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STUDY OF AEROSOLS IN INDOOR - OUTDOOR MICROENVIRONMENTS FOR URBAN HOUSEHOLDS OF DELHI

By

MONIKA SHARMA

Environmental Science and Engineering Department

Submitted

In fulfilment of the requirements of the degree

of

DOCTOR OF PHILOSOPHY

to

DEPARTMENT OF ENVIRONMENTAL SCIENCE AND ENGINEERING

DELHI TECHNOLOGICAL UNIVERSITY

DELHI-110042, INDIA

NOVEMBER 2025

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STUDY OF AEROSOLS IN INDOOR - OUTDOOR MICROENVIRONMENTS FOR URBAN HOUSEHOLDS OF DELHI

A Thesis

Submitted in fulfilment of the requirements for the award of the degree Of

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By

MONIKA SHARMA
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ENVIRONMENTAL SCIENCE AND ENGINEERING DEPARTMENT

Under the guidance of
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DEPARTMENT OF ENVIRONMENTAL SCIENCE AND ENGINEERING
DELHI TECHNOLOGICAL UNIVERSITY
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DECLARATION

I hereby declare that the research work presented in this thesis entitled " **Study of aerosols in indoor - outdoor microenvironments for urban households of Delhi**" is original and carried out by me under the supervision of Dr. Rajeev Kumar Mishra, Associate Professor, Department of Environmental Science and Engineering, Delhi Technological University, Delhi, and co-supervision of Prof. Mukesh Khare, Emeritus Professor, Department of Civil Engineering, Indian Institute of Technology Delhi being submitted for the award of Ph.D. degree to Delhi Technological University, Delhi, India. The content of this thesis has not been submitted either in part or whole to any other university or institute for the award of any degree or diploma.

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List of publications

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6. Krithika, N., Jain, R., **Sharma, M**., & Mishra, R. K. (2023). Organic Farming in India and its Way Forward. *Defence Life Science Journal*, *8*(3), 239–247. https://doi.org/10.14429/dlsj.8.18975.

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12. **Sharma, M.**, Khare, M., & Mishra, R. K. (2025). Impact of Solid Waste Dump Yards Fire on Air Quality of National Capital Delhi. In *Select Proceedings of the 8th Indian International Conference on Air Quality Management (IICAQM 2023)* (Vol. 582, p. 115). Springer Nature. DOI: 10.1007/978-981-96-2359-4_9

Abstract

Rapid urbanization increases the population density in urban regions, which compromises the standard of living. Indoor air quality in urban regions is a serious concern. This study analyzed the concentration of indoor particulate matter and particle number concentration in urban clusters where significant socioeconomic differences exist within the same geographical domain. This study also estimated the seasonal variations of indoor and outdoor particle number concentrations in different socioeconomic household conditions in the urban city Delhi. This study investigated the impact of festival activities on household indoor air quality in megacity Delhi. The study included different phases and activities during the festival and normal conditions and analysed the impact of different emissions. The portable aerosol spectrometer was employed to measure quasi-ultrafine, sub-fine, fine, and coarse particle concentrations in the kitchen, bedroom, and outdoor conditions. Indoor air quality is crucial for the well-being of residents, as people spend 80% of their time indoors.

Particulate matters (PM_{10}, $PM_{2.5,}$ and PM_1) were measured in two major indoor microenvironments (kitchen and bedroom) along with outdoors of the selected households during winter, summer, and monsoon seasons. Four major income groups were considered for the study. A poorly ventilated kitchen was found to have higher concentrations of PM_{10} (247 µg/m^3), $PM_{2.5}$ (200 µg/m^3), and PM_1 (153 µg/m^3), respectively. Indoor, PM_1 contributed ~40 to 85 % to PM_{10}. During winter, the seasonal mean I/O ratio of PM_{10}, $PM_{2.5}$, and PM_1 ranged between 1.1 and 1.8 in bedroom and between 0.8 and 2.2 in kitchen. The influence of outdoor particulate matter concentration on indoor air was observed to be high during winter, followed by summer and monsoon. The higher concentration in kitchen leads to an exposure of 0.10 µg, and in bedroom, it was 0.11 µg for adults with a higher breathing rate. The exposure depends on the concentration and exposure time. The $PM_{2.5}$ depositions were found more in the lower lung regions.

The findings of the study revealed that quasi-ultrafine (250 to 500 nm) particle concentration was high (2.1×10^6 #cm^{-3}) in urban poor households during the winter season. Indoor quasi-ultrafine particle concentration ranged between ~10^5–10^6 #cm^{-3} in the kitchen and bedroom. In a properly ventilated kitchen, a significant reduction in

indoor particle number concentration (1.2×10^6 #cm^{-3} to 7.1×10^5 #cm^{-3}) was observed. The number concentration of coarse particles was found to be the lowest (< 1.1×10^3 #cm^{-3}) among other sizes. However, indoor sources resulted in a higher I/O ratio of 40. Lower-income group kitchens exhibited a higher number concentration of different-sized particles, which also influenced bedroom concentration.

During the festival period, the indoor ultrafine particle concentration was found to be 6.7 × 10^4 #cm^{-3}, which was the highest observed indoor concentration throughout the study. The particle number concentration of the nanoparticles in indoor environment ranged from 10^4 to 10^5 #cm^{-3}. Ultrafine size range particles contributed up to 85% to the total particle numbers. Fireworks contributed to higher particle numbers in indoors, followed by cooking, dusting, and worshiping. The size distribution pattern of the particles emitted during cooking activities and fireworks were found to be different. Particle size range 10 to 30 nm contributed 31 % to total particle numbers on fireworks day, whereas on a normal day, it contributed only 13 %. During a normal day, 100 to 1000 nm size particles contributed ~50 % to the total particle numbers. The diurnal pattern of the indoor environment was different to the outdoor. The outdoor fireworks activities also influenced indoor pollutants with respect to trace metals, which makes the indoor air quality more toxic and affects the occupants' health.

Indoor particle number concentration (PNC) varies significantly in different microenvironments. Cooking, dusting, and incense stick burning are major indoor activities that generate different-sized particle numbers. The number concentration of the quasiultrafine particles (qUFP) was found to be a maximum of (10^6 #cm^{-3}), followed by subfine (10^5 #cm^{-3}), fine (10^4 #cm^{-3}), and coarse (10^3 #cm^{-3}) particles. The winter season exhibits a higher decay period of particles in indoor. The number concentration of particles observed during nighttime was higher than the concentration during daytime. The particles generated during cooking took more time to decay, up to 320 minutes, followed by dusting (120 to 300 minutes) and incense stick usage (< 200 minutes). Roasting, stir frying, and gravy preparation emit a higher concentration of qUFP (4 to 5×10^6 #cm^{-3}) and sub-fine (6 to 8×10^5 #cm^{-3}) particles. More fine particles were generated during stir-frying (3×10^4 #cm^{-3}) and coarse particles (2×10^3 #cm^{-3}) were emitted at high levels during roasting. The boiling method of cooking generates a very

less number of qUFP and subfine particles (< 10^5 #cm^{-3}). The measured particle number concentration linearly correlated with particulate matter, and the influence of indoor sources was found to be more in the studied microenvironments. Indoor number concentrations were found to be higher than in the outdoor environment. Households with good infrastructure conditions were found to have less influence on one microenvironment than another. Improving indoor air quality relies not only on sources but also on ventilation status, built infrastructure, occupants' behaviour, and the influence of outdoor air. Since people spend the majority of their time indoors, it will be more vulnerable to residents. Indoor pollution in households needs to be mitigated and regulated for a better standard of living.

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LIST OF ABBREVIATIONS

AD	After Diwali
AERs	Air Exchange Rates
APs	Air Purifiers
AQI	Air Quality Index
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AT	Atmospheric Temperature
BC	Black Carbon
BD	Before Diwali
BF	Breathing Frequency
CO	Carbon Monoxide
CO_2	Carbon dioxide
COPD	Chronic Obstructive Pulmonary Disease
CFD	Computational Fluid Dynamics
CFU/m^3	Colony Forming Units per cubic meter
CNG	Compressed Natural Gas
CPC	Condensation Particle Counter
CPCB	Centre Pollution Control Board
DD	Diwali Day
DF	Deposition Fraction
DMA	Differential Mobility Analyzer
DMN	Default Mode Network
EC	Elementary Carbon

ECCs	Elderly Care Centers
ELPI	Electrical Low-Pressure Impactor
FVC	Forced Vital Capacity
GMD	Geometric Mean Diameter
GTB Nagar	Guru Tegh Bahadur Nagar
HAP	Household Air Pollution
HEPA	High Efficiency Particulate Air
HI	Hazard Index
HIG	High Income Group
HQ	Hazard Quotient
IAP	Indoor Air Pollution
IAQ	Indoor Air Quality
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
ILCR	Incremental Lifetime Carcinogenic Risk
I/O	Indoor/Outdoor
KW-Test	Kruskal-Wallis Test
LDMA	Long Differential Mobility Analyzer
LIG	Low Income Group
LMICs	Low and Middle-Income Countries
LPG	Liquefied Petroleum Gas
LPM	Liter Per Minute
Max	Maximum
MERV	Minimum Efficiency Reporting Value
MIG	Middle Income Group

Min	Minimum
MRSA	Methicillin-Resistant Staphylococcus Aureus
MPPD	Multiple Path Particle Dosimetry
NAAQS	National Ambient Air Quality Standards
N_{acc}	Accumulation Mode
N_{atk}	Aitken Mode
NCR	National Capital Region
ND	Normal Day
N_{nuc}	Nucleation Mode
NOAA	National Oceanic and Atmospheric Administration
NO_x	Nitrogen Oxides
NPF	New Particle Formation
NPs	Nanoparticles
N_{total}	Total Particle Number Concentration
OC	Organic Carbon
OM	Organic Matter
OPC	Optical Particle Counter
PACs	Portable Air Cleaners
PAHs	Polycyclic Aromatic Hydrocarbons
PM	Particulate Matter
PMAY	Pradhan Mantri Awas Yojana
PMC	Particle Mass Concentration
PNC	Particle Number Concentration
PND	Particle Number Distribution

PNSD	Particle Number Size Distribution
ppb	Parts Per Billion
PTEF	Polytetrafluoroethylene Membrane Filters
qUFP	Quasi Ultrafine Particles
RDD	Respirable Depository Dose
RH	Relative Humidity
RT	Respiratory Tract
SBS	Sick Building Syndrome
SD	Standard Deviation
SDG	Sustainable Development Goals
SES	Socioeconomic Status
SIA	Secondary Inorganic Aerosol
SMPS	Scanning Mobility Particle Sizer
SOC	Secondary Organic Carbon
SV	Stratum Ventilation
T	Temperature
TEM	Transmission Electron Microscopy
TEOM	Tapered Element Oscillating Microbalances
TEs	Trace Elements
TSPM	Total Suspended Particulate Matter
TV	Tidal Volume
TVOC	Total Volatile Organic Compounds
UFP	Ultra Fine Particulates
UNSDGs	United Nations Sustainable Development Goals

UP	Urban Poor
URT	Upper Respiratory Tract
USD	United States Dollar
VC	Vital Capacity
WHO	World Health Organization
WS	Wind Speed
$\mu g/m^3$	Microgram Per Meter Cube

CHAPTER-1

INTRODUCTION

1.1 Background

Air pollution is one of the leading environmental risk factors for human health. (Echenique et al., 2012; Fuller et al., 2022; Metrics, 2020). It is responsible for millions of deaths annually due to urbanization in developing countries. The major sources of air pollution in urban regions include traffic (Lestari and Mauliadi, 2009), industries (Mooibroek et al. 2022), waste burning (Sharma, et al. 2024), road dust (Lin et al. 2023), construction, etc. (TERI and ARAI, 2018). Based on the different emission activities, the characteristics and concentration of pollutants vary significantly (Sharma et al. 2025). The major pollutants include particulate matter (PM) PM_{10} and $PM_{2.5}$, sub-fine and ultrafine particles (UFPs) (Mohan et al. 2024; Rajagopal et al. 2024). The high concentration of particulate matter can impair the lungs of people exposed to it, especially infants and children, whose lung functions are still growing (Rajagopal et al., 2024; Tran et al., 2023). In elderly people, $PM_{2.5}$ concentrations can induce premature mortality for those who have existing respiratory problems (Jodeh et al. 2018).

The major types of air pollution include outdoor and indoor air pollution (Elf et al., 2018; Sahu and Gurjar 2020). Compared to outdoor air pollution, indoor air pollution is more harmful because humans spend 90% of their time in indoor environments such as homes and offices (Liaqat et al., 2025; Vilčeková et al., 2023). Like outdoor pollution, numerous sources contribute to Indoor pollution, which include cleaning (Stamp et al., 2022), cooking (Islam et al., 2021), smoking (Neuberger et al., 2013), building characteristics (Jeong et al., 2021), ventilation (Jinnawar et al., 2025; Rim et al., 2012; Sharma et al., 2012), and the influence of outdoor air quality (Batbold et al., 2024). The indoor air quality (IAQ) also depends on the existing meteorological conditions, occupants' behavior, and lifestyle. In urban areas, residential zones are located adjacent to roads, where the indoor air quality is worse than in other regions (Kulshreshtha and Khare., 2011). The poor IAQ leads to serious health issues such as asthma exacerbation, sick-building syndrome, and increased blood pressure (Vu et al., 2017). Delhi, India's capital, is a densely populated city with an approximate population of 33 million

(https://worldpopulationreview.com) (Mishra et al., 2019). In Delhi, different socio-economic household strata fall within a small geographic domain, and indoor PM concentration varies drastically among these strata (Sharma et al., 2025). Indoor air quality is a major area of concern in these regions, and very few studies have reported indoor PM status in these regions (Goel et al., 2021; Katoch and Kulshrestha. 2022; Kulshreshtha et al., 2008; Kulshreshtha and Khare., 2010; Vijay et al., 2024).

1.2. Particles in indoor environment

Air pollution is one of the main threats to human health, particularly in megacities where pollution levels are exceeding (Hama et al., 2020; Pandey et al., 2024) . According to their source of emission, geography, and local meteorology, the pollutant particles vary in size and composition (Chithra & Shiva Nagendra, 2014; Echenique et al., 2012; Gaur et al., 2016b, 2016a; Xie et al., 2022). Particulate matter (PM) is among the primary air pollutants, and it is made up of a complex mixture of chemical and biological components (Fig.1.1) (Zwozdziak et al., 2017).

