid locations around it (Figure 4.6) remained relatively low and stable (around 450–600 ppm CO₂), which is the typical background CO₂ concentration at a university campus. The descriptive statistical summary of indoor and outdoor CO₂ concentrations across the monitored university microenvironments is presented in Table 4.3.

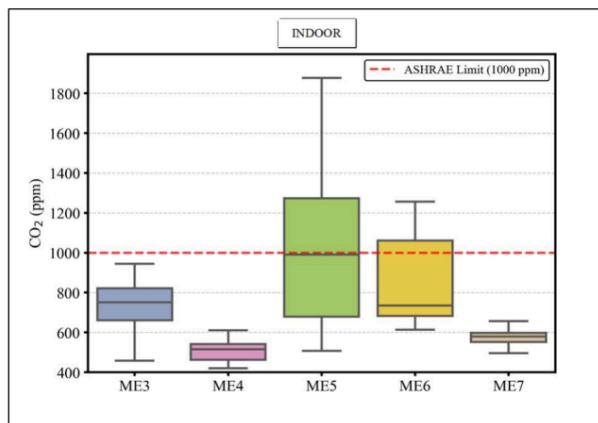


Fig 4. 5 Spatial variations of CO₂ across selected indoor microenvironments

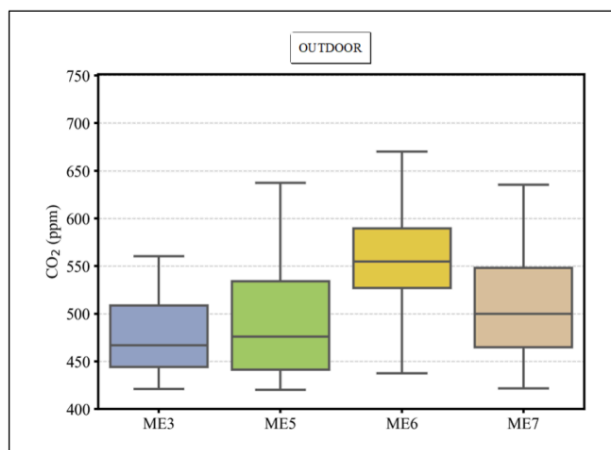


Fig 4. 6 Spatial variations of outdoor CO₂ across selected microenvironments.

2

Table 4. 3 Statistical summary of indoor and outdoor CO₂ concentrations (ppm) across monitored university microenvironments.

Microenvironments (MEs)	Parameter	Mean $\pm$ SD	Median	IQR	Min	Max
ME3: Admin Building Office (Indoor)	CO ₂	720.6 $\pm$ 129.8	750.8	161.0	457.6	944.1
ME3: Admin Building Office (Outdoor)	CO ₂	475.4 $\pm$ 34.6	466.1	64.4	402.5	560.2
ME4: Library (Indoor)	CO ₂	502.6 $\pm$ 44.3	512.7	78.2	388.2	610.9
ME4: Library (Outdoor)	CO ₂	272.4 $\pm$ 40.0	263.6	66.4	201.8	365.5
ME5: AB-4 (well ventilated) Classroom (Indoor)	CO ₂	1018.0 $\pm$ 349.2	991.0	593.6	507.7	1877.6
ME5: AB-4 (Outdoor)	CO ₂	476.7 $\pm$ 54.2	464.4	96.1	391.3	637.5
ME6: TW3 (concrete) Class (Indoor)	CO ₂	849.5 $\pm$ 198.8	735.6	378.8	613.5	1255.8
ME6: TW3 (Outdoor)	CO ₂	556.1 $\pm$ 42.1	554.8	62.5	437.5	699.0
ME7: SPS (Fiber Roof) (Indoor)	CO ₂	576.5 $\pm$ 31.5	579.4	46.0	496.1	673.5
ME7: SPS (Outdoor)	CO ₂	503.4 $\pm$ 53.1	498.0	85.3	364.7	711.8

4.3 Temporal Patterns of Particle Number Concentration

The temporal variation was significant for all pollutant fractions across the 12-hour monitoring windows, largely as a consequence of the variety of occupancy, and ventilation scheduling, and episodic indoor source activities. The relative temporal variability of the various size fractions was largest for the qUFP fraction, which is thought to be sensitive to both short-lived combustion events and outdoor traffic.

The early monitoring hours (08:00-10:00 h), when the doors were opened many times, windows open, and outdoor air is brought in with its high qUFP burden, showed the highest PNC in most microenvironments, followed by the steady-state values when the doors were closed and windows closed due to temperature changes in mechanically cooled rooms. Concentrations tended to gradually decrease towards mid-day, and in high occupancy areas, there was a small secondary peak in the afternoon that coincided with a return of students following lunch breaks. The temporal variation of different particle number concentration fractions across the selected indoor microenvironments is illustrated in Figure 4.7.