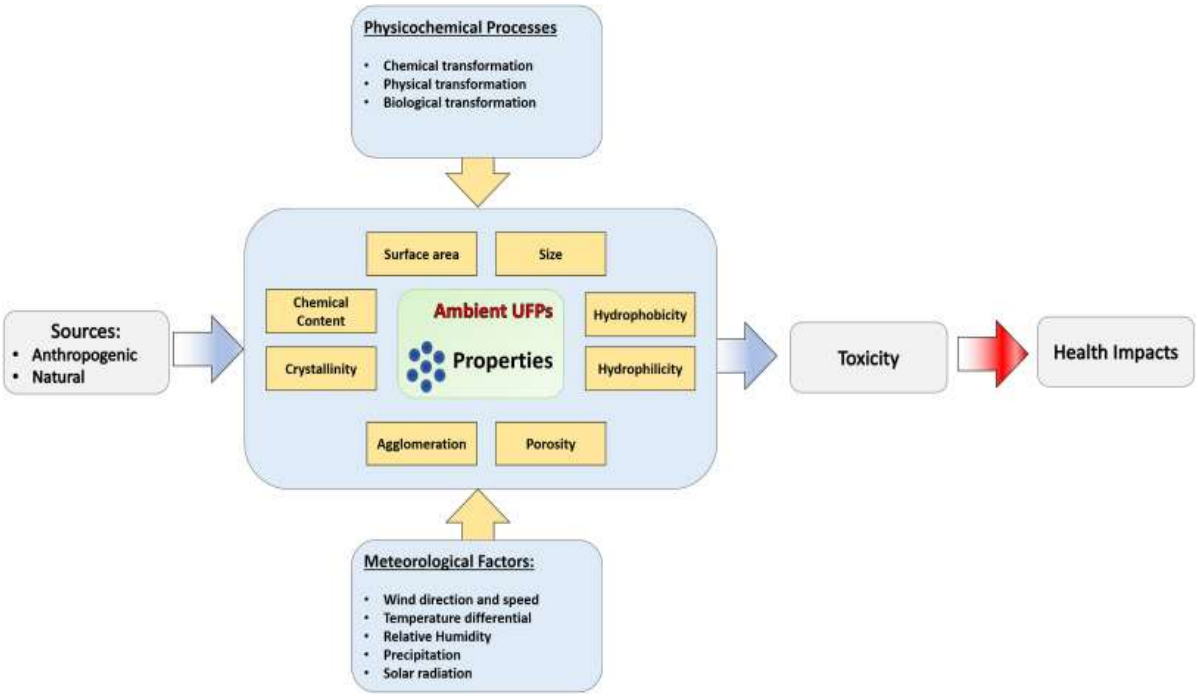

Figure 1.1 General overview of UFPs. Source: (Abdillah & Wang, 2023)

Depending on the aerodynamic diameter, particles are divided into coarse, fine, and ultrafine, ranging from nanometers (nm) to microns (μm), being the PM_{10}, $PM_{2.5}$, and

$PM_{0.1}$ particles. More specifically, it has been recognized that particles with a size smaller than 100 nm are considered as atmospheric nanoparticles (Rajagopal et al., 2024).These particles are classified as coarse (2.5–10 µm), fine (0.1–2.5 µm), and ultrafine (<0.1 µm) based on aerodynamic diameter, where the degree of toxicity increases with decreasing particle size. Because of their size, these particles can enter the lungs and translocate to vital organs, resulting in significant negative effects on human health. Besides, PM pollutants have been linked to respiratory conditions, genotoxic, mutagenic, and carcinogenic activity in human beings (Hofman et al., 2016; Slezakova et al., 2019a)

1.3 Major sources of indoor particle number concentrations

Indoor air pollution has emerged as a major environmental health concern, particularly in densely populated and low-income regions. Studies across the United States, China, India, and other parts of Asia have documented a wide variety of indoor pollutants, including particulate matter ($PM_{2.5}$, PM_{10}), carbon monoxide (CO), carbon dioxide (CO_2), volatile organic compounds (VOCs), black carbon (BC), nitrogen oxides (NO_x), phthalates, polycyclic aromatic hydrocarbons (PAHs), and biological contaminants like mold and allergens (Gaur et al., 2016b). These pollutants originate from diverse indoor sources such as cooking (especially biomass and open flame cooking), heating appliances, smoking, building materials, cleaning products, incense and mosquito coil burning, and infiltration from outdoor air, particularly during wildfire events (Bhui et al., 2023). Shah et al., (2024) assessed indoor $PM_{2.5}$ and CO_2 levels in Texas homes, identifying peak $PM_{2.5}$ levels near 118 µg/m³ during cooking events, though electric stove use and good ventilation helped keep toxicity potential within safe thresholds. Similarly, Wang et al., (2018) found that cooking significantly contributed to $PM_{2.5}$, black carbon, and nicotine exposure among pregnant women. Shezi et al., (2020) highlighted how cost-effective exposure models could predict individual pollutant exposure by integrating personal behaviors, variables, and environmental data. He et al., (2022) studying Seattle during wildfire season, found that HEPA filters significantly lowered indoor $PM_{2.5}$ concentrations, reducing the indoor/outdoor ratio from 0.82 to 0.43. Their findings underscored the effectiveness of indoor air filtration during acute pollution events. Zhang et al., (2017) analyzed long-term $PM_{2.5}$ levels in Beijing and noted seasonal variations, with winter seeing higher concentrations due to industrial emissions, coal use, and

biomass burning. Zhou et al., (2020) investigated the infiltration of ultrafine particles (UFPs) and black carbon in indoor and transportation environments, concluding that indoor UFP levels could sometimes exceed outdoor levels depending on air purifiers and ventilation. (Jin et al., 2015) also highlighted VOC and particulate pollution resulting from incense burning in temples, a culturally relevant but often overlooked source of indoor contaminants.

In broader Asian contexts, studies have revealed that personal exposure to $PM_{2.5}$ is highest during cooking activities, particularly in China (~428 µg/m³), Nepal, Laos, and India. Women and children were identified as the most vulnerable demographic groups due to their proximity to indoor pollution sources (Liu et al., 2020 ; Pokhrel et al., 2015). In India, indoor air pollution remains a significant public health concern, particularly in low-income communities. Emetere et al., (2024) reviewed common sources, including biomass combustion, kerosene stoves, insecticides, and building materials such as asbestos and radon-emitting concrete. These pollutants contribute to respiratory diseases, cognitive deficits, and long-term carcinogenic risks. Karmakar et al., (2024) conducted field studies across Indian rural and urban households, capturing six months of pollutant data and correlating exposure levels with daily activities.

1.4 Physicochemical properties of ultrafine particles.

Quasi-ultrafine particles are usually represented in terms of particles per unit volume of air or particle number (PN) (Villanueva et al., 2021). UFPs, because of a diameter of less than 0.1 µm, suspend in the air for an extended time longer than larger particles. It's been found that the residence time, dispersion, transport, and emission processes of UFPs in the air are purely based on the environmental conditions (Fig.1.2). These include the meteorological factors of the geographic area with respect to wind direction and wind speed, temperature variations, relative humidity, mixing height, precipitation and solar radiation and the physicochemical processes that are carried out within the atmosphere (Morelli et al., 2016; Nguyen et al., 2022; Zhang et al., 2015) . UFPs are usually unstable and become larger particles through the coagulation and condensation process. However, the number of UFPs per unit volume is greater compared to the larger particles (Moreno-Ríos et al., 2022).

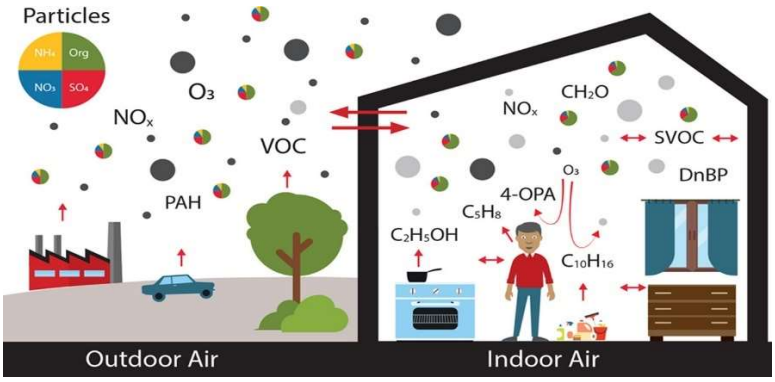

Figure 1.2 Properties of UFPs and the affecting factors. Source: (Goldstein et al., 2021)

1.5 UFP's and associated health effects

It has become widely accepted that UFPs are associated with adverse cardiovascular and respiratory health effects in humans because they have more penetration power than PM_{10} and $PM_{2.5}$ (Bekö et al., 2013; Chen et al., 2020; Joshi et al., 2016; Li et al., 2023; Møller et al., 2020). Hofman et al. (2016) summarized that UFPs have significant access to the alveolar region of the lungs, unlike larger particles, where they are more effectively deposited as a result of rapid diffusion and where clearance mechanisms may be relatively slow(Guo et al., 2020; Hofman et al., 2016). The UFPs can diffuse through the cells of the human body and may be transported to the different organs through the blood (Fig. 1.3). UFPs contain large amounts of toxic components, and their potential adverse health effects would not be predicted from their mass alone (Madureira et al., 2020; Slezakova et al., 2019a). In fact, a number of studies indicate that number, surface area, and chemical composition are more important than UFP mass as health issues are concerned (Jesus et al., 2019; Vicente et al., 2024). UFP, as well as larger particles are also deposited throughout the respiratory tract (RT)(Shupler et al., 2018, 2024; Shupler et al., 2020; Tawiah et al., 2022). The composition of UFP includes a variety of organic components, elemental carbon, and trace metals, which result in the generation of reactive oxygen species, followed by inflammation that has cardiovascular and respiratory effects. This mechanism has gained considerable acknowledgement over the last decade (Bourdrel et al., 2017; Martins et al., 2015; Morelli et al., 2016; Moreno et al., 2020; Murray et al., 2020).

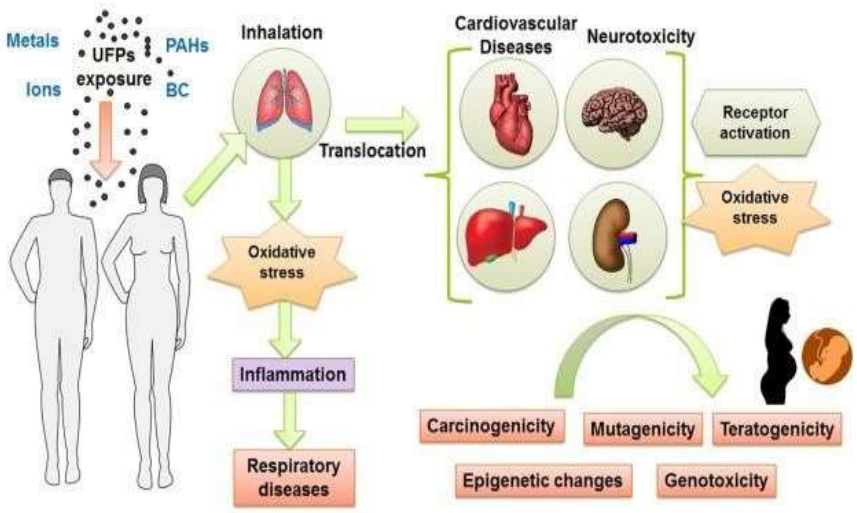

Figure 1.3 Toxicological effects from exposure to UFPs. Source: (Moreno-Ríos et al., 2022)

1.6 Indoor environment aerosol exposure

Globally, >2.6 billion people depend on solid fuels, including biomass and coal. Approximately 4 million people die prematurely from illnesses attributed to indoor air pollution (IAP) resulting from inefficient cooking practices using polluting stoves that operate on solid fuels and kerosene (WHO, 2021). Fuel combustion, especially for cooking, and emissions from the use of cleaning appliances are major sources of IAP (Hussein et al., 2015). Indoor Air Quality (IAQ) refers to the level of air pollutants and thermal conditions (temperature and relative humidity) that affect the health, comfort, and performance of occupants inside a building. The high concentration of air pollutants indoors is a major concern in Delhi city, which has been reported many times as one of the polluted cities in the world (Bhardawaj et al., 2022; Katoch & Kulshrestha, 2022). People spend about 80 - 90% of their time indoors. Therefore, managing the IAP has become an essential need for protecting human health. Improving indoor air quality (IAQ) aligns with the United Nations Sustainable Development Goals (UNSDGs, 2015), about improving health and well-being (Goal 3) by providing affordable and clean energy (Goal 7) in sustainable cities and communities (Goal 11). In addition, reducing IAP is crucial for gender equality (Goal 5) and reducing inequalities (Goal 10), as women in developing countries are disproportionately exposed to emissions from burning of solid fuels such as coal and biomass for cooking, thereby subjecting them to higher risk of IAP

related diseases (Varghese et al., 2005). Evidence suggests that air pollutant concentrations in the indoor environment consistently exceed those in the outdoor due to confined conditions, which results in a 1000-times higher probability for indoor pollutants to infiltrate the lungs (Gray et al., 2013; Loureiro et al., 2025). Exposure to high levels of particulate matter (PM) has been linked to numerous adverse health impacts such as heart disease, pneumonia, stroke, lung cancer, and chronic obstructive pulmonary disease. The IAP is affected by many factors such as the types of cooking fuel, types of cookstove, structural characteristics, ventilation, geographical location, geographical and meteorological conditions, behaviour and exposure time (Kang et al., 2024; Wargocki & Wyon, 2017; Yan et al., 2024) . Particles emitted during cooking have been identified as a significant source of IAP. Epidemiological studies have shown a strong positive correlation between health effects and cooking-related PM (Duanmu et al., 2024; Indu & Shiva Nagendra, 2023). Furthermore, exposure to health-damaging pollutants such as $PM_{2.5}$ and black carbon, resulting from the incomplete combustion of cooking fuels, has been related to high morbidity and mortality rates. Improving housing standards has become a priority for many low-income and middle-income countries (LMICs), following the recognition of the impact of poor architectural design of households on human health (Hofman et al., 2016). Significant increase in the concentration of indoor PM, gaseous and volatile organic compounds was found in low-income homes in LMICs. Efforts are therefore being made to enhance access to improved cookstoves such as e-cookers and clean fuels to preserve human health and the environment (Hussein et al., 2015; Shupler et al., 2020; Q. Zhang et al., 2017).

1.7. Major gaps in the existing literature

There are a few studies that have been done in this area with reference to Delhi (India).

Previous studies on the IAQ of Delhi (India) have only focused on a specific area and community.

The seasonal variation of indoor particulate matter and its sources under different socioeconomic status conditions remains unknown.

An extensive study is needed to measure household particle number concentration at residences of different income groups in Delhi.

The influence of meteorological parameters on particulate number concentrations in the Indoor environment is a potential area to explore.

A very limited number of in-kitchen exposure works have been performed in Delhi, and the data that is available are often inconsistent and for short durations, with varying sampling methodologies.

1.8 Objectives of the study

i. To investigate the seasonal variations of particulate matter (PM_{10}, $PM_{2.5}$ and PM_1) in indoor-outdoor residential microenvironment in different socioeconomic strata
ii. To study the particle number concentrations of UFPs in residential microenvironment covering different socioeconomic population strata
iii. To study the influence of I/O relative humidity and ambient temperature on particle mass and number concentrations in residential microenvironment

1.9 Organization of thesis

The thesis comprises five major chapters, and the brief outline is provided below chapter-wise.

Chapter 1 deals with the introduction, in which detailed information about the different types of particles its sources and properties. This chapter also discuss the global scenario of the indoor air quality and also the need for study in the Delhi city. This chapter enlists the major literature gaps found in the literature. This chapter provides platform for the development of other subsequent chapters such as literature review, methodology, result and discussion and conclusions.

Chapter 2 provides a detailed literature study, which is available globally as well as for the study region. The literature review includes different types of indoor pollutants, different sources, different ventilation conditions, different chemical composition of the particles and its sources. This chapters describes the differences in mass and number concentration of the particles, its size distributions. The chapter also includes the different types of instruments available for the study and the major pollutants which needs to be focused while analysing the indoor air quality. The final section of the chapter includes

research studies related to exposure and potential health impacts of the indoor air pollutants.

Chapter 3 In this chapter the detailed description of the methodology of the study is provided. The information includes how the study area is selected, what is the methodology used for the measurements, different types of instruments used in the study. Details about the different households used for the study. This also provides information about the different statistical tools and software's which are used for the data analysis and visualization of the data. This chapter is complete methodology section of the study.

Chapter 4 includes detailed results and a discussion of the study. The first section of the study contains the quantification and measurements of the different size indoor pollutants including the number and mass concentration during different seasons is discussed. The section contains analysis related to the role of meteorological parameters in the indoor particle's concentration. This section also provides information about the different chemical composition of the measured pollutants and in the final section it provides information about the health hazards and calculated risks from the indoor air quality of the study has also been discussed.

Chapter 5 summarizes the detailed conclusions of the study, which are obtained through the field studies and the outcomes of the major findings. The results also highlight the importance of urban built infrastructure in reducing the indoor air quality, as well as the role of different types of ventilation systems in the indoor environment.

1.10 Summary

Air pollution plays a significant role in human well-being. This chapter provides a detailed overview of indoor and outdoor pollutants, including their sources, physicochemical properties, and associated health risks, with a particular focus on ultrafine particles. Additionally, it highlights the existing research gap and provides a brief outline of the major chapters included. All five chapters of the study provide different types and aspects of information which can be used for developing strategies and polices for improving indoor air quality**.**

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CHAPTER -2

LITERATURE REVIEW

2.1 Introduction

Indoor air pollution has emerged as a significant environmental and public health concern, especially in rapidly urbanising cities like Delhi. It results from a combination of outdoor pollutant infiltration and emissions from daily household activities such as cooking, cleaning, smoking, and the use of incense or candles. Fine and ultrafine particles, along with gases like carbon monoxide and volatile organic compounds, accumulate in enclosed spaces with poor ventilation. Prolonged exposure to these pollutants can lead to respiratory infections, allergies, and cardiovascular problems. The situation worsens during winter when ventilation remains limited, and outdoor pollution levels are high. Addressing indoor air pollution therefore requires both cleaner household practices and broader emission control measures at the city level. Creating public awareness and adopting preventive strategies are crucial to ensure a healthier indoor environment for urban residents.

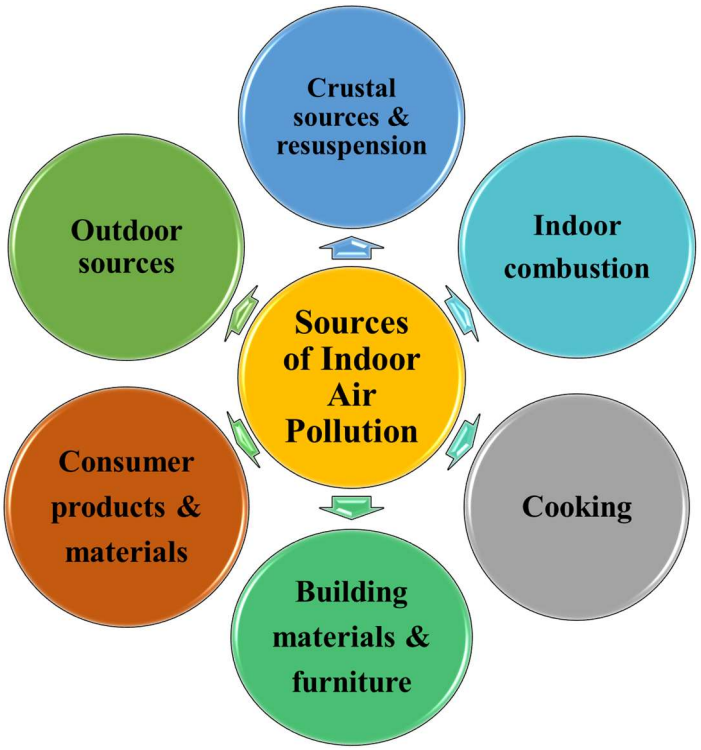

Fig 2.1 Different sources of urban ultrafine particles in Indoor environments.

2.2 Status of indoor pollution in rural and urban households

The status of air pollution in urban households is defined by consistently high concentrations of overall particulate matter (PM), significantly influenced by pollution originating from outside the home, coupled with substantial localized indoor emissions, particularly ultrafine particles (UFP) (Manigrasso et al., 2017; Segalin et al., 2020a). Urban population spend a majority of their time (80 - 90%) indoors, making indoor air quality crucial for total personal exposure (Kluizenaar et al., 2017; Rahman et al., 2017). Concentrations frequently exceed international guidelines. For example, the average indoor $PM_{2.5}$ concentration in urban areas of Hanoi, Vietnam, was approximately four times higher than the WHO guideline of 15.0 $\mu g/m^3$ (Vo et al., 2022). Similarly, in Dhaka city, the mean indoor $PM_{2.5}$ concentration was 75.69 $\mu g/m^3$, far surpassing the WHO 24-h guideline (Yasmin et al., 2024). Outdoor sources—such as traffic emissions, industrial emissions, and domestic coal burning from surrounding households are significant contributors to indoor pollution via infiltration (Abdel-Salam, 2021a; Chen et al., 2020; Garbarienė et al., 2022; Rivas et al., 2015). Homes were characterized by Martins et al., (2020) and found that the finest fraction ($PM_{0.25}$), constituting the largest mass fraction (30–71% of PM_{10}), linked to indoor combustion activities such as cooking. Organic Carbon (OC) was the major contributor across all indoor size ranges in both environments. Overall, indoor PM concentrations were often higher than outdoor levels, and fine carbonaceous components (Elemental Carbon, EC, in $PM_{0.25}$ and OC in $PM_{0.25-0.5}$) were associated with penetrating traffic exhaust emissions. Begum et al., (2009) conducted a study on Indoor Air Pollution (IAP) from PM emissions in different households in Dhaka (Bangladesh) and found that the impact of fuel type, kitchen location, and ventilation conditions on IAQ, as well as the contributions from different sources, was determined by the measured tracemetal composition of indoor PM. Various factors like ventilation rate, kitchen location, and fuel type influenced PM concentrations significantly. Usage of LPG resulted in lower PM levels. Abdel-Salam, (2013) reported on indoor PM in urban residences in Cairo (Egypt), found that indoor PM levels were compared with the outdoor in all homes, and also tried to understand how the ambient air quality influences the indoor particulate levels in the built infrastructure. Houses had I/O > 1, showing that indoor sources as major IAP contributors. Mutahi et al., (2021) conducted a study on $PM_{2.5}$ and its composition in rural and urban settlements in N'gando

(Kenya). This study found that indoor air quality was worse than outdoor air, especially in rural areas. $PM_{2.5}$ levels were observed significantly higher in indoors than outdoors, with a difference in the orders of magnitude and up to 1000 $\mu g/m^3$ for $PM_{2.5}$ in rural settlements. In Beijing, studies showed that 54% to 63% of the indoor $PM_{2.5}$ originated from outdoors when windows were closed (Huang et al., 2015). Outdoor air infiltration accounted for 40% of the total variability in indoor $PM_{2.5}$ concentration in Dhaka (Yasmin et al., 2024). However, indoor combustion sources, mainly cooking and smoking, are key drivers of non-ambient pollution. In urban environments where clean fuels (like gas or electricity) are predominantly used for cooking, activities like Chinese cooking (e.g., stir-frying, deep-frying) cause acute concentration spikes, significantly increasing PM concentrations in the kitchen by 44% to 159% for a short term (Liu et al., 2020a; Zhao & Zhao, 2020). Notably, non-ambient sources accounted for the majority of indoor UFP contributions in Chinese urban residences (Garbarienė et al., 2022; Matson, 2005; Pekey et al., 2010). Overall, the indoor microenvironment contributes significantly to total personal exposure, estimated to be nearly 75% of total $PM_{2.5}$ inhalation exposure for urban residents in some locations (Chen et al., 2020; Ji & Zhao, 2015; Kalimeri et al., 2019; Yamamoto et al., 2010) .

In contrast, the status of air pollution in rural households is dominated by extremely high indoor concentrations resulting from the widespread, often inefficient, combustion of traditional solid fuels (such as wood, coal, animal dung, and biomass) for cooking and heating (Du et al., 2020; Pervez et al., 2019; Qi et al., 2019). Nearly half of the world's population relies on solid fuels, with reliance reaching almost 98.8% among residents in Ethiopia (Mulat et al., 2024). The resultant household air pollution (HAP) is severe and leads to PM concentrations that consistently exceed safety guidelines prescribed by the WHO (Guercio et al., 2021; Patel et al., 2017; Quansah et al., 2017a). For instance, rural households in Jimma town, Ethiopia, measured median $PM_{2.5}$ concentrations of 294 $\mu g/m^3$ and PM_{10} of 270 $\mu g/m^3$, exceeding the WHO recommended values by more than 18 times (Mulat et al., 2024). In rural Shanxi Province, China, average indoor Elemental Carbon (EC) and Organic Carbon (OC) concentrations showed significant seasonal increases due to coal burning during the heating period, resulting in pollution levels considerably higher than those reported in urban areas (Men et al., 2021). Critically, in rural homes using solid fuels, internal combustion sources are the overwhelmingly

dominant contributors to indoor pollution. In rural coal-using households in China, internal sources contributed approximately 70% of the indoor $PM_{2.5}$ during the heating period, with coal burning for heating alone contributing around 47% (Luo et al., 2022; Men et al., 2021). The severity of exposure is intensely influenced by the kitchen configuration and ventilation. In rural India (Telangana), concentrations of PM_{10} and $PM_{2.5}$ were higher in enclosed indoor kitchens compared to separate outdoor kitchens due to poor ventilation and smaller sizes. Respiratory dosages for women in indoor kitchens were found to be 10.6 times higher for PM_1 and 9.6 times higher for $PM_{2.5}$ compared to outdoor kitchens with the same fuel type (Deepthi et al., 2019). Furthermore, the use of traditional three-stone stoves resulted in significantly higher $PM_{2.5}$, PM_{10}, CO_2, CO, and VOC concentrations compared to improved stoves or electric stoves (Estévez-García et al., 2020; Wallace et al., 2008a, 2008b; Wallace et al., 2004).

The status of air pollution exposure, therefore, reflects distinct challenges based on location, primarily due to differing dominant sources, which necessitate tailored mitigation efforts, all while acknowledging the profound global health burden posed by PM exposure. Globally, HAP from solid fuel use is linked to millions of premature deaths annually from respiratory and cardiovascular diseases (Karaca et al., 2024; Zhang et al., 2021). The primary distinction is that urban IAP is highly susceptible to outdoor ambient conditions, while rural IAP is generally dominated by extremely high-emitting internal household combustion sources (Garbarienė et al., 2022; Lee et al., 2016; Zou et al., 2024). Despite the dominance of specific sources in each setting, both urban and rural environments often report indoor PM levels above WHO guidelines (Matson, 2005; Musyoka & Muindi, 2022a; Sidhu et al., 2017). In urban areas, personal exposure to ambient pollution (which is classified as a carcinogen) should be reduced through measures like installing air purifiers (APs) or home sealing, which can significantly decrease indoor concentrations, especially when ambient levels are high (Moreno-Ríos et al., 2022; Park et al., 2023; Torkmahalleh et al., 2017). Meanwhile, mitigation in rural settings focuses primarily on transitioning households away from solid fuels toward cleaner alternatives like LPG or electricity, which can reduce kitchen $PM_{2.5}$ concentrations by 40%–70% (Men et al., 2021). Other critical rural interventions include promoting the use of improved stoves and ensuring adequate ventilation and separation of kitchens from the main dwelling areas. Because women and children typically spend

the most time in contaminated indoor microenvironments, especially during cooking, they face the highest risk of health impacts in both urban and rural settings (Kaur et al., 2015; Masiwal et al., 2021; Matz et al., 2015; Musyoka & Muindi, 2022a).

2.3 Status of indoor air pollution in kitchens

The status of indoor air pollution (IAP) in kitchens is characterized by extremely high, transient concentrations of particulate matter (PM), volatile organic compounds (VOCs), and other gases, primarily driven by cooking activities (Stabile et al., 2015; Xiang et al., 2021a) . Concentrations frequently far exceed international safety guidelines, posing significant health risks, particularly to cooks and household members in proximity (Alves et al., 2021). Cooking is recognized as a major source of PM, especially ultrafine particles (UFP/$PM_{0.1}$) and fine particles ($PM_{2.5}$) (Jeong, 2015; Wan et al., 2011). In urban residential settings where clean fuels like natural gas or electricity are common, activities such as Chinese cooking (e.g., stir-frying, pan-frying, and deep-frying) cause rapid, massive spikes in pollutants (Lee et al., 2017; Sofuoglu et al., 2015). For instance, Chinese cooking activities can elevate indoor gas species by 21 % - 106 % and PM by 44 % - 159 % compared to background concentrations, with $PM_{2.5}$ concentrations reaching peak values between 189 and 238 $\mu g/m^3$ in some urban homes during cooking (Abdel-Salam, 2021a; S. Liu et al., 2020b; Zhao & Zhao, 2020). In commercial kitchens, the situation is often worse; Chinese stir-frying can yield $PM_{2.5}$ concentrations exceeding 20,000 $\mu g/m^3$. Even when using clean fuels, indoor $PM_{2.5}$ levels in urban Chinese kitchens can exceed the WHO guideline of 25 $\mu g/m^3$ (Lyu et al., 2022). Besides PM, gaseous pollutants like CO, CO_2, NO_2, and TVOCs frequently exceed national standards in poorly ventilated kitchens (Chen et al., 2017a; Du et al., 2017a; Fadel et al., 2022; He et al., 2004; Kim et al., 2018; Liu et al., 2020a).

The severity of IAP exposure in kitchens is highly dependent on the type of fuel used, the cooking method, and the kitchen's physical characteristics, such as size and ventilation (Abhijith et al., 2022; Ashrae, 2021; Francisco et al., 2017; Sun & Wallace, 2021). In rural and low-income settings globally, the use of solid fuels (such as wood, coal, and biomass) for cooking and heating leads to catastrophic pollution levels in kitchens, far surpassing those found in urban homes that use cleaner fuels (He et al., 2023; Musyoka

& Muindi, 2022b; Pervez et al., 2019; Sidhu et al., 2017). For instance, in rural households in Jimma town, Ethiopia, the median $PM_{2.5}$ concentration was 294 $\mu g/m^3$ and PM_{10} was 270 $\mu g/m^3$ (Mulat et al., 2024). In Indian rural households using biomass, concentrations of PM_{10}, $PM_{2.5}$ and PM_1 were significantly higher in enclosed indoor kitchens compared to separate outdoor kitchens due to reduced ventilation and smaller sizes. Specifically, indoor kitchens showed pollutant dosages 10.6 times higher than outdoor kitchens for PM_1. The use of traditional three-stone stoves further exacerbates pollution, resulting in much higher pollutant concentrations than improved or electric stoves (Deepthi et al., 2019; Indu et al., 2024). In contrast, using cleaner fuels like LPG resulted in substantially lower average $PM_{2.5}$ concentrations in kitchens compared to using solid fuels, although even LPG-using kitchens often still exceed WHO guidelines (Gould et al., 2020; Wallace et al., 2004).

Mitigation efforts are crucial as occupants, particularly women and children, spend significant time in these polluted microenvironments (Estévez-García et al., 2020; Stabile et al., 2015). The range hood or exhaust fan is the most common intervention, and studies consistently confirm its effectiveness in pollutant removal. Running a range hood can decrease inhalation exposure to $PM_{2.5}$ in the kitchen by 90 % – 95 % and significantly increase the decay rate of $PM_{2.5}$ (Zhao, et al., 2024; Shi et al., 2023). However, the actual efficacy of exhaust hoods is often compromised in residential kitchens (especially in Chinese residential kitchens), because the measured airflow rates are often much lower (30 %–40% of the nominal rate) due to the lack of sufficient makeup air when doors or windows are closed (Chen et al., 2017, 2018; Du et al., 2017; Zheng et al., 2022). Poor ventilation and kitchen design (such as confined or small, enclosed spaces) are primary factors intensifying pollution levels and health risks, as seen in many Asian residential settings (Jung et al., 2018a, 2018b). Consequently, for improved health outcomes, measures like transitioning to cleaner fuels in rural areas, ensuring proper ventilation through exhaust fans, and utilizing air curtains or purifiers in urban settings are recommended to effectively manage and reduce high-peak, short-term exposures generated in the kitchen (Adedeji, 2022; Arora et al., 2020; Chowdhury et al., 2019; Jung & Abdelaziz Mahmoud, 2023; Kuma & Abbass, 2023; Thakur & Patel, 2024a; Zhang et al., 2021).

Among these, cooking and combustion-related activities (for instance, using an electric stove or oven, smoking, or lighting a candle or match) are identified as the most significant UFP sources (Afshari et al., 2005). These activities can generate particles at a rate of 2.02×10^{12} #/min, ranging from 7.86×10^{12} #/min to 5.25×10^{13} #/min (He et al., 2004; Hussein et al., 2006). Zhang et al. (2010) discovered that individuals are subjected to significantly elevated levels of UFP during cooking, with concentrations reaching up to 550 times higher than ambient levels.

2.4 PM and PNC measurements-based methods of cooking

Apart from cooking fuel, cooking oil, the cooking method, utensils used for cooking and the cooked dish also play a major role in contributing to the indoor pollutant levels in kitchens. And the methods of cooking vary from extreme cold and hot to moderate geographic regions within the country to continents across the world. Numerous studies have investigated indoor air quality and the generation of air pollutants (PM, PNC, and VOCs) related to cooking activity.

Amouei Torkmahalleh et al., (2017) conducted a controlled investigation on five PM size fractions ranging from 3.3 µm to less than 0.43 µm emission during grilling low-fat ground beef in a campus house using an electric stove with no mechanical or natural ventilation. Elements composition analysis showed that Fe (0.42 mg m^{-3}), Ti (0.27 mg m^{-3}), Sr (0.27 mg m^{-3}), Ba (0.24 mg m^{-3}), and Li (0.23 mg m^{-3}) were the five most abundant trace elements in the PM produced during grilling ground beef. Pb, Mn, and V concentrations were found to be greater than the World Health Organization (WHO) exposure limit. Amouei Torkmahalleh et al., (2018) also conducted a study on the contributions of electric burners, cooking pans, meat, and salt to PM emissions during grilling at two places of Nazarbayev University, Kazakhstan. The study investigated PM emission during grilling ground beef in Kazakhstan, implemented a controlled experimental protocol to separate the contributions of the burner, empty pan, and meat, and found that a frequently used electric burner showed an almost insignificant contribution to grilling PM number and mass concentrations compared to the emissions from the pan or the meat itself. The research demonstrated that the number of ultrafine particles (UFP) emitted from the heated detergent-washed pan was as high as those

emitted from heated meat. Chen et al., (2018) conducted a study and determined the emission rates (ERs) of multiple pernicious air pollutants, including $PM_{2.5}$, UFPs, and VOCs (formaldehyde, benzene, toluene), generated during typical Chinese residential cooking. The study considered five major factors like cooking method, ingredient weight, type of meat, type of oil, and meat/vegetable ratio. The measured mean emissions were 2.0 ± 3.0 mg/min for $PM_{2.5}$ and 9.1 ± 6.9 × 10^{12} #/min for UFPs. Formaldehyde and TVOCs had mean ERs of 1.2 ± 0.7 mg/min and 1.3 ± 1.3 mg/min, respectively. Cooking method was the most influential factor for the emission rates of most pollutants ($PM_{2.5}$, UFPs, formaldehyde, TVOCs, and benzene). Stir-frying and pan-frying generated significantly more $PM_{2.5}$, UFPs, formaldehyde, and TVOCs than boiling and steaming.