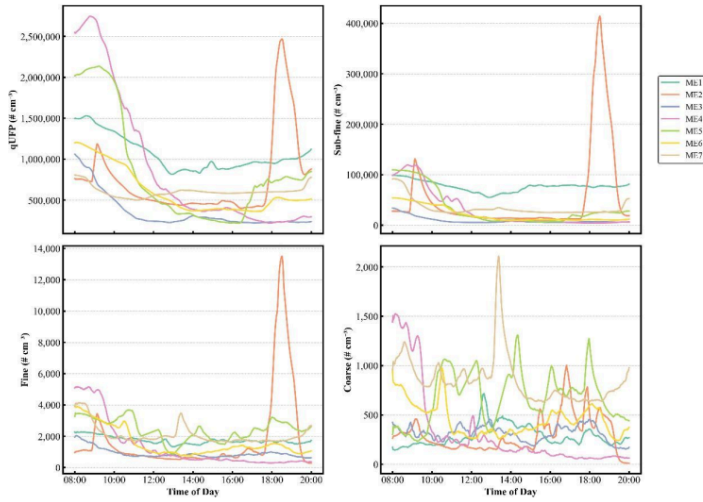


Fig 4. 7 Temporal variation of qUFP, subfine, fine and coarse fractions across selected microenvironments.

4.4 Temporal patterns of PM Mass Concentrations

PM_{2.5} in ME4 (Central Library) was consistently higher throughout the 12-hour monitoring period (120–180 $\mu\text{g m}^{-3}$) and had no mid-day drop, as HVAC-recirculated PM_{2.5} would gradually be accumulated within a closed space without outdoor air intake. This pattern is more likely to be observed in classrooms that have a lower air exchange rate, as compared to classrooms that have higher air exchange rates, which have a morning-peak/mid-daytime decline pattern. The temporal variation of PM₁, PM_{2.5}, and PM₁₀ concentrations across the monitored indoor microenvironments is presented in Figure 4.8.

The reduced mid-day PM_{2.5} concentrations in ME5 (Academic Block) and ME3 (Admin Office) suggest that good ventilation performance or lower peak occupancy is achieved during the mid-day period. The fibre roof of ME7 allowed for more natural ventilation during the day when the differential between the indoor and outdoor temperature was greater, resulting in a moderate diurnal decline.

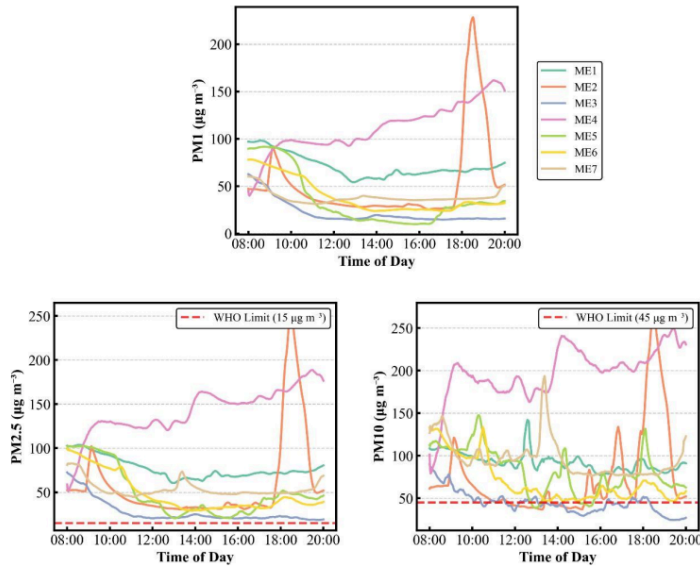


Fig 4. 8 Temporal variations of PM₁, PM_{2.5} and PM₁₀ across selected microenvironments.

4.5 Temporal CO₂ Patterns

The temporal patterns of CO₂ highly correlated with occupancy schedules. During monitoring in ME5 (Academic Block), CO₂ increased significantly from ~550 ppm at the beginning of the monitoring period, reaching peak concentrations over 1,700 ppm by the 3rd–4th hour of monitoring, following the start of the class, and then dropped slightly during breaks. ME5 showed a slow recovery to baseline, with CO₂ staying elevated even during moderate occupancy, showing a poor recovery rate of ventilation when fresh-air supply is not provided.

There was also an accumulation of CO₂ in the occupied hours, with concentrations often reaching or exceeding the 1000 ppm ASHRAE recommended limit, indicating moderate ventilation

insufficiency with increased occupancy. CO₂ levels at ME3 were comparatively stable during the day with moderate rises with most levels staying below the recommended level. ME4 had the lowest CO₂ levels during the monitoring period, which suggests a relatively lower occupancy density and/or better air exchange conditions.

ME7 (Fibre-Roof Classroom) showed much faster CO₂ recovery values declining to near-outdoor levels (~500 ppm) during break periods which are consistent with natural ventilation providing adequate fresh-air flushing during unoccupied intervals. The resilient ventilation benefit of the semi-open roof construction of ME7 is evident in the CO₂ profile of the building during the day. The temporal variation of indoor CO₂ concentrations across the selected university microenvironments is illustrated in Figure 4.9.