A study conducted by Naseri et al., (2019) investigated the neurological effects of indoor aerosol generated from frying ground beef in sunflower oil on an electric stove without mechanical ventilation. UFPs, particulate matter (PM), CO_2, indoor temperature, RH, oil, and meat temperatures were monitored continuously throughout the experiments. The UFP peak concentration was recorded to be approximately 2.0×10^5 particles/ cm^3. The laboratory investigation done by Lee et al., (2020), on characterizing air pollutants from grilling pork (pork belly and marinated ribs) found that fine particulate matter ($PM_{2.5}$) accounted for a high proportion of the total PM emitted, ranging from 96% to 99% of total suspended particles (TSP). Specifically, pork belly generated significantly higher $PM_{2.5}$ emission factors (754 mg-PM·kg-meat^{-1}) compared to marinated pork ribs (137 mg-PM·kg-meat^{-1}), a difference likely driven by pork belly's higher fat content and the suppressive effect of the marinade. In terms of odorous compounds, ammonia and acetaldehyde were quantitatively the most common emissions, but aldehydes were the most significant contributors to the total odor intensity. Analysis of volatile organic compounds (VOCs) showed benzene, vinyl acetate, and hexene were most abundant for pork belly, while butane, vinyl acetate, and n-dodecane dominated emissions from marinated ribs. Won et al., (2020) studied the size distribution of 60–560 nm particles released during 1 hour of cooking with different methods (roasting, frying, and boiling) and found that roasting produced the highest particle number concentration (approximately 2.5 × 10^6 cm^{-3}), followed by frying and then boiling. Particles in the 100–180 nm range accounted for the largest proportion, though frying yielded the highest concentration of particles below 100 nm. Roasting showed a rapid increase in particles

below 180 nm within the first 10 minutes, with larger particles increasing after 40 minutes, while frying and boiling exhibited a gradual increase over time.

A study by Alves et al. (2021) investigated chemical and toxicological profiling of emissions generated from cooking, especially in modern kitchens where different dishes of the Latin cuisine (fried horse mackerel, stuffed chicken, and grilled/fried pork) were prepared using an electrical cooktop and range hood, revealed significant indoor air quality issues, despite the use of clean cooking facilities. Different sizes of particulate matter (PM_{10}, $PM_{2.5}$, and PM_{1}) and total volatile organic compounds (TVOCs) were continuously measured, and it was found that fine particles comprised more than 86% of the PM_{10} mass concentrations. PM_{10} emission rates ranged from 124 to 369 μg min^{-1}. Critically, the PM_{10} emitted when grilling pork was classified as "very toxic" and contributed to non-negligible cancer risks that exceeded the acceptable limit for typical usage patterns, while samples from the other dishes were classified as "toxic"; this toxicity positively correlated with heavier PAHs, glyceridic compounds, di-acids, and amino acids. A monitoring campaign was conducted by Lyu et al. (2022) across six types of commercial kitchens (Teppanyaki, Chinese, Western, Fried Chicken, Barbecue, and Hotpot) in Chinese cities to measure real-time PM2.5 concentrations and emission rates, along with a health risk assessment for chefs. The findings revealed that $PM_{2.5}$ concentrations in all tested commercial kitchens far exceeded the WHO-recommended mean annual indoor limit of 5 μg/m^3, leading to greater health risks for kitchen workers. The teppanyaki kitchen posed the highest overall exposure risk, having the highest mean $PM_{2.5}$ concentration in the breathing zone (850.4 ± 533.4 μg/m^3) and resulting in the highest annual $PM_{2.5}$ inhalation rate for chefs. However, the real-time data showed that the highest peak concentrations (reaching over 20,000 μg/m^3) and the highest single mean emission rate (9.98 mg/min for stir-frying cabbage) occurred during Chinese stir-frying, demonstrating that concentrations varied greatly depending on the dish and cooking stage (Lyu et al., 2022). A monitoring campaign utilizing validated low-cost sensors in five UK student studio flats identified domestic cooking as a major source of indoor particulate matter (PM_{10} and $PM_{2.5}$). PM concentrations varied significantly by method, ranking from highest to lowest emissions: deep-frying (PM_{10} median 151 mg m^{-3}) and stir-frying (PM_{10} median 63 mg m^{-3}) significantly exceeded water-based methods (boiling and steaming), with oil-based methods causing approximately six times the

emission rates of water-based methods. Oil-based concentrations often exceeded recommended air quality standards. Crucially, the use of kitchen extractors proved to be an effective intervention, showing removal efficiencies between 10.5% and 63.0% and accelerating pollutant decay, which significantly shortened the PM residence time (the duration pollutants remained in the air). For deep-frying and stir-frying, using the extractor cut the time taken for PM_{10} to drop below the WHO health limit (45 mg m^{-3}) by 47.1% to 75.5% (Tang & Pfrang., 2023a). A study by Karaca et al., (2023) assessed indoor $PM_{2.5}$ levels generated by cooking activities in typical, poorly ventilated Kazakh households, utilizing a combined approach of monitoring (low-cost sensors and personal samplers) and modeling (USEPA's IAQX v1.1). The study found that $PM_{2.5}$ concentrations during cooking ranged from 13 to 266 μg/m^3, resulting in an overall daily average of 79.7 μg/m^3 in the sampled homes, which significantly exceeds the WHO guideline of 25 μg/m^3. Factors such as kitchen size, air exchange characteristics, and the type of food and cooking style influenced these concentrations. The modeling revealed that cooking activities contributed highly variable percentages to overall indoor $PM_{2.5}$, ranging from 9% to 94%. Importantly, cooking was identified as a major contributor to indoor $PM_{2.5}$ during the non-heating period of the year, whereas outdoor pollution and ventilation practices played the primary role during the colder heating period (Karaca et al., 2023).

A comparative study conducted by Tang et al., 2024 in a controlled research kitchen investigated emissions from five methods of cooking chicken breast (pan-frying, stir-frying, deep-frying, boiling, and air-frying), finding that oil-based methods generated substantially higher levels of both PM and VOCs than water-based ones. Pan-frying resulted in the highest peak emissions for both $PM_{2.5}$ (median 92.9 μg m^{-3}) and increased VOCs (median 260 ppb). While the cooking temperature was identified as the key factor positively correlated with the emission strength of both pollutants, the amount of oil used demonstrated contrasting effects: it was negatively correlated with PM concentrations but generally positively correlated with VOC mixing ratios (Tang et al., 2024). Recently, Zhang et al., (2024) conducted the study to see the impact of Chinese catering enterprises on the workers in the Beijing-Tianjin-Hebei region. Indoor monitoring in kitchen breathing areas showed that TVOC concentrations in several cuisines, including Barbecue, Sichuan and Hunan Cuisine, Snacks, and Noodles, exceeded the Chinese

indoor standard limit (600 μg/m³), with Hazardous VOCs ranging up to 53 - 357 μg/m³. Crucially, the non-carcinogenic risk was primarily driven by acrolein, which accounted for 50.9% - 99.5% of the Hazard Index (HI), and the total Incremental Lifetime Carcinogenic Risk (ILCR) exceeded the acceptable threshold of 1.00×10^{-6} for all tested cuisines, largely attributed to 1,3-butadiene, 1,2-dichloroethane, acetaldehyde, benzene, and 1,2-dichloropropane (Zhang et al., 2024). Zeng et al., (2025) conducted a comprehensive study in eight Japanese apartments, found that cooking is the primary indoor activity affecting air quality, increasing $PM_{2.5}$ mass concentration by 2–96 times and the Indoor/Outdoor (I/O) ratio to eight, which is 3–4 times higher than other activities like walking or vacuuming. Cooking-emitted particles, predominantly in the high-risk 0.3–1.0 μm size range, spread extensively across adjacent spaces, affecting dining rooms and even bedrooms. Frying and baking produced the highest $PM_{2.5}$ concentrations (exceeding 55 μg/m³), sometimes reaching 140 μg/m³, which surpasses the Japanese guideline of 35 μg/m³ in 31% (five of 16) of the cases. Crucially, the use of range hoods significantly enhanced particle removal efficiency by 2 - 3 times for 0.3 - 3.0 μm particles, showing a superior ability to remove smaller particles in the 0.3 - 0.5 μm range by 3 - 9 times.

2.5 Ultrafine measurements in the cooking environment

Cooking activities are found in residential areas, commercial restaurants, and open cooking (Xiang et al., 2021b). Cooking activities with solid fuels and biomass are known for emitting different types of pollutants, but the gas fuels and electric stoves are used widely globally, and their emissions are known less (Tang and Pfrang, 2023). During the cooking process, the nanoparticles are formed due to the incomplete combustion of food, oil, and fuel. Studies revealed that during the cooking process, the concentration of the PNC increases around 1 to 30 times compared to the background, which influences the indoor PNC concentration by 15 times (Pokhrel et al., 2015b). During the cooking process, such as steaming, frying, boiling, and the type of meal cooked, such as vegetables, rice, and meat, also influences the particle number concentration. Stir frying increases particle concentration about 85 times higher than the normal concentration (Lenz et al., 2023). During the cooking process, the concentration increases from 9.1×10^3 $\#cm^{-3}$ to 7.7×10^5 $\#cm^{-3}$. Frying of chicken increases particle concentration from 3.7×10^3

#cm^{-3} to 3.6×10^{5} #cm^{-3} rapidly (Sun and Singer, 2023). The concentration of the nanoparticles also changes based on the different cooking styles, such as Indian, Italian, Chinese, and American cooking activities (K. Kang et al., 2023). The stir-frying method is considered to be one of the most nanoparticle-emitting cooking methods (Zhang et al., 2021). During cooking hours, the concentration in households increases by 10-fold times in the living room and 20 to 40 times in the kitchen (Kuye and Kumar, 2023). Summary of different cooking-related studies shows the concentration of the cooking activities varies between a concentration of 1.5×10^{6} cm^{-3} to 5.6×10^{6} cm^{-3} concentration of particles (Gabdrashova et al., 2021). The emission rates during cooking vary between 0.35×10^{11} min^{-1} and 7.3×10^{11} min^{-1}. Emission rates for stoving activity are 51.4×10^{11} min-1 and for toasting, it was 16.7×10^{11} min^{-1}. During cooking activity, the nanoparticle emissions vary based on the type of fuel used, food type, cooking method, and type of cooking stoves (Delapena et al., 2018). Gas-based cooking and electric stoves both produce a higher number of nanoparticles at high-temperature cooking (Gould et al., 2020b). Compared to the frying technique, the boiling way of cooking was found to emit fewer particles. All the different types of cooking emit particles in the size range of particles < 100 nm (Kota et al., 2022). The cooking activity in urban regions is also one of the major sources of urban nanoparticles concentration from the non-exhaust sources, which has an influence on both indoor and outdoor nanoparticles concentration (Zhang et al., 2022).

2.6 PNC and PM measurements due to tobacco smoking

Tobacco smoking emits different types of toxic substances and pollutants, which cause serious health effects for active and passive smokers (Mosonik et al., 2019). In Italy, the concentration of the nanoparticles reduced from 7.7×10^{4} #cm^{-3} to 3.8×10^{4} #cm^{-3} when smoking was banned in a public building (Wu et al., 2021). Water pipe smoking emits particle numbers 5 times higher than a normal cigarette (Fawzy et al., 2024). Detailed study reveals that one cigarette can typically produce particles of about ~ 10^{11} to 10^{12} #cm^{-3} particles min^{-1} or ~10^{12} #cm^{-3} particles $cigarette^{-1}$ (Schraufnagel, 2020). The mean concentration of particle number emitted during the smoking of five different brands of cigarettes was $3.36\pm0.34\times10^{11}$ #cm^{-3}, and similar studies also report the concentration of about 3.8×10^{11} #cm^{-3}. Total particles emitted by a single cigarette concentration range from $0.64\pm0.19\times10^{12}$ particles $cigarette^{-1}$. Few studies report elevated concentrations of

nanoparticles in the indoor environment, which is 2.7 $\times 10^4$ cm^{-3}, which is 1.5 times higher than the background concentrations. Another study reports elevated concentration of 2 $\times 10^5$ cm^{-3} to 3.5$\times 10^6$ cm^{-3}. Studies also found that the peak concentration attained during smoking lasts for 20 minutes, and it takes 300 minutes to attain the original background concentration (Fuller et al., 2022). The results suggest that the smoking nanoparticle emission not only releases different types of toxic substances into the atmosphere but also emits higher concentrations of atmospheric nanoparticles, which are very harmful, especially in indoor environments.

2.7 Different emissions from candle burning in indoor environments

Emissions from burning candles have their subsequent impact on indoor air quality (IAQ) and potential human health risks. Researchers investigate the emission of various pollutants from candles, including volatile organic compounds (VOCs), nitrogen oxides (NOx), and particulate matter ($PM_{2.5}$, ultrafine particles), exploring how factors like wax type, fragrance, and burning conditions affect these emissions. (Derudi et al., 2014; Kapalo et al., 2022; Salthammer et al., 2021) The comprehensive analysis of candle emissions highlights significant and avoidable risks posed by certain types of candles, particularly those with lead-core wicks, as well as widespread contamination from typical scented paraffin candles (Massoudi & Hamidi, 2017; Wasson et al., 2002). Candles with lead metal wick cores were found to emit lead into the air at a mean rate of 770 µg Pb/h, ranging up to 1700 µg/h, with a 38 cm candle capable of emitting approximately 104,000 µg of lead over its lifespan. The lead particulate, identified as Sodium Lead Carbonate Hydroxide [$NaPb_3(CO_3)_2OH$], is sub-micron in size and likely easily absorbed in the lungs and gastrointestinal tract (Van Alphen, 1999). Exposure modeling demonstrated that daily burning of a single lead-wick candle in a poorly ventilated room could elevate a child's blood lead levels (PbB) by a minimum of 24 to 40 µg/dl, potentially causing PbB levels to exceed the critical 10 µg/dl safety limit (Nazir et al., 2024; Salthammer et al., 2021). Separately, studies focusing on paraffin and scented candles, which are often composed of petroleum derivatives, revealed emissions of various hazardous materials, including volatile organic compounds (VOCs) such as formaldehyde, acetaldehyde, acrolein, naphthalene, benzene, and toluene (known carcinogens) (Massoudi & Hamidi, 2017). These pollutants are associated with serious health issues, including cancer,

asthma, and respiratory problems (Kristensen et al., 2023; Salthammer et al., 2021; Yun et al., 2025).

The studies also provided detailed insights into combustion byproducts and particle dynamics. The presence of fragrances significantly impacts emissions, as scented candles consistently generate higher levels of VOCs than unscented ones (Nazir et al., 2024; Salthammer et al., 2021; Yun et al., 2025). In one investigation comparing consumer choice, higher-priced scented candles accumulated TVOC concentrations at an order of magnitude higher than similarly scented, lower-cost candles (Jadach, Crystal., 2025). Regarding combustion gases, testing confirmed that burning a candle produces a substantial amount of CO_2, with a single measured candle generating 5.28 mg/s of CO_2, which represents about 54% of the CO_2 produced by a sedentary adult human (Kapalo et al., 2022). Candle burning also generates NO_2, UFPs, and fine particulate matter ($PM_{2.5}$ and PM_1) that, due to their size, disperse extensively and remain elevated at distances up to 6 meters from the source (Andersen et al., 2021; Derudi et al., 2014). Furthermore, one novel investigation found that burning scented candles significantly altered the indoor airborne microbiome, leading to a dramatic increase in nano-sized bacterial extracellular vesicles (n-ABE) of *Phyllobacterium myrsinacearum*, a change that may have potential health implications (Yun et al., 2025). The overall findings support the conclusion that regular candle burning, especially under stressed conditions or in poorly ventilated spaces, presents risks that necessitate improved ventilation and careful consumer choice regarding candle composition and wick material (Derudi et al., 2014; Massoudi & Hamidi, 2017; Bansal, 2024; Rodríguez et al., 2024).