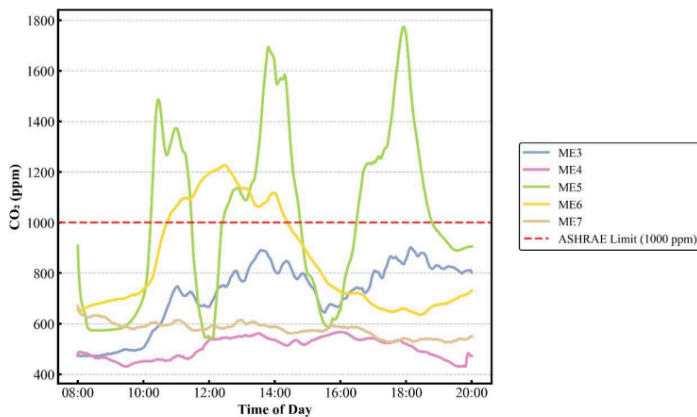


Fig 4. 9 Temporal variations of CO₂ across selected microenvironments.

4.6 The Incense Burning Episode in ME2

A significant episodic event of the entire study was a large single-hour qUFP rise in ME2 (AC Hostel) at the 11th monitoring hour (approx. 19:00 hrs) when the qUFP levels jumped from

background level ($3.0\text{--}6.0 \times 10^5$ particles cm^{-3}) to $\sim 2.1 \times 10^6$ particles cm^{-3} (3.5–7 times higher in one hour). This event temporally coincided with incense burning observed in the room during the monitoring session.

At the same time, the sub-fine fraction in ME2 increased to around 3.2×10^4 particles cm^{-3} (from the background of 3.5×10^4 particles per cm^3), and the fine PNC increased to around 9800–10000 particles cm^{-3} (from the background of 1900–2000 particles per cm^3). Most importantly, the coarse particle fraction showed no statistically significant response for this event, indicating that combustion, rather than mechanical resuspension was the source mechanism. Because of the negligible contribution of incense burning to CO_2 compared to human respiration, the lack of a CO_2 peak during this event gives a good diagnostic signature: PM and PNC peaks without CO_2 peaks identifies a point combustion source, not an occupancy-driven ventilation deficit. The influence of the indoor incense-burning episode on size-resolved particle number concentration fractions in ME2 is illustrated in Figure 4.10.

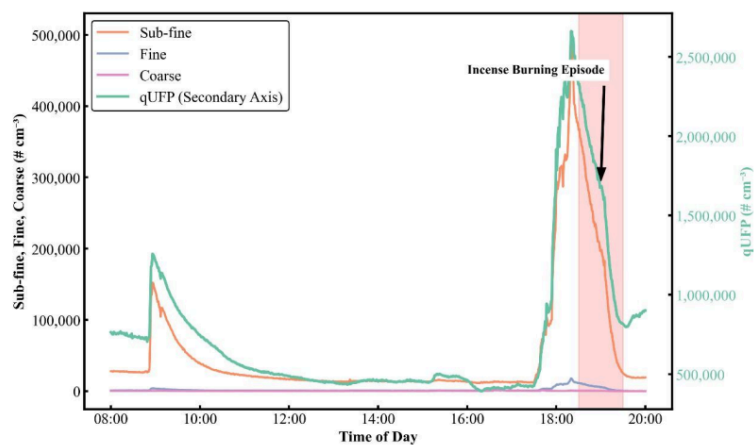


Fig 4. 10 Impact of an indoor incense-burning episode on size-resolved particle number concentrations in ME2 (AC Hostel).

During the incense burning period, $PM_{2.5}$ concentration in ME2 increased to a value of around $250 \mu g m^{-3}$, which is over 16 times the WHO 24-hour AQG (2021). This acute, short-term exposure (even within an hour) has implications with regards to respiratory health because of the high deposition efficiency of the ultrafine particles produced by the burning incense, especially in the alveolar and tracheobronchial parts of the respiratory tract. The impact of the indoor incense-burning episode on PM concentration levels in ME2 is presented in Figure 4.11.

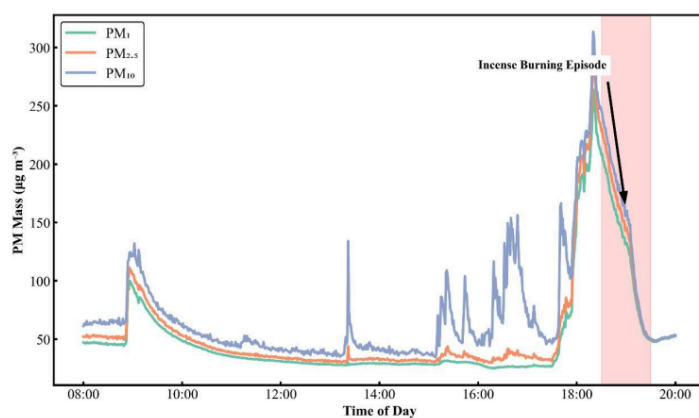


Fig 4. 11 Impact of an indoor incense-burning episode on PM concentrations in ME2 (AC Hostel).