2.8 PNC and PM emission from burning incense sticks in indoor

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Studies investigating indoor air pollution sources consistently confirm that combustion activities, such as cooking, cigarette smouldering, and incense burning, are important sources of particulate matter in residential environments Fiore et al., 2023; Wang, et al., 2024; Wong et al., 2020). Incense sticks are used during religious rituals, meditation centers, and in gyms. Incense burning is confirmed as a significant source of indoor air pollution, generating complex mixtures of particulate matter (PM) and gaseous pollutants that pose multiple health risks. Key emissions include UFPs, $PM_{2.5}$, PM_{10} and Volatile

Organic Compounds (VOCs) such as benzene, formaldehyde, acetaldehyde, and acrolein (Wong et al., 2020; Wu et al., 2012). Concentrations often greatly exceed safety limits; for instance, PM_{10} levels in temples have reached up to 2184 μg/m³, substantially surpassing the Indian ambient air quality standard of 100 μg/m³ (Goel et al., 2017). Furthermore, short-term peak concentrations of benzene and formaldehyde generated by some incense products notably exceed WHO guideline values, with benzene levels found to be higher than the genotoxic carcinogen's reference concentration by factors ranging from 100 to 3600 times (Silva et al., 2021). The concentration and type of pollutants vary based on the incense form, with cone-type incense showing a greater probability of being more pollutant than stick type, and are also influenced by environmental factors like low atmospheric pressure, which enhances gas diffusion, and higher ambient temperature, which increases the combustion rate and pollutant concentration. A research study conducted by Wu et al. (2012) on emission rates from incense burning and ultrafine particles (UFP) reported a mean value of $0.44 \pm 0.33 \times 10^{11}$ particles min^{-1}. In residential houses in Hanoi, Vietnam, incense burning events significantly affected indoor air quality, increasing the geometric mean of indoor $PM_{2.5}$ concentration by 120% after adjusting for other factors, and generating peak concentrations up to 825.5 μg/m³ (L. K. Tran et al., 2021). Furthermore, research into gaseous emissions revealed that incense burning releases dangerous substances, including the carcinogens benzene and formaldehyde, which presented worrying exposure levels often exceeding WHO guideline values(Di Fiore et al., 2023; Gupta et al., 2023).

The inhalation of incense smoke is associated with numerous adverse health outcomes, including airway dysfunction, acute irritative respiratory symptoms in temple workers, and cough symptoms in children (Chuang et al., 2011; Lin et al., 2008; Rana, 2018). Analysis of allergenic terpenol compounds found that while Thai incense powder contained higher total concentrations, Taiwanese incense smoke had significantly higher $PM_{2.5}$ terpenol emission factors, primarily driven by geraniol (the most allergenic terpenol), which constituted 66.3% – 83.5% of terpenols in the smoke $PM_{2.5}$ and whose high concentration is created specifically through the combustion process (Kuo & Tsai, 2017; L. K. Tran et al., 2021). Crucially, regular indoor incense burning is detrimental to cognitive and brain health in older adults, showing a negative association with global cognition, executive functions, visuospatial functions, and memory observed over three

years (Wong et al., 2020). Neuroimaging revealed that users exhibit decreased functional connectivity in key Default Mode Network (DMN) areas. While some studies link incense burning to elevated cord blood IgE levels and increased cancer risk (e.g., childhood leukemia) due to carcinogens and mutagenic components, other epidemiological findings report conflicting results, suggesting that confounding factors like diet may mask negative health associations (Lin et al., 2008; Rana, 2018; Wong et al., 2020). To mitigate risks, researchers strongly recommend employing good ventilation to dilute indoor air pollutants and reduce exposure.

2.9 Indoor air quality in educational buildings (Schools/Universities)

Indoor air quality is a crucial component of a human's life. School microenvironments play a vital role since children, adolescents, and adults spend 5-7 hours in school on a daily basis, and they deserve particular attention, which must be clean and healthy. Indoor Air Quality (IAQ) in schools, emphasizing that children (aged 3–14) spend up to 90% of their day indoors, making them highly susceptible to environmental pollutants that can affect their health, productivity, and academic performance. In academic institutions/schools, students spend time in different microenvironments of the school, like the laboratory, classes, the library, the sports complex, etc. This results in exposure variation of indoor pollution with respect to the microenvironment and locations of schools. A study was performed by Mazaheri et al., (2014) to observe the exposure of UFPs to urban Australian State school children and reveal significant air pollution exposure and the efficacy of various control and mitigation strategies. Studies in Australia found that the home microenvironment contributes the majority (55.3%) of children's total daily alveolar particle dose, although activities like outdoor time at school and home cooking/eating had the highest dose relative intensities. Critically, monitoring in London schools showed that indoor air quality (IAQ) is severely degraded during occupied hours due to high occupancy levels increasing PM_{10} concentrations by up to 145% and leading to CO_2 concentrations frequently breaching the recommended 800 ppm due to occupant respiration and inadequate ventilation rates. Mitigation strategies were proven effective: a green screen reduced outdoor particulate matter (PM) concentrations by up to 44%, air purifiers reduced indoor PM_{10} by 49% - 57%, and the 'school street' initiative reduced local traffic-related PM by 30% - 36% during pick-up times. Research on Detached

Mechanical Ventilation (DMV) systems demonstrated that CO_2 threshold-dependent control logics are most effective, maintaining high IAQ (CO_2 below 800 ppm during occupied hours in simulation) while leading to significant energy savings compared to constant airflow strategies.

Reche et al., (2014) investigated outdoor and indoor Ultrafine Particle (UFP: $N_{10–700}$) number concentration and average diameter at 39 primary schools in Barcelona, Spain. A major finding highlighted the significant influence of traffic emissions on children's exposure, noting that indoor and outdoor UFP levels were approximately 40% higher on average at schools located nearer heavy traffic. A significant increase in indoor particle concentration was detected after school hours, reaching concentrations up to three times higher than outdoor levels, likely associated with cleaning activities. Gennaro et al., (2014) analysed pollutant concentrations result from a combination of indoor sources and the intrusion of outdoor pollution. Internal sources, such as building and furnishing materials, cleaning activities, and occupant movement, significantly contribute to the indoor levels of Formaldehyde and Carbonyl compounds, Volatile Organic Compounds (VOCs), and coarse Particulate Matter (PM_{10}) through dust resuspension. Fine pollutants like Ultrafine Particles (UFP) and gaseous pollutants like Nitrogen Oxides (NOx), and Ozone (O_3) primarily intrude from outdoor traffic or urban pollution, generally showing indoor/outdoor (I/O) ratios near or below one due to deposition indoors. A critical determinant of poor IAQ is inadequate ventilation, which is often signalled by high levels of carbon dioxide (CO_2), sometimes peaking up to 4,000 ppm. Hassanvand et al., (2015) investigated and characteristics of polycyclic aromatic hydrocarbons (PAHs) and metal(loid)s in size-fractionated indoor and outdoor particulate matter (PM_{10}, $PM_{2.5}$, and PM_1) in a school dormitory in Tehran. A key finding was that the annual levels of indoor and outdoor PM_{10} and $PM_{2.5}$ were much higher than the guidelines issued by the World Health Organization (WHO). Chemical analysis showed that the most abundant metal(loid)s were Si, Fe, Zn, Al, and Pb, with mineral elements (Al, Si, Fe) mainly stemming from local soil resuspension and road dust, while trace metal(loid)s was linked to anthropogenic sources. The PAHs concentrations were predominantly bound to the $PM_{2.5}$ fraction (83 – 88%), which can penetrate deep into the alveolar regions of the lungs. Indoor/outdoor ratios generally showed that particulate metal(loid)s and PAHs had infiltrated from the outdoor air into the indoor environments. Madureira et al., (2016)

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investigated the sources and health hazards of air pollutants in 73 naturally ventilated primary school classrooms in Porto, Portugal. Inadequate ventilation was a widespread issue, evidenced by 86% of classrooms having median CO_2 concentrations exceeding 1000 ppm during occupation, a problem linked to occupant behavior (reduced airing) and high density. Indoor air quality was further compromised by Particulate Matter (PM_{10}), where median indoor levels significantly exceeded outdoor levels and WHO guidelines, suggesting strong influence from indoor sources like particle resuspension and building characteristics (e.g., damp spots), demonstrated a potentially high health risk for school children. The study, conducted in a Portuguese pre-school by Oliveira et al., (2016) , revealed that Total Volatile Organic Compounds (TVOCs) highly exceeded the limit by 3.3 times. Indoor particulate matter composition showed that crustal elements (Ca, Na, Al, K) were the most abundant (82 – 84% of total elements), mainly resulting from resuspension of mineral dust and children's activities. Conversely, significantly enriched trace metals (e.g., Ni, Cu, As, Zn, Cd, Sn, Sb, and Pb) were predominantly associated with outdoor anthropogenic emissions, particularly traffic. Wang et al., (2019) investigated $PM_{2.5}$ and associated heavy metals in college student dormitories in Nanjing, China. While the average indoor $PM_{2.5}$ concentration was observed to be ~ 61 $\mu g \cdot m^{-3}$. Chromium (Cr), exhibited extreme contamination. The heavy metals mainly originated from a mixture of coal combustion and industrial sources (~71%), vehicle exhausts and traffic-related road dust (11%), and fugitive emissions ascribed to student activities (5.68%), with Nickel (Ni) specifically linked to indoor student activities. Despite contamination, the health risk assessment determined that both carcinogenic and non-carcinogenic risks via inhalation were within safe limits for the students, although the risk was ~3–7 times higher in the dormitory due to the extensive time students spent indoors.

Kalimeri et al., (2019) quantified the Indoor to Outdoor (I/O) ratios for $PM_{2.5}$ and NO_2 in school microenvironments across numerous European countries to study the influence of outdoor air quality on indoor exposure. The sources explicitly state that the high $PM_{2.5}$ I/O ratios in schools (with a mean of 1.44 ± 1.01 and 59% of ratios exceeding unity) are most likely caused by the resuspension of dust within the school environment. This dust resuspension is attributed to the students' activities and constant movement, especially given that the raw data were retrieved from primary schools and kindergartens, where

activities often involve crafting. This demonstrates the presence of relatively significant indoor $PM_{2.5}$ sources generated by occupant activity in schools. Sánchez-Soberón et al., (2019) measured and characterized coarse ($PM_{10-2.5}$), accumulation mode ($PM_{2.5-0.25}$), and quasi-ultrafine ($PM_{0.25}$) particulate matter (PM) collected inside twelve educational centers in Tarragona County, Spain, during cold and warm seasons to evaluate respiratory and digestive health risks for children. Average PM levels were higher during the cold season. Coarse PM was found to be highly influenced by mineral matter, while organic matter and elemental carbon (OM + EC) were prevalent in the quasi-ultrafine fraction ($PM_{0.25}$). The fine fractions ($PM_{2.5-0.25}$ and $PM_{0.25}$) were the main contributors to both digestive and respiratory risks. Slezakova et al., (2019) characterized ultrafine particle (UFP) exposure in various indoor and outdoor microenvironments within 20 primary schools in Oporto, Portugal, and results demonstrated large temporal and spatial variations in UFP concentrations. Median UFP levels in classrooms (1.56×10^3-16.8×10^3 # cm^3) were typically lower than concurrent outdoor levels (1.79×10^3- 24.1×10^3 # cm^3), indicating that outdoor emissions significantly contributed to indoor UFP (I/O ratios of 0.30–0.85). Among the indoor microenvironments assessed, canteens exhibited the highest UFP levels, particularly in schools where cooking was conducted on the premises, which also led to significantly elevated UFP in nearby classrooms. Conversely, libraries reported the lowest UFP concentrations.

The study performed by Carrion-Matta et al., (2019) characterized indoor and outdoor $PM_{2.5}$ sources across 32 inner-city school classrooms in the Northeastern U.S. over three seasons (fall, winter, and spring). Average indoor $PM_{2.5}$ concentrations (5.2 $\mu g/m^3$) were found to be lower than outdoor concentrations (6.5 $\mu g/m^3$), resulting in a mean I/O ratio of 0.8, confirming the penetration of outdoor pollution indoors. The major identified indoor sources were secondary pollution (41%) and motor vehicles (17%), followed by biomass burning (15%), Ca rich particles (12%), soil dust (6%), and marine aerosols (4%). Source contributions varied seasonally, indicating different scales of influence: secondary pollution and marine aerosols were regional sources with the highest contributions in the spring, driven by higher infiltration, whereas motor vehicles and biomass burning were categorized as local sources in the vicinity of the schools, showing higher contributions during the fall and winter. The European SINPHONIE (School Indoor Pollution and Health: Observatory Network in Europe) study, conducted by

(Baloch et al., 2020), characterized IAQ and comfort parameters in schools across 23 European countries, involving school children, to determine their association with health disorders. The study found that children were frequently exposed to indoor air pollutant concentrations that exceeded recommended standards, with levels of $PM_{2.5}$, radon, and carbon dioxide CO_2 noted as particularly high. Key findings showed that exposure to higher levels of $PM_{2.5}$, benzene, limonene, ozone, and radon were significantly associated with increased odds of suffering from various health outcomes, including upper airways, lower airways, eye, and systemic disorders. Slezakova et al., (2019) characterized ultrafine particle (UFP) exposure in various indoor and outdoor microenvironments within 20 primary schools in Oporto, Portugal, and results demonstrated large temporal and spatial variations in UFP concentrations. Median UFP levels in classrooms (1.56 x 10^3-16.8 x 10^3 # cm^3) were typically lower than concurrent outdoor levels (1.79 x 10^3-24.1 x 10^3 # cm^3), indicating that outdoor emissions significantly contributed to indoor UFP (I/O ratios of 0.30 - 0.85). Among the indoor microenvironments assessed, canteens exhibited the highest UFP levels, particularly in schools where cooking was conducted on the premises, which also led to significantly elevated UFP in nearby classrooms. Conversely, libraries reported the lowest UFP concentrations.

Martins et al., (2020) characterized size-segregated particulate matter (PM) inside urban homes and schools in Lisbon, Portugal, finding that children were exposed to significantly higher PM concentrations in schools than in homes. The PM mass size distribution differed by location: in schools, the coarse fraction ($PM_{2.5 - 10}$) dominated (28–59% of PM_{10} mass), attributed primarily to particle resuspension from high human occupancy and mineral matter, including sources like chalk use. Abhijith et al., (2022) investigated air pollution, ventilation, and indoor air quality in three primary schools in London, focusing on understanding the extent of pollution and determining effective mitigation strategies. Findings of the study showed that high occupancy levels significantly impacted indoor air quality, increasing PM_{10} concentrations by up to 145% and CO_2 by up to 83% due to student activity and respiration, especially in classrooms with poor ventilation. Fine particulate matter $PM_{2.5}$ and PM_1 concentrations were mainly influenced by outdoor levels. The assessment of mitigation measures showed that a green screen along the school boundary reduced outdoor particle levels by up to 44% during perpendicular wind conditions. Installing air purifiers in a classroom resulted in

substantial reductions, lowering indoor PM_{10} concentrations by an average of 49–57%. Furthermore, the implementation of a school street (car-free hours) reduced outdoor PM concentrations by up to 36% during pick-up time. Shree et al., (2024) reviewed indoor air quality (IAQ) in schools, found that children are highly vulnerable to poor conditions because they spend extensive time in high-occupancy environments and breathe more air per unit of body weight. The primary indoor air pollutants identified—including high levels of CO_2, VOCs, and PM are linked to adverse health effects such as lethargy, asthma, cardiovascular disease, and reduced student performance. Deterioration of IAQ is driven by both spatial factors (like inadequate ventilation and proximity to traffic, which increases PM) and non-spatial factors (like high occupant density and the use of chalkboards, which contribute to PM_{10} concentration. The study advocates for mitigation strategies, including enhancing ventilation rates, utilizing high-efficiency filters (like HEPA or MERV 13), and controlling indoor sources by replacing materials such as chalkboards and certain insulating materials. Agarwal et al., (2024) assessed the Indoor Air Quality (IAQ) across 12 laboratories in an Indian engineering institute by monitoring Particulate Matters ($PM_{1.0}$, $PM_{2.5}$ and PM_{10}), TVOC, Formaldehyde, and CO_2. Elevated concentrations of all pollutants were observed in several labs. The study attributed the presence of IAPs primarily to nearby outdoor activities, sweeping and dusting, wood furniture, paints, and poor ventilation. Statistical analysis confirmed that Particulate Matter of all sizes generally shared a common source within each lab, and that TVOC and HCHO were highly positively correlated, suggesting a unified source of emission like wooden furniture and paints. The laboratories showing high coarse particle concentrations were linked to particle re-suspension and outdoor dust, while CO_2 concentrations often indicated reduced air exchange due to closed environments. Chiesa & Vigliotti, (2024) studied indoor and outdoor Carbon Monoxide (CO) concentrations in naturally ventilated rooms in central Shanghai during the summer. The results showed a positive correlation between indoor and outdoor CO concentrations. The monitoring data indicated that the I/O ratios of CO concentrations were less than, but close to, 1 in the natural ventilating rooms where internal CO sources were negligible. Diurnal cycles at Site 1 (near a central traffic artery) showed two CO concentration peaks on weekdays (8:00–10:00 and 17:00–19:00), which was attributed to morning and evening traffic; Site 2 (far from streets) generally showed lower concentrations. Nath et al., (2025) conducted

a study across 19 schools in Tezpur, Northeast India, assessed indoor air quality and settled dust, revealing that average indoor $PM_{2.5}$ concentrations significantly exceeded the WHO 24-hour recommended guideline levels, which were within established standards, indicating adequate ventilation. Analysis of settled dust showed moderate contamination. Elements like Zn, Pb, Cd, and Ni were highly enriched due to anthropogenic sources, particularly in urban schools.