4.7 Interpretation of I/O Ratio

The indoor-to-outdoor (I/O) ratios are a diagnostic tool for dividing the indoor pollutant burden between indoor source generation ($I/O > 1$) and outdoor infiltration ($I/O < 1$). Values close to unity represent a balance of indoor and outdoor contributions. The I/O ratio framework is most informative, if calculated separately for each of the PM size fractions because the physicochemical processes involved in indoor source generation and outdoor infiltration are strongly influenced by PM size.

4.8 PM Mass I/O Ratios

ME4 (Central Library) recorded the highest I/O ratios for all PM mass fractions ($PM_{10} = 1.8$, $PM_{2.5} = 3.4$, $PM_1 = 3.8$). The progressive increase from PM_{10} to PM_1 I/O demonstrates the preferential indoor generation and retention of fine over coarse particles, consistent with the known sources: printer and photocopier toner emissions, resuspension of cellulose-based book and shelf dust, and re-entrainment of particles through the centralized HVAC recirculation system. The PM_1 I/O of 3.8 in an HVAC system operating in a recirculation-only mode highlights the potential for recirculation-only HVAC to increase, not decrease, indoor fine particle concentrations when filters are not fully maintained or exist. The indoor-to-outdoor (I/O) ratios of PM_1 , $PM_{2.5}$, and PM_{10} concentrations across the selected microenvironments are illustrated in Figure 4.12.

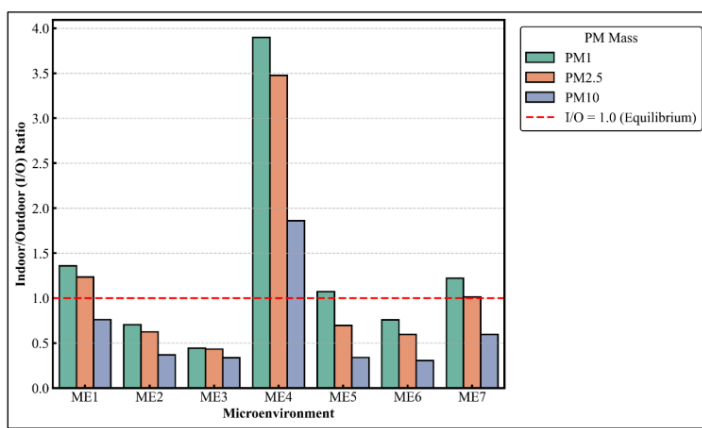


Fig 4. 12 Ratios of Indoor to Outdoor (I/O) PM levels across selected microenvironments

ME1 (Non-AC Hostel) showed moderate I/O values for $PM_{2.5}$ and PM_1 (>1) but PM_{10} below unity, indicating outdoor dominance for coarse particles. ME3 and ME6 always had I/O ratios below unity (0.3–0.7), denoting outdoor source dominance with relatively good air exchange. ME7 showed $PM_{2.5}$ and PM_1 I/O ratios close to unity (~ 1.0 – 1.2), indicating a balanced contribution. ME5 showed intermediate ratios (~ 0.8 – 1.1).

4.9 PNC I/O Ratios

The more complex pattern was observed with number-based I/O ratios. The sub-fine I/O ratio was highest for ME1 (~2.3), which indicates that there is strong emission activity from the source room and this can possibly be correlated to residential activity or behaviour. qUFP I/O was highest in ME4 (~2.1) and ME5 (~1.85), indicating substantial indoor generation of ultrafine particles in both the library (HVAC and electrostatic sources) and the high-occupancy classroom (respiratory aerosol, foot-traffic resuspension). ME3 and ME2 were both dominated by outdoor sources, with qUFP I/O < 1 on a 12-hour average, although there was some incense release from outdoor sources in ME2. The indoor-to-outdoor (I/O) ratios of particle number concentration fractions across the monitored microenvironments are presented in Figure 4.13.

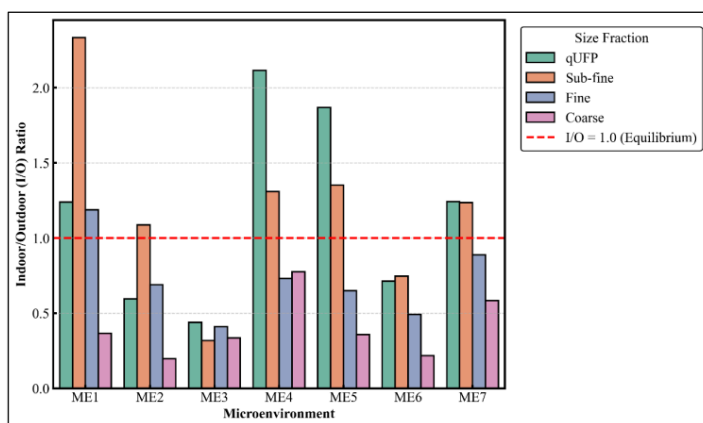


Fig 4. 13 Ratios of Indoor to Outdoor (I/O) PNC levels across selected microenvironments.

Coarse particle I/O ratios were found to be lower than unity in all the microenvironments (0.17–0.75), indicating that the infiltration of coarse particles is the major source in all cases and gravitational deposition is the predominant removal mechanism during the outdoor-to-indoor transport.

An important finding is that number-based I/O indicators exceeded unity in more microenvironments than mass-based indicators; for example, ME5 showed PM_1 I/O ≈ 1.05 while qUFP I/O ≈ 1.85 ; demonstrating that PM mass metrics structurally underrepresent indoor source contributions from the health-relevant particle fraction.

4.10 Respiratory Deposition Dose Results

The RDDs were estimated ³² for PM_1 , $PM_{2.5}$, and PM_{10} for all seven microenvironments, for both sitting and light activity, in order to understand the mass of PM deposited to the respiratory tract of occupants per minute. The calculated RDD values are presented in both Table 4.1. Across all microenvironments, the RDD followed the consistent size-fraction hierarchy $PM_{10} > PM_{2.5} > PM_1$; this was a result of both higher mass concentrations in coarser size fractions and higher total deposition fractions assigned to PM_{10} and $PM_{2.5}$ in the upper respiratory tract under the ICRP (1994) model.

The highest RDD across all PM fractions and both activity levels was recorded at ME4 (Central Library Reading Hall). At light activity, the PM_{10} , $PM_{2.5}$, and PM_1 RDD values for ME4 were 4.21, 3.06, and $1.22 \mu\text{g min}^{-1}$, respectively, substantially exceeding all other microenvironments. The $PM_{2.5}$ RDD of $3.06 \mu\text{g min}^{-1}$ at ME4 is equivalent to a deposited mass of 2.20 mg day^{-1} for a 12-hour occupancy, which is 9.7 times the WHO 24-hour $PM_{2.5}$ guideline of $15 \mu\text{g m}^{-3}$ when scaled to exposure time, and is comparable to values reported for high-exposure indoor cooking environments in Indian studies (Gautam et al., 2016). The main reason for the elevated RDD for ME4 is due to the central HVAC recirculation system that operates continuously for 12 h throughout the day, with no fresh air being brought in, causing a continuous increase in $PM_{2.5}$ levels from $125 \mu\text{g m}^{-3}$ at 08:00 h to $175 \mu\text{g m}^{-3}$ at 14:00 h. This is further compounded by the high occupant load of 55–60 persons generating bioaerosols, the large quantity of paper and books generating cellulose-based fine dust, and the large enclosed volume (1396.8 m^3) that sustains prolonged particle residence.

ME1 (Non-AC Hostel) ranked second across all PM fractions at both activity levels, with PM_{10} , $PM_{2.5}$, and PM_1 RDD values of 1.95, 1.64, and $0.77 \mu\text{g min}^{-1}$, respectively, under light activity.

The elevated RDD at ME1 reflects the prolonged long hour residential occupancy in the complete absence of mechanical air filtration, which allows uninterrupted outdoor emission infiltration through unfiltered vents and accumulation of indoor-generated submicron particles from occupant activities. The time-averaged concentrations recorded in ME2 were also moderated by the AC system limiting thermal and humidity induced particle generation, but episodic incense burning events recorded during monitoring (during which $PM_{2.5}$ rose to $205 \mu g m^{-3}$) would drive the instantaneous RDD well above these daily average concentrations, and the closed AC environment would not allow any dilution.

ME7 (Fibre-Roof Classroom) had the highest PM_{10} RDD at $2.04 \mu g min^{-1}$ (light activity), which was attributed to the high concentration of coarse PNC, as a result of the release of fibrous particles from the roofing material and resuspension from student traffic. The $PM_{2.5}$ RDD values were similar for ME5 (Academic Block Classroom) and ME6 (Concrete Classroom) with values of $1.05 \mu g min^{-1}$ and $1.02 \mu g min^{-1}$, respectively. In spite of the increased inhalation rate of light activity, the 8-hour classroom occupancy was shorter and the PM concentrations were moderate, leading to significantly lower cumulative daily deposition than the residential and library microenvironment.

The lowest RDD values measured were at ME3 (Administrative Office) for all fractions, $PM_{10} = 0.93$, $PM_{2.5} = 0.57$, $PM_1 = 0.23 \mu g min^{-1}$ at light activity, which correlated with the lowest measured PM concentrations, limited 8-hour operating hours and lower occupancy density of 8-10 persons. The RDD values across all microenvironments are presented in Table 4.4.

Table 4. 4 Respiratory Deposition Dose (RDD; $\mu\text{g min}^{-1}$) across seven microenvironments.