After going through all the studies, chalk, dusting and student movement, activity along with poor ventilation, resulted in higher concentrations of particulate matter, and the influence of the location of the school, located especially near a major traffic intersection, also infiltrated highly and resulted in a lower I/O ratio and high occupancy of students with poor ventilation turned out to high concentrations of CO_2 in schools.

2.10 Indoor air quality in hospitals and healthcare facilities

The cumulative findings across various studies underscore that IAQ in healthcare and care facilities is frequently compromised by high concentrations of numerous chemical, particulate, and biological contaminants, often exceeding safety guidelines established by international bodies (Ibrahim et al., 2024; Loureiro et al., 2025; Bansal, 2024; Parkavi et al., 2025; Reddy et al., 2021). Particulate matter (PM) consistently presented concentration levels above recommended limits; for instance, a university hospital in Saudi Arabia reported average indoor PM_{10} levels of 255 µg/m³ and Total Suspended Particulates (TSP) of 1845 µg/m³, both exceeding the Air Quality Guidelines of 150 µg/m³ (El-Sharkawy & Noweir, 2014) . Similarly, 24-hour average $PM_{2.5}$ concentrations in a Manila (Philippines) maternity ward exceeded the WHO standard of 15 mg m^{-3} nearly 70% of the time indoors (Rosales et al., 2025). (Zaman et al. (2021) explored the air quality indicators with emphasis on the indoor pollutant concentrations of the hospitals in Dhaka (Bangladesh), including seasonal variations, the influence of outdoor pollutants on indoor air quality, and the toxicity potential of the health exposure. PM levels were observed to be lower in the indoor environment as compared to that outdoors. However, NO_2, a gaseous pollutant, was higher. Indoor VOCs were almost twice that of the outdoors, and higher in post-monsoon than in winter.

Even in European facilities, fine PM ($PM_{2.5}$) concentrations in a Greek hospital's Triage room ranged up to 26.27 µg/m³, briefly exceeding the 24-hour limit of 25 µg/m³, while the median $PM_{2.5}$ across French healthcare facilities was 9.0 µg/m³ (Baudet et al., 2021; Loupa et al., 2016). Chemical pollutants exhibited high concentrations tied primarily to indoor activities: studies in French private healthcare facilities found alcohols (Ethanol: 378.9 µg/m³; Isopropanol: 23.6 µg/m³) and aldehydes (Formaldehyde: 11.4 µg/m³; Acetaldehyde: 6.5 µg/m³) to be the most quantified Volatile Organic Compounds (VOCs) (Baudet et al., 2021). In Spanish Elderly Care Centers (ECCs), formaldehyde (CH_2O) concentrations were particularly high, reaching 1.47 ± 0.15 ppm in one dining room, exceeding the reference safety limit of 0.24 ppm (Rodríguez et al., 2024). Furthermore, critical findings include the presence of chemical compounds derived from medications distributed in the air of a Greek hospital, and elevated CO levels in Spanish ECCs (up to 20.7 ± 5.8 ppm), which exceeded the Spanish legal limit of 9 ppm (Loupa et al., 2016; Rodríguez et al., 2024).

Concentrations of biological contaminants and toxic elements, despite being variable, pose substantial health risks that demand careful mitigation. Airborne bacterial and fungal concentrations sometimes reached thousands of Colony Forming Units per cubic meter (CFU/m³), such as in Spanish ECCs where maximal fungal counts reached 11,140 CFU/m³ in a dining room, far surpassing the recommended value of <200 CFU/m³ (Rodríguez et al., 2024). Even common facilities showed concerning microbial loads, with median air concentrations of bacteria and fungi in French facilities measured at 14 CFU/m³ and 7 CFU/m³, respectively (Baudet et al., 2021). High concentrations of antibiotic-resistant bacteria were also detected; the Saudi Arabian hospital Emergency Room reported the highest concentration of MRSA isolates at 7.5 ± 6.51 cfu/m³ (El-Sharkawy & Noweir, 2014). Exposure to certain heavy metals detected in qUFP in a Brazilian nursing home, such as Chromium and Arsenic, resulted in a Lifetime Carcinogenic Risk (LCR) that significantly exceeded the threshold value of 1×10^{-6} (reaching 4.6×10^{-5} outdoors and 2.2×10^{-5} indoors for the chronic scenario) (Sousa et al., 2021). These pollutant concentrations translate directly into moderate non-carcinogenic risks for elderly occupants in centers studied in Spain (Hazard Index of 5.4) due to exposure to pollutants like CH_2O (HQ 2.69) and $PM_{2.5}$ (HQ 1.44) (Rodríguez et al., 2024). Importantly, mitigation efforts showed measurable success: the use of Portable

Air Cleaners (PACs) with HEPA filters achieved a pollutant removal efficiency of approximately 35% for PM and 67% for bacteria in Spanish ECCs. Furthermore, computational studies demonstrated that applying Stratum Ventilation (SV) could significantly reduce health hazards associated with CO_2 concentrations in elderly care bedrooms by 41.7% to 58.4% compared to traditional ventilation methods (Bansal, 2024; Wu et al., 2024).

2.11 Sick Building Syndrome

Sick Building Syndrome (SBS) is characterized as a condition where building occupants experience acute health and comfort effects that appear linked to the time spent within a specific structure, yet no specific illness or cause can be identified (Fig. 2.2). The symptoms are typically non-specific and are relieved soon after the person leaves the affected building (USEPA, 1991; Jalaludin, 2012; Zhang et al., 2014). Symptoms are commonly classified into three main groups: general symptoms (GS), mucosal symptoms (MS), and dermal symptoms (DS). General symptoms often include fatigue or tiredness, headache, dizziness, nausea, and difficulty in concentrating. Mucosal symptoms involve irritation of the mucous membranes, such as eye, nose, or throat irritation, dry cough, or a stuffy/runny nose (Weng et al., 2025). Dermal symptoms relate to the skin, including dryness, itching, or flushing of the hands and/or face. The overall prevalence of SBS can be high; if more than 20% of building occupants report experiencing SBS symptoms, the building is typically concluded as having the syndrome (Aziz et al., 2023; Odunola et al., 2025; Sun et al., 2018; Zhang et al., 2025).

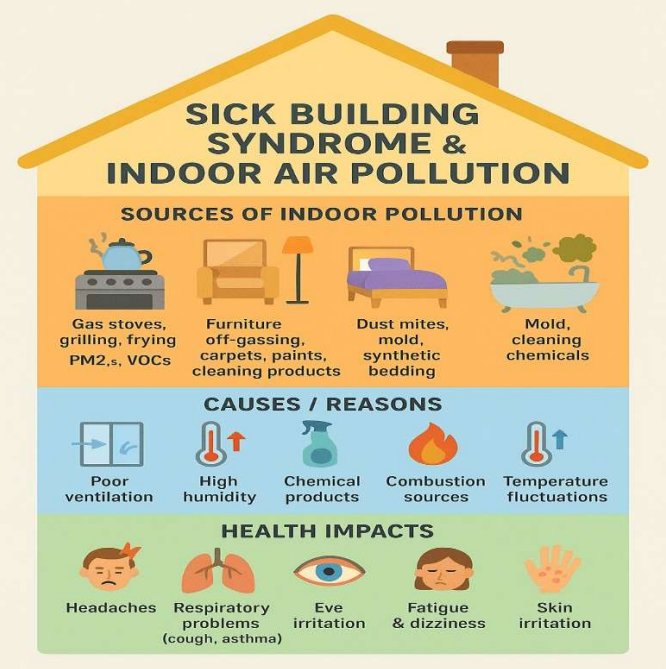

Figure 2.2 Sick Building Syndrome among adults.

The prevalence of SBS is attributed to the complex interplay of environmental factors, as no single parameter has been identified as the sole cause (Ullhaque, 2025). A major contributing environmental factor is inadequate ventilation, which can fail to dilute air pollutants. Ventilation efficiency is often indicated by indoor carbon dioxide (CO_2) concentrations; high CO_2 levels suggest inadequate ventilation and are positively associated with the onset of mucosal and general SBS symptoms (Jalaludin, 2012; Zhang et al., 2014; Zhang et al., 2025). Chemical contaminants from indoor sources, such as Volatile Organic Compounds (VOCs), including formaldehyde, are emitted by materials like adhesives, carpeting, office equipment (e.g., photocopiers and printers), and cleaning agents (Aziz et al., 2023; Ullhaque, 2025). Biological contaminants, such as bacteria, molds, pollen, and viruses, which breed in areas of dampness or stagnant water within the building (like in HVAC systems or water-damaged materials), are also cited causes. Indeed, mold/dampness on floors/ceilings, moldy odor, and window pane condensation in winter are indoor factors strongly associated with symptoms, including fatigue, headache, throat, and dermal issues (Aziz et al., 2023; Sun et al., 2018).

Personal and psychosocial factors also play a critical role in the occurrence and reporting of SBS symptoms. The female gender is frequently associated with a higher prevalence

of symptoms compared to males, potentially due to higher sensitivity or likelihood of reporting (Ghosh et al., 2024). A history of asthma or allergic rhinitis is consistently found to have a strong association with most SBS symptoms. Furthermore, psychological factors, such as poor mood, job dissatisfaction, or work-related stress, are known to contribute to or exacerbate general symptoms (Lu et al., 2016). To mitigate SBS, solutions often focus on pollutant source control and improved ventilation. Effective measures include regular housekeeping, routine maintenance of HVAC systems (e.g., cleaning filters), isolating contamination sources like printing machines, and ensuring ventilation meets or exceeds recommended standards, such as the ASHRAE Standard 62 minimum of 15 cfm of outdoor air per person (20 cfm/person in office spaces) (Sun et al., 2018; Zhang et al., 2025).

2.12 Seasonal variation of indoor pollutants due to meteorological variability

Seasonal variation dramatically affects particulate matter (PM) concentration across geographical regions, reflecting distinct seasonal drivers for fine $PM_{2.5}$ and coarse PM_{10} fractions. In Lahore, Pakistan (2019), $PM_{2.5}$ concentrations peaked in winter (79 - 42 $\mu g/m^3$ while PM_{10} concentrations were highest in summer (135 - 63 $\mu g/m^3$) (Ahmad et al., 2025). Similarly, in Central Delhi, fine particles were most prevalent during the post-monsoon and winter seasons, whereas coarse particles were more pronounced during the summer (Rani & Kulshrestha, 2025). Meanwhile, in Colombo, Sri Lanka (2019–2021), average concentrations of primary pollutants like $PM_{2.5}$ (29.5 $\mu g/m^3$), PM_{10} (48.8 $\mu g/m^3$), CO (690 ppb), and NO_2 (8.6 ppb) reached their maximum during the Northeast Monsoon season (Shelton et al., 2022). Indoor pollution in residential settings, such as Alexandria, Egypt, also follows a strong seasonal pattern, with indoor levels of PM_{10} (119.4 - 30.9 $\mu g/m^3$), $PM_{2.5}$ (85.2 - 25.8 $\mu g/m^3$), CO, and CO_2 being significantly higher in winter compared to summer (Abdel-Salam, 2021).

Meteorological conditions are pivotal drivers of these seasonal shifts, controlling both pollutant accumulation and dispersion mechanisms. Temperature (T) generally exhibits a strong negative correlation with fine PM concentrations during winter (Chithra et al., 2014). This inverse relationship occurs because low winter temperatures cause temperature inversions, leading to a shallow planetary boundary layer that restricts

vertical mixing and favors the accumulation of pollutants, notably $PM_{2.5}$. Conversely, in summer, warmer temperatures prevent inversions, allowing pollutants to disperse (Chan, 2002; Chen et al., 2020; Tiwari et al., 2014; Zhang et al., 2015). For coarse particles in summer, however, a moderate positive correlation with Temperature exists in Delhi, as high temperatures facilitate convective activities and local resuspension of dust and soil particles. High Relative Humidity (RH) often shows a strong positive correlation with submicron and fine particles in winter, enabling hygroscopic growth and promoting gas-to-particle partitioning, which increases PM concentrations (Rani & Kulshrestha, 2025). Wind speed (WS) typically correlates negatively with PM (Lahore, Colombo) because strong winds dilute and disperse surface emissions, though high WS in summer can increase coarse particles via long-range transport of dust (Ahmad et al., 2025; Shelton et al., 2022). Furthermore, drastically reduced Air Exchange Rates (AERs) observed in Alexandria homes during winter (1.1- 0.4 h^{-1}) compared to summer (4.5 - 0.9 h^{-1} directly contribute to poor indoor air quality during the cold season (Abdel-Salam, 2021).

Seasonal variations are also profound in aerosol composition and size distribution. In Thessaloniki (Greece), quasi-ultrafine particle mass during the cold period was dominated mainly by Organic Matter (34–36%), reflecting higher secondary organic carbon (SOC) attributed to the semi-volatility of wintertime emissions. In contrast, during the warm period, the mineral/trace element content (17–18%) often became the dominant component. Secondary Inorganic Aerosol (SIA) content also increased in the warm period (10–12% vs. 5–7% in the cold period), suggesting enhanced photochemical formation (Samara et al., 2016). In Nanjing, the size distribution of semi-volatile components, such as NO_3^- and OC, exhibited a peak shift in Geometric Mean Diameter (GMD) values from the fine mode (< 2.1 µm) in winter to the coarse mode (> 2.1 µm) in warm seasons, demonstrating a strong dependency on ambient temperature (Shao et al., 2017). In Delhi, the particulate matter displayed a bimodal distribution pattern during winter and post-monsoon (peaks in submicron/fine and coarse ranges), but shifted to a unimodal distribution during summer and monsoon, typically peaking intensely in the coarse range (4.7–5.8 µm), indicative of dust and soil particle dominance in dry conditions. Additionally, inorganic ions showed seasonal GMD dependency on relative humidity, with NH_4^+, NO_3^-, and SO_4^{2-} having the highest GMD values at RH > 70%,

which is ascribed to the hygroscopic growth effect of salts (Avery et al., 2019; Rani & Kulshrestha, 2025).

2.13 Socioeconomic status and indoor air pollution

The role of Socioeconomic Status (SES) fundamentally dictates susceptibility to poor Indoor Air Quality (IAQ) and elevated health risks, particularly in low-income and developing countries, where exposure disparities are rooted in structural deficiencies and economic limitations (Maung et al., 2022; Nugrahanti et al., 2025; Pipal et al., 2021). A primary structural driver is substandard housing, characterized by small, confined living spaces and overcrowding, which was observed in 88.2% of households in one Kolkata slum study (Dutta et al., 2022). These dwellings often lack essential infrastructure elements: for instance, over 70% of homes in Mumbai slums had no more than one window per floor, and cross-ventilation was absent in approximately 90% of them, particularly in homes headed by individuals with low educational attainment (Anand & Phuleria, 2021, 2022). Furthermore, economic hardship limits access to clean household energy, as poverty is reported to be the principal obstacle preventing households from adopting cleaner fuels. This reliance on polluting fuels, such as solid biomass (wood, dung, coal, kerosene), forces approximately 3 billion people globally to face Household Air Pollution (HAP) for cooking and heating (Albadrani, 2025; Al-Thani & Isaifan, 2025). In regions like Nigeria, unreliable access to utilities, such as electricity, compels residents to use polluting alternatives like kerosene and paraffin, further decreasing living standards and IAQ (Ogbonna et al., 2024).