Microenvironment	Activity	PM ₁ RDD Total ($\mu\text{g/min}$)	PM _{2.5} RDD Total ($\mu\text{g/min}$)	PM ₁₀ RDD Total ($\mu\text{g/min}$)
ME1 – Non-AC Hostel	Sitting	0.231	0.493	0.586
ME1 – Non-AC Hostel	Light Activity	0.768	1.643	1.953
ME2 – AC Hostel	Sitting	0.172	0.379	0.477
ME2 – AC Hostel	Light Activity	0.574	1.262	1.588
ME3 – Admin Office	Sitting	0.069	0.172	0.279
ME3 – Admin Office	Light Activity	0.231	0.574	0.930
ME4 – Central Library	Sitting	0.366	0.919	1.262
ME4 – Central Library	Light Activity	1.221	3.064	4.206
ME5 – Academic Block	Sitting	0.113	0.314	0.520
ME5 – Academic Block	Light Activity	0.377	1.046	1.732
ME6 – Concrete Classroom	Sitting	0.126	0.306	0.437
ME6 – Concrete Classroom	Light Activity	0.419	1.020	1.456
ME7 – Fibre-Roof Classroom	Sitting	0.123	0.345	0.612
ME7 – Fibre-Roof Classroom	Light Activity	0.411	1.149	2.038

4.11 Lung-Deposited Surface Area Results

Lung-Deposited Surface Area (LDSA) was also estimated for each microenvironment based on the size-resolved PNC data from the Grimm 11-A aerosol spectrometer, in addition to the mass-based RDD analysis. For particles less than 1 μm in diameter, the health effects are controlled mainly by surface reactivity and oxidative potential, and not by PM mass, which is why LDSA is gaining increasing recognition as a more biologically relevant measure of exposure than the PM mass

(Morawska et al., 2017). The LDSA values across all microenvironments and size fractions are presented in Table 4.5.

It was found that the fine particle fraction (1.00–2.50 μm) accounted for 70–90% of total LDSA in all seven microenvironments. The dominance originates from the highest combination of per-particle surface area ($\pi \times d_p^2$, $d_p = 1.75 \mu\text{m}$), as well as from the highest particle number concentration (PNC) for all size fractions, similar to the results of Geiss et al. (2016) and Kuula et al. (2022) observed in urban indoor settings. The coarse fraction contributed 4–27% of total LDSA, with ME7 recording the highest coarse LDSA contribution (17,432 $\mu\text{m}^2 \text{cm}^{-3}$) due to the elevated coarse PNC from fibre-roof material fragmentation. The qUFP and sub-fine fractions contributed less than 5% of total LDSA despite having the highest particle number concentrations, due to their small d_p^2 values that limit their per-particle surface area contribution.

The highest total LDSA was recorded at ME1 (Non-AC Hostel) at 118,587 $\mu\text{m}^2 \text{cm}^{-3}$, followed by ME2 (AC Hostel) at 87,092 $\mu\text{m}^2 \text{cm}^{-3}$. The dominance of ME1 is mainly due to its fine PNC of 91,453 particles cm^{-3} , achieved by the continuous presence of residence, with no mechanical filtration, in which fine suspended particles progressively accumulate from clothing, bedding and the activities of the people inside, and outdoor fine aerosols continuously infiltrate through unfiltered openings. The high fine LDSA of 78,558 $\mu\text{m}^3 \text{cm}^{-3}$ was also achieved by ME2, and was further enhanced by the episodic incense-burning event which produced a high concentration of fine PNC (up to ~9,800 particles cm^{-3} at Hour 18), and by the closed AC environment which resulted in longer particle residence time and lack of natural dilution.

Table 4. 5 Lung-Deposited Surface Area (LDSA; $\mu\text{m}^2 \text{cm}^{-3}$) across seven microenvironments.

Microenvironment	LDSA qUFP	LDSA Subfine	LDSA Fine	LDSA Coarse	LDSA Total
ME1 – Non-AC Hostel	621.6	2,776.7	109,281	5,907	118,587
ME2 – AC Hostel	436.4	1,996.0	78,558	6,101	87,092
ME3 – Admin Office	199.8	323.5	12,730	6,381	19,634
ME4 – Central Library	514.3	1,078.8	42,455	6,160	50,208
ME5 – Academic Block	484.4	1,195.0	47,028	13,842	62,549
ME6 – Concrete Classroom	352.8	740.3	29,136	9,091	39,320
ME7 – Fibre-Roof Classroom	352.8	1,205.1	47,426	17,432	66,416

4.12 Integrated RDD–LDSA Health Risk Classification

Even though the PM mass concentrations and the mass-based RDD were the highest of all on campus, ME4 (Central Library) ranked 50,208 $\mu\text{m}^2 \text{cm}^{-3}$, placing it 5th in LDSA. This was due to the fact that this fine PNC (35,529 cm^{-3}) was still relatively low compared to the PNC of ME1 (91,453 cm^{-3}). This highlights one of the main results of the present study: the clear divergence between ME4's ranking in mass-based RDD (1st) and number-based LDSA (5th). It shows that, despite the fact that an environment with a high concentration of large particles (created by HVAC-recycled coarser fractions and paper dust) results in a high surface area-mediated oxidative burden to the alveoli, this burden is controlled by the fine and submicron particle number concentration. The lowest LDSA values were obtained for ME6 (Concrete Classroom) with 39,320 $\mu\text{m}^2 \text{cm}^{-3}$, and for ME3 (Administrative Office) with 19,634 $\mu\text{m}^2 \text{cm}^{-3}$, respectively, and were consistent with the lower PNC profiles across all size fractions respectively.

Based on the combined RDD–LDSA framework: ME4 is classified as HIGH health risk (highest RDD, chronic); ME1 as MODERATE-HIGH (highest LDSA); ME7, ME2, ME5, and ME6 as MODERATE; and ME3 as LOW-MODERATE. These classifications should be interpreted as relative rankings within the study dataset, not absolute health risk determinations; all seven

microenvironments exceeded WHO PM_{2.5} AQG thresholds under the 12-hour occupancy-period comparison. The integrated exposure and health risk classification based on Respiratory Deposition Dose (RDD) and Lung-Deposited Surface Area (LDSA) metrics across the selected microenvironments is summarized in Table 4.6.

Table 4. 6 Integrated exposure and health risk assessment based on Respiratory Deposited Dose (RDD), and Lung-Deposited Surface Area (LDSA) across selected microenvironments.

MEs	RDD PM ₁ Light (µg/min)	RDD PM _{2.5} Light (µg/min)	RDD PM ₁₀ Light (µg/min)	LDSA Total (µm ³ /cm ³)	RDD Rank	LDSA Rank	Health Risk Level
ME1	0.7682	1.6429	1.9532	118,586.5	2	1	MODERATE-HIGH
ME2	0.5737	1.2624	1.5882	87,091.7	3	2	MODERATE
ME3	0.2308	0.5742	0.9296	19,634.1	7	7	LOW-MODERATE
ME4	1.2205	3.0636	4.2062	50,208.2	1	5	HIGH
ME5	0.3773	1.0460	1.7320	62,549.2	5	4	MODERATE
ME6	0.4191	1.0204	1.4556	39,320.2	6	6	MODERATE
ME7	0.4113	1.1490	2.0382	66,415.9	4	3	MODERATE

CHAPTER 5

CONCLUSIONS, FUTURE SCOPE AND SOCIAL IMPACT

5.1 Conclusions

The present study aims to conduct a comprehensive assessment of indoor particulate exposure in seven representative microenvironments of a major technical university campus in Delhi, considering both particulate mass concentrations, carbon dioxide (CO₂), ³¹ particle number concentrations (PNC), Lung-Deposited Surface Area (LDSA) and Respiratory Deposited Dose (RDD). The study integrates exposure - based metrics of mass, number and deposition to offer a comprehensive picture of the characteristics of indoor aerosols and their possible health effects in university settings.

The major findings of the study are summarized as follows:

- (1) The quasi-ultrafine particles (qUFP; 0.25–0.50 μm) had the largest particle number fraction in all the microenvironments monitored, followed by subfine, fine and coarse particles, thus creating a consistent size hierarchy (qUFP > subfine > fine > coarse). This high prevalence of qUFP in different building types reflects the high concentration of the urban background aerosol in Delhi and the effective transfer of combustion particles from traffic into indoor environment.
- (2) From a mass-based exposure point of view, the Central Library (ME4) was identified as the most critical microenvironment. It recorded the highest PM₁, PM_{2.5}, and PM₁₀ concentrations, with median PM_{2.5} levels ($\sim 145 \mu\text{g m}^{-3}$) substantially exceeding both the WHO Air Quality Guideline and India's National Ambient Air Quality Standards. ME4 also had the highest PM_{2.5} RDD ($3.064 \mu\text{g min}^{-1}$), and was placed in the high health risk range, suggesting that high inhalation exposure can occur from extended time spent in poorly ventilated, HVAC-dependent environments.
- (3) ME1 (Non-AC Hostel), by contrast, had the highest total Lung-Deposited Surface Area ($118,587 \mu\text{m}^2 \text{cm}^{-3}$), suggesting that it offers the highest chance of surface exposure of the alveoli

to fine and submicron particles. High particle number concentrations and extended residential exposure were the main contributors to the elevated LDSA. This result indicates that moderate mass concentrations of PM can still be a significant health risk, even when measured by particle surface-area exposure.

(4) The most prominent episodic aerosol event observed during the monitoring campaign was caused by the distinct short-term combustion event of the incense burning in the AC Hostel (ME2). In this period the concentration of qUFP grew by around 3.5–7 times in an hour, with $PM_{2.5}$ exceeding $250 \mu g m^{-3}$. No corresponding increases in coarse particle concentrations and CO_2 levels was found, which confirmed combustion as the dominating source. This observation demonstrates the relevance of the short-term exposure peaks of indoor activities by occupants.

(5) The diurnal variation of CO_2 concentrations closely reflected occupancy patterns across the monitored environments. Peak concentrations in the classroom areas (specifically ME5 and ME6) were found to be above the 1000 ppm ASHRAE recommended limit when the buildings were at maximum occupancy. The results show that split air-conditioning systems with no separate provision for fresh air could prove to be not enough for good ventilation when the number of occupants is large.