The combination of poor infrastructure and reliance on polluting activities results in significantly higher pollutant concentrations in low-SES households (Boulanger et al., 2017; Jafta et al., 2017a). In low-SES urban homes in Delhi, indoor $PM_{2.5}$ concentrations were documented as extraordinarily high—more than 20 times the WHO standards—and were only 10% lower than in high-SES households (Greenstone et al.,2023). Extreme disparities were noted in South India, where women and children in low-income households were exposed to median $PM_{2.5}$ levels averaging 1300 $\mu g/m^3$, far exceeding concentrations found in higher-income homes (510 $\mu g/m^3$) (Shah et al., 2023). Beyond cooking fuels, SES influences behavioral factors that drive exposure: indoor tobacco

smoking is a major source of exposure that varies by socioeconomic status, with lower socioeconomic background associated with higher $PM_{2.5}$ exposure in slums. Additionally, culturally ingrained combustion practices common in developing countries, such as burning mosquito coils or incense, contribute substantially to poor air quality (Kurmanbekova et al., 2025; Mutahi et al., 2021b; Nugrahanti et al., 2025; Ogbonna et al., 2024). Critically, the inadequate or impaired ventilation prevalent in low-SES housing acts as a shared determinant of exposure clustering, trapping pollutants like $PM_{2.5}$, NO_2, and volatile organic compounds (VOCs), allowing them to accumulate and spread through confined, multi-functional living spaces (Al-Thani & Isaifan, 2025; Anand & Phuleria, 2021; Colton et al., 2014a; Sanbata et al., 2014)

The disproportionate exposure suffered by low-SES populations translates directly into severe health disparities and higher mortality risk (Colton et al., 2014b; Kurmanbekova et al., 2025). Globally, HAP exposure contributes to millions of deaths annually from cardiopulmonary diseases, including stroke, COPD, and lung cancer. Women and children are identified as the most vulnerable groups, accounting for nearly 60% of HAP-related premature deaths, primarily due to their prolonged time spent indoors near high-emission sources (Dommasandra Rajanna et al., 2024; Estévez-García et al., 2020b; Nardocci et al., 2023). Beyond pollutants generated by combustion, substandard housing conditions often associated with low SES, such as dwelling unit dampness/mold, are linked to adverse health outcomes, including phlegm and shortness of breath in adults, and cough and phlegm in children (Ogbonna et al., 2024; Quansah et al., 2017a; Stanley & Amesi, 2021). Quantitatively, logistic regression analysis in studies demonstrated that individuals in the highest income quintile exhibited 0.22 times lower odds of mortality due to indoor air pollution compared to those in the lowest income quintile (Albadrani, 2025; Maung et al., 2022; Pipal et al., 2021). These findings underscore the urgency for targeted policies focused on increasing clean energy accessibility, as having access to clean fuel for cooking was associated with 0.59 times lower odds of mortality, thereby reducing IAQ exposure disparities in vulnerable, low-income communities (Colton et al., 2014a; Jafta et al., 2017b; Maung et al., 2022; Mutahi et al., 2021b; Quansah et al., 2017b; Wafula et al., 2023).

2.14 Health impacts of indoor air pollution

Exposure to air pollution, both ambient and indoors, represents an existential threat to global public health, driving millions of premature deaths and significant economic losses worldwide (Baudet et al., 2021; Fuller et al., 2022; Liu et al., 2022; Loureiro et al., 2025). The gravest consequences stem from chronic risks, particularly carcinogenicity associated with fine particulate matter ($PM_{2.5}$) and its chemical components. In domestic Chinese cooking, poor ventilation leads to an integrated inhalational carcinogenic risk from heavy metals (2.7×10^{-3}) that is three orders of magnitude higher than the acceptable risk level (1.0×10^{-6}). The primary contributors to this potential carcinogenic risk are Cr (VI), Arsenic (As), and Nickel (Ni). Similarly, exposure to trace elements (TEs) bound to $PM_{2.5}$ presents unacceptable carcinogenic risk for vulnerable groups, such as elderly adults (>60 years) residing near roadsides in winter, where the accumulative risk reached 1.4×10^{-4}, with Chromium and as accounting for approximately 90% of the total risk. Furthermore, long-term exposure to ambient $PM_{2.5}$ is associated with an average increase of 11% in cardiovascular mortality for every 10 µg/m³ increase in annual concentration.

Cardiopulmonary health is severely compromised by exposure to airborne pollutants, both acutely and chronically (Hussein et al., 2015; Shukla et al., 2025). Epidemiological studies link chronic $PM_{2.5}$ exposure to diseases, including respiratory, and cancer (Bourdrel et al., 2017; Lequy et al., 2022; Yang et al., 2019). Short-term air quality changes are associated with an increased risk of acute events such as myocardial infarction, stroke, and acute heart failure, even at pollution levels below European standards (Ji et al., 2022; Kalimeri et al., 2016; Niu et al., 2025). In laboratory studies simulating domestic Chinese cooking, short-term exposure to cooking oil fumes caused a significant reduction in lung function, specifically declining forced vital capacity (FVC) and vital capacity (VC) after multiple cooking operations (Du et al., 2017). For population relying on solid biomass fuels (e.g., in rural Pakistan), commonly reported respiratory symptoms among children include coughing (60.3%), watery eyes (57%), phlegm (38%), breathing difficulty (27.3%), headaches, nausea, dizziness, asthma, tuberculosis, and pneumonia (Liaqat et al., 2025; Zahra Naqvi et al., 2025). Additionally, children are susceptible to non-carcinogenic risks, as seen in Hanoi, where the Hazard Index from TEs in indoor $PM_{2.5}$ exceeded the safety threshold (HI > 1) in winter for infants, toddlers,

and preschool children, mainly driven by Manganese (Mn) contamination (Vo et al., 2022).

A growing body of research highlights the adverse neurological and mental health consequences linked to air pollution, particularly ultrafine particles (UFPs) and nanoparticles (NPs) (Kluizenaar et al., 2017; Rivas et al., 2015; L. Wallace & Ott, 2011). There is emerging evidence associating poor air quality (both indoor and outdoor) with poor mental health, cognitive issues, and specific mental disorders such as depression, anxiety, personality disorders, and schizophrenia (Bhui et al., 2023; Loureiro et al., 2025; Rizwan et al., 2013; Wells et al., 2017). Crucially, the neuropathology characteristic of fatal neurodegenerative diseases, including Alzheimer's disease (AD) and Parkinson's disease (PD), is now believed to start in pediatric ages. Combustion-derived UFPM and magnetic nanoparticles are identified as key factors contributing to the early onset of these diseases (Calderón-Garcidueñas et al., 2025). The vulnerability starts even earlier, as UFPM/NPs have been detected in the mitochondria of the fetal brain in the uterus (Naseri et al., 2019). Direct exposure studies confirm neurotoxicity: exposure to UFPs from frying activities significantly impacts human brain activity, notably causing statistically significant changes in the Alpha band in the right temporal lobe (Lee et al., 2017; Naseri et al., 2019). The complex interplay between pollution exposure, socioeconomic deprivation, and psychosocial vulnerabilities creates a "pro-inflammatory exposome" that exacerbates both physical and mental illnesses (Bhui et al., 2023; Fuller et al., 2022).

2.15 Literature summary of some global studies similar to the proposed study

City (Country)	Study focus	Aim & Key findings	Reference
Lanzhou (Northwest	$PM_{2.5}$ household concentrations and personal exposure among	•This study described $PM_{2.5}$ concentrations in households and individual inhalation exposure levels in urban dwellers during the summer and winter seasons.	(Li et al., 2016)

China)	urban residents	•Notable seasonal fluctuations in indoor $PM_{2.5}$ levels were noted in chosen microenvironments. •Compared to households using gas or electricity, those utilizing coal had substantially higher indoor $PM_{2.5}$ concentrations	
Nanjing (China)	Seasonal Indoor PM and its determinants	•This study examined the factors that influence indoor $PM_{2.5}$ levels in urban homes and concentrated on how they varied seasonally. •Outdoor $PM_{2.5}$ majorly contributed to indoor $PM_{2.5}$ levels in homes. •The relationship between indoor and outdoor $PM_{2.5}$ levels was shown to be more significant during transition seasons as compared to winter and summer seasons.	(Shao et al., 2017)
São Paulo (Brazil)	Size–segregated PM inside the residences of the elderly	•This study quantified size–segregated PM mass concentration and their exposure doses in the elderly residences. •$PM_{2.5}$ accounts for 78% of total PM_{10}. • With I/O values of 1.89 and 1.06 for $PM_{2.5}$ and PM_{10}, respectively, indoor sources were the most common.	(Segalin et al., 2017)
		•This study examined the elemental distribution pattern and PM mass concentration in residential sites'	

Agra (India)	Quasi-accumulation and quasi-ultrafine ranges in residential areas.	indoor and outdoor air across three different particulate fraction size ranges (coarse, quasi-accumulation, and quasi-ultrafine), as well as the impact of high traffic emissions on the partitioning trend. • The airborne particulate concentration was found to be higher in indoors (PM_{10} = 263 ± 59 µg/m^3; $PM_{2.5}$ = 212 ±38 µg/m^3) than outdoors (PM_{10} = 194 ± 15 µg/m^3; $PM_{2.5}$= 152 ± 16 µg/m^3).	(Rohra et al., 2018)
Chennai (India)	Characteristics of IAP under various fuel types and kitchen types in rural regions	The objective of this study was to Characterize PM concentrations in various fuel-kitchen configurations, estimating respiratory dosage for the various individuals (elderly, women, and small children), and assessing the related health effects were the goals of this study. • Due to inadequate ventilation and a smaller region of dispersion, PM concentrations were higher in enclosed indoor kitchens than in outdoor and open kitchens. • A high $PM_{2.5}/PM_{10}$ ratio indicates that tiny particles were more prevalent from cooking, which is more intense in homes with barriers and closed kitchens.	(Deepthi et al., 2019)

Nanjing (China)	Spatial distribution of indoor $PM_{2.5}$	•This study aimed to test the CONTAM model's capacity to predict $PM_{2.5}$ concentrations in numerous residential buildings across China. •Indoor $PM_{2.5}$ levels are influenced by socioeconomic factors such as home ownership and household income.	(Shao et al., 2019)
São Paulo (Brazil)	Chemical composition and sources of qUFPs inelderly residences.	•The study quantified the sources of qUFP in indoor elderly households. • Sulphate and nitrate were the dominating ions in qUFP identified in senior home •Cooking and wall painting were recognised as indoor sources by the qUFP composition. • The main outside sources of indoor qUFP were vehicles and secondary inorganic aerosols.	(Segalin et al., 2020b)
Cairo (Egypt)	Outdoor and indoor factors influencing PM and CO_2 levels	•This study identified the numerous indoor and outdoor factors and sources influencing indoor PM and CO_2 levels in selected domestic homes. • Due to insufficient ventilation, most of the kitchens had higher indoor $PM_{2.5}$ and CO_2 levels than the respective living rooms. •Indoor air emissions were linked to a number of household activities, including heating, washing, and smoking.	(Abdel-Salam, 2021a)

Delhi, India	Assessment of the size distribution of PNC in kitchen environments	•The study analyses the distribution of PM in JNU hostel and canteen kitchens, including number, surface area, and volume. •Compared to the monsoon and summer seasons, the PNC was higher during the winter. • 95 - 99% of the TSPM was attributed to finer-sized particles.	(Singh et al., 2021)
Medellín (Colombia)	Exposure levels of $PM_{2.5}$ and BC in rural homes	•The aim of this study was to measure indoor air pollutants ($PM_{2.5}$ and BC) in various environments,inhabited by individuals with impairments. •In comparison to densely populated, traffic-heavy urban areas, BC concentrations were around 2.5 times greater in rural locations. The average $PM_{2.5}$ and BC levels in homes using firewood were highest (10.9–3303 µg m^{-3}) and (2.6–51.2 µg m^{-3}), compared to gas (2.6–6 µg m^{-3}).	(Vallejo et al., 2021)
Medellín (Colombia)	Spirometry alteration due to exposure to atmosphere pollutants in rural residences	•This study looked at how changes in respiratory function in a sample of rural residents were related to levels of $PM_{2.5}$, CO, and intradomiciliary BC. •Spirometric parameters exhibited a negative correlation with indoor air pollution levels. •Pollutant concentrations were greater in residences that used biomass as	(Piracón et al., 2021)

		cooking fuel.	
Cairo (Egypt)	Seasonal fluctuations of indoor air pollutant levels inresidential buildings	•This study determined the main sources of air pollutants in residential buildings and investigated the relationship between indoor and outdoor PM levels. • This study also investigated potential factors controlling the indoor air quality of urban residences. Indoor levels of air pollution were found to be high during winter, followed by the summer season. • Number of occupants and volume of room were among the major factors influencing indoor levels of PM, CO, and CO_2 during winter and summer seasons	(Abdel-Salam, 2021b)
The 12 cities include Dhaka (Bangladesh), Chennai (India), Nanjing (China), Medellín (Colombia), São Paulo (Brazil), Cairo	In-kitchen aerosol exposure	•The study identified parameters influencing kitchen exposure to fine and coarse particle fractions and developed exposure profiles for low-income home. • Smaller volume kitchens used cleaner fuels but had higher cooking exposure compared to larger ones. •Frying was the most particle-emitting activity observed during cooking. • Compared to natural gas and LPG kitchens, households that used charcoal increased average $PM_{2.5}$	(Kumar et al., 2022)

(Egypt), Sulaymaniyah (Iraq), Addis Abeba (Ethiopia), Akure (Nigeria), Blantyre (Malawi), Dar-es-Salaam (Tanzania), and Nairobi (Kenya).		exposure during cooking sessions by 1.3 and 3.1 times, respectively.	
Italy	Airborne particles emitted by different indoor sources	•This study calculated mass fractions emitted from different indoor sources. •They were mostly in the 10^{-6} -10^{-5} #cm^{-3} range. •The outcome of the study showed that all the sources (incenses, candles, mosquito-coils, and cooking activities) emitted fresh particles with a significant contribution of PM_1 fraction to PM_{10}.	(Caracci et al., 2024)
University of Birmingham (UK)	Analysis of impact of cooking methods on $PM_{2.5}$ and	•Pan-frying had the greatest peak median concentrations of $PM_{2.5}$ (μgm^{-3}) (92.9), followed by stir-frying (26.7), deep-frying (7.7), boiling (0.7), and air-frying (0.6). •Pan-frying had the highest median	(Tang et al., 2024)

	VOCs	concentrations of VOCs (ppb) at 260, followed by deep-frying at 230, stir-frying at 110, boiling at 30, and air-frying at 20.	
Tokyo (Japan)	Study of cooking and other indoor activities	•The average $PM_{2.5}$ concentrations in each home ranged from 3 to 140 $\mu g/m^3$, with concentrations in the kitchen and surrounding areas increasing by 2-96 times while cooking. • I/O ratio varied between from 0.8 to 12.1.	(Zeng et al., 2025)

2.16 Summary

This chapter presents a detailed literature review that reveals the levels of PNC and PM and other pollutants in different indoor environments (healthcare facilities, schools/universities, work places, residential buildings) because each type of indoor space contains its own unique mix of sources, activities, ventilation type, intensity of sources, building materials, and infrastructure exhibits significant variations across different indoor settings. This chapter also provides detailed information on IAQ, which is linked to both short-term and long-term health risks, based on exposure and levels of pollutants indoors. Additionally, the global status of indoor and outdoor air pollution is discussed, along with the research gaps that need to be addressed in future studies.