(6) The comparison of RDD and LDSA showed substantial variation in the ranking of the monitored environments for health risk. While ME4 ranked first in terms of mass-based deposited dose, ME1 ranked first in terms of alveolar-deposited particle surface area. This difference indicates that mass- and number-based exposure metrics measure different aspects of inhalation risk and thus should be used in combination to evaluate indoor aerosol exposures more holistically.

Overall, the study highlights the importance of integrating PM, PNC, CO_2 , RDD, and LDSA for improved understanding of indoor air pollution dynamics and respiratory exposure risks within educational institutions located in highly polluted urban regions such as Delhi.

5.2 Recommendations

Based on the observations made during the present study, several measures can be suggested to reduce indoor particulate exposure and improve the indoor environmental conditions in educational buildings.

1. Classrooms, libraries, and other highly occupied spaces should be provided with adequate fresh-air ventilation systems. Installation of CO₂-based demand-controlled ventilation (DCV) systems can help maintain proper indoor ventilation during occupied periods and reduce excessive CO₂ accumulation.
2. Indoor spaces operating with recirculation-based HVAC systems should be equipped with efficient particulate filtration systems such as HEPA or MERV-13 filters to reduce the build-up of fine particulate matter indoors.
3. Regular cleaning, inspection, and replacement of HVAC filters should be carried out to maintain filtration efficiency and prevent re-suspension of deposited particles within indoor spaces.
4. Indoor combustion-related activities such as incense burning, smoking, and use of open flames should be avoided in enclosed or mechanically ventilated environments because these activities can generate extremely high short-term ultrafine particle concentrations.
5. Educational institutions should introduce routine indoor environmental monitoring programs for PM_{2.5}, particle number concentration (PNC), CO₂, temperature, and ventilation conditions to identify high-exposure indoor locations.
6. Occupancy management and ventilation scheduling should be improved, especially in classrooms and libraries, in order to minimize pollutant accumulation during peak occupancy periods.
7. Awareness programs related to indoor air pollution and respiratory health should be conducted for students, faculty members, and administrative staff to encourage better indoor environmental practices.
8. Indoor air pollution monitoring should also be incorporated into institutional environmental policies and green building assessment frameworks for educational buildings in India.

5.3 Future Scope

Although the present work provides detailed information regarding indoor particulate exposure in university environments, several aspects can be explored further in future studies.

1. Long-term monitoring covering different seasons may be conducted to understand the influence of meteorological conditions on indoor pollutant behaviour.
2. Future studies may include additional gaseous pollutants such as VOCs, NO₂, O₃, and formaldehyde for a more comprehensive assessment of indoor air pollution.
3. Personal exposure monitoring using wearable sensors may help in understanding individual exposure patterns among students and staff.
4. Chemical characterization and source apportionment studies can be carried out to identify major indoor and outdoor pollution sources contributing to indoor aerosol concentrations.
5. Computational fluid dynamics (CFD) modelling may be used in future studies to understand indoor airflow characteristics and pollutant transport mechanisms.
6. Further investigations may also evaluate the performance of different ventilation systems, air purifiers, and filtration technologies in reducing indoor particulate exposure.
7. Similar studies can be extended to schools, hospitals, offices, and residential buildings located in different urban regions of India.
8. Additional epidemiological and toxicological studies are required ³ to better understand the long-term health impacts associated with ultrafine particle exposure in indoor environments.

5.4 Societal Implications

Indoor air pollution is increasingly becoming an important environmental and public health issue, particularly in educational institutions where students and staff spend long hours indoors. The findings of the present study highlight the importance of maintaining cleaner and better-ventilated indoor environments to reduce respiratory exposure and improve occupant wellbeing.

The study emphasizes that indoor pollutant exposure is not influenced only by outdoor pollution

levels, but also by indoor activities, occupancy conditions, and ventilation characteristics. Therefore, proper ventilation management and regular indoor environmental assessment are necessary for creating healthier educational spaces.

The outcomes of this work may help university authorities, policymakers, architects, and environmental planners in developing better indoor environmental management strategies for institutional buildings. The findings can also support future policies related to indoor air pollution monitoring and sustainable building design in urban regions.

The present study also contributes towards ³⁹several United Nations Sustainable Development Goals (SDGs), including:

- SDG 3: Good Health and Well-Being - by promoting healthier indoor environments and reducing respiratory exposure risks.
- SDG 4: Quality Education - through improvement of indoor learning conditions and student comfort.
- SDG 11: Sustainable Cities and Communities - by supporting sustainable indoor environmental management practices in urban institutions.
- SDG 13: Climate Action - through promotion of efficient ventilation practices and environmentally responsible pollution control approaches.

Overall, the study highlights the need for greater attention toward indoor environmental quality within educational institutions, especially in densely populated urban regions such as Delhi.

MULTI-METRIC EVALUATION OF INDOOR AIR POLLUTANTS AND HEALTH RISKS ACROSS DIFFERENT MICROENVIRONMENTS IN A UNIVERSITY CAMPUS OF DELHI, INDIA

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