16

CHAPTER-3

METHODOLOGY

3.1 Introduction

The air quality in the global south region is deteriorating at an alarming rate. The majority of the growing urban regions are located in the global south region, especially in the Asian subcontinent. The current study was conducted in the Indian subcontinent, which is one of the highly populated regions. Delhi city is the capital city of the country with a population of about 33.81 million as per the government report, with an increase of about 2.63% from the previous year (Guttikunda et al., 2023). The city experiences severe pollution events, and it is ranked among the highly polluted cities globally, which is the proposed study region. Delhi, due to its geographical location and climatic conditions, experiences different pollution events. The air pollution-related human health risks in the city are estimated to be around 7 million premature deaths. Delhi city has an area of around 1483 km^2. The air pollution in the urban regions is a complex mixture of different sources. The rapid urbanization in these regions is responsible for the poor air quality, which is generated through various processes such as emissions from industries, transportation, thermal power, solid waste burning, residential sectors mainly. Apart from ambient air pollution in these rapidly developing urban cities, indoor air pollution is one of major growing concern. Indoor air pollution in Delhi has quietly grown into a major public health concern, often overshadowed by the city's well-known outdoor smog. Many homes, whether in old neighbourhoods or modern apartments, struggle with poor ventilation. Everyday activities-cooking on high flames, burning incense, or using mosquito coils-release fine particles and gases that linger in closed spaces. During winter, when the city's air quality dips sharply, these pollutants mix with the outdoor smog that seeps indoors, creating a thick and persistent layer of contaminated air. Even households that rely on LPG or electric cooking are not entirely safe, as dust, chemicals from cleaning products, and fumes from paints or furnishings contribute to poor indoor quality. Children, elderly people, and individuals with asthma or allergies tend to feel the impact more quickly, experiencing irritation, cough, or difficulty breathing. Despite growing awareness, many homes still lack adequate cross-ventilation or effective air-cleaning

solutions. Space constraints, nearby traffic, and overcrowded surroundings also make it harder for families to keep indoor air fresh. While personal measures can help, the broader issue remains tied to Delhi's overall air quality, which continually feeds pollutants into living spaces. Improving indoor conditions will require a mix of cleaner household practices, better building design, and sustained improvements in outdoor air quality across the city. The emission from residential sector contributes to indoor and outdoor ultrafine particles emission in Delhi city, considered for this research study.

3.2 Study location characteristics

The study was conducted in four different urban households in Guru Tegh Bahadur Nagar (GTB Nagar), located in the northern part of Delhi (Fig.3.1). In this selected region, people of different socio-economic strata reside within this small geographical domain. It is surrounded by various educational institutes and a mixture of commercial and residential zones with a high population density. The study region is well connected with road network, metro facilities, railway station, and state bus terminal within an aerial distance of 3 km. Four different households were selected for the study based on the Pradhan Mantri Awas Yojana - housing for all (Urban) 2021 guidelines (PMAY Guidelines, 2021), depending on their annual household income. The selected study region comprises all major income groups Urban Poor (UP), Low Income Group (LIG), Middle Income Group (MIG), and High-Income Group (HIG). UP/Slum is defined as a compact area of at least 300 people or about 60 to 70 households in poorly built congested tenements (Table.3.1). LIG households have an annual income between 3600 and 7200 USD, MIG households have an annual income between 7200 and 21600 USD, whereas HIG households have an annual income of more than 21,600 USD. The study region encompasses approximately 1.04 km^2 with a population of ~19,883 (males: 10,652; females: 9,231; Economic Survey of Delhi, 2021–22). Its climatic conditions include cold winters with extreme summers and moderate rainfall. Temperatures in the study region reach a minimum of 4 °C in winter and a maximum of 46 °C during summer. The study region receives an annual average precipitation of approximately 811 mm. The study area is well connected by road, rail transport, and metro connectivity.

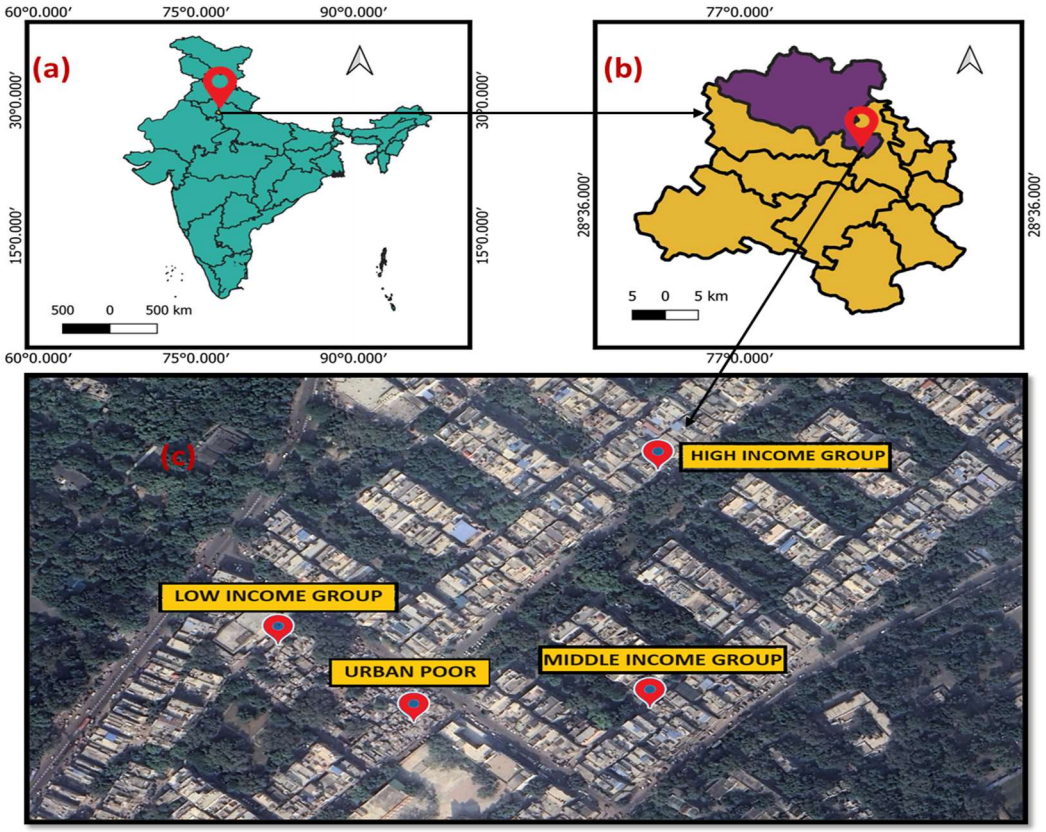

Figure 3. 1 (a) Map of India with all the states of the country, (b) Map of Delhi city with major road network, (c) Geographical location of the study area.

surrounded by many higher educational institutions, schools, hospitals, gymnasiums, and cafes. This study area was selected because it comprises households of varying socioeconomic conditions ranging from urban poor to high-income groups of residents and falls within a small geographic domain (Fig 3.3).

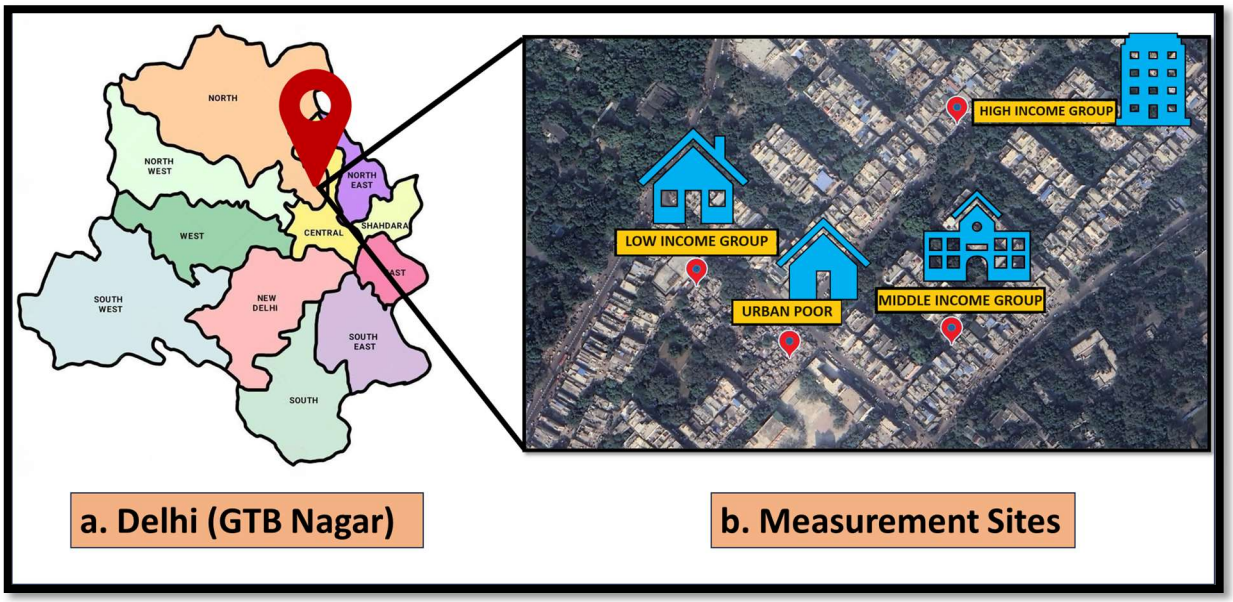

Figure 3. 2 (a) Map of Delhi city with major road network, (b) geographical location of the study location.

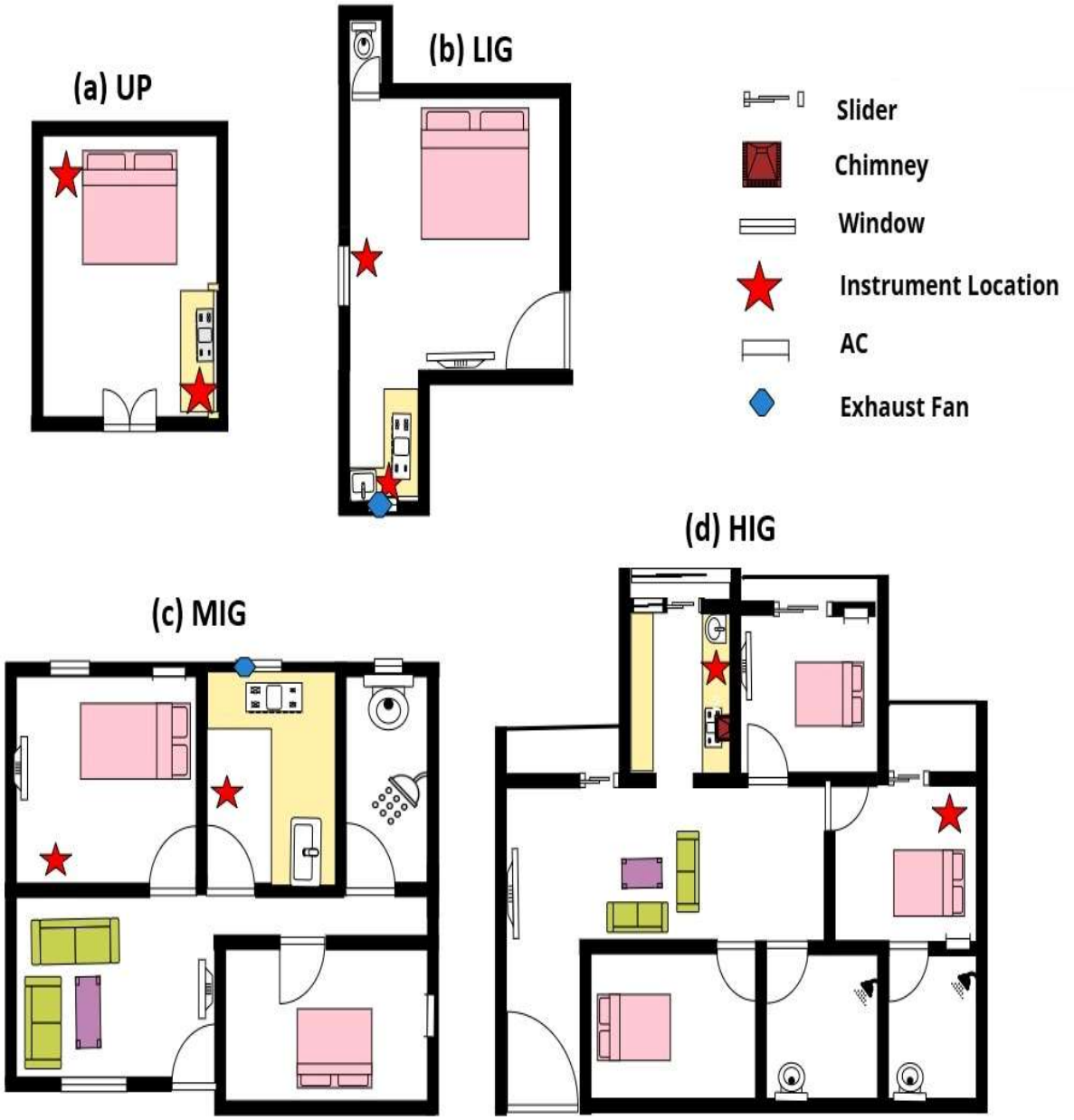

Figure 3.3 Layout of households in four selected income groups: (a) Urban Poor (UP), (b) Low-Income Group (LIG), (c) Middle-Income Group (MIG), and (d) High-Income Group (HIG).

Table 3.1 Characteristics of different selected households of the study.

Characteristics of the house	Urban poor (UP)	Low-Income Group (LIG)	Middle-Income Group (MIG)	High-Income Group (HIG)
No of occupants	5	5	4	4
Total no of rooms (excluding kitchen)	1	1	2	3
Cooking in a Day (times)	2-3	2-3	2-3	2-3
Separate Kitchen	No Separate kitchen	Kitchen attached to bedroom	Separate	Separate
Kitchen ventilation	No	Window (1) + Door (1)	Window (1) + Door (1) + Exhaust fan (1)	Window (1) +Door (2) +Hood (1)
Bedroom ventilation	Door (1)	Window (1) + Door (1)	Window (1) + Door (1)	Door (2)
Fuel used for cooking	LPG	LPG	LPG	LPG
Floor materials	Exposed brick	Mosaic	Tiles	Tiles
Wall materials	Un-plastered brick wall	Plastered walls	Plastered walls	Plastered walls
Ceiling	Asbestos sheet	Reinforced cement concrete	Reinforced cement concrete	Reinforced cement concrete

3.3 Instrumentation

The particle number concentrations were measured using a portable aerosol spectrometer (Model:11A, Grimm Aerosol Technik, Germany). The instrument provides particle number concentration size ranges from 250 nm to 32 µm across 31 different-size channels (Fig 3.4). The particulate matter (PM_{10}, $PM_{2.5}$, and PM_1) was measured using an optical particle counter. The instrument works on the principle of light scattering technique where the air sample is passed through a cell consisting of the light source (λ = 683 nm), and detector. The instrument has a flow rate of 1.2 L/min ±5 % and a rinsing air flow rate of 0.3 L/min. The sampling frequency of the instrument is adjustable from 6 seconds to

1 hour and the optimum temperature of operation is 4 to 40 ℃, RH < 95 %. The instrument can be operated through both Alternating Current (AC) and Direct Current (DC). The instrument can detect particle numbers up to 30,000,000 particles/Litre. The optimum operating temperature of the instrument is between 0 to 40°C. The meteorological parameters, such as Temperature (T) and Relative Humidity (RH), were measured through battery operated real-time HOBO sensor (MX 1101). The optimum working temperature of the sensor is -20 to 70 ℃ with an accuracy of ± 0.21°C from 0° to 50°C and a drift of 0.1°C/ year and relative humidity from 15% to 95% non-condensing (Munckton & Rajagopalan, 2024).

3.4 Data collection and analysis

The measurements were done for three seasons: monsoon (July to September 2022), winter (December 2022 to February 2023); summer (April to June 2023); and in all four selected households (Gulia et al., 2022). In each household, 15 days of data were collected every season. In indoor, 14 days of data (7 days in kitchen and 7 days in bedroom) and 1 day in outdoor environments were collected one after the other, respectively. The particulate matter (PM_{10}, $PM_{2.5}$, PM_1) data was collected at an interval of 5 minutes, and meteorological parameters (T and RH) at an interval of 1 minute parallelly in selected households. Further, both data were converted into a 15-minute average and a 1-hour average based on the requirement for analysis. The major indoor activities, such as cooking, cleaning, and worship, vary significantly during these periods. All the households selected for the study use the same fuel for cooking (LPG), and all the measurements were done on the ground floor of the households. A questionnaire survey was also conducted to collect information about each household.

Figure 3.4 Pictorial view of the GRIMM OPC instrument.

Households were selected based on the basis of the socioeconomic conditions defined by the Pradhan Mantri Awas Yojana (PMAY Guidelines, 2021), categorised as Urban Poor (UP), Low-Income Group (LIG), Middle-Income Group (MIG), and High-Income Group (HIG). Throughout the monitoring period, the available data for analysis in the kitchen was >90% in UP, MIG, and HIG households, and >75% in LIG households. Similarly, in the bedroom, >90% of data was available in UP and LIG households, while in MIG and HIG, it was >80 %, and in outdoor, <95% data was available for analysis. To reduce disparities in data collection, uniform criteria were adopted to select the households: (i) Each household should be located in the same geographical domain, (ii) Each household should use LPG as a fuel for cooking, (iii) It should be located on the ground floor, (iv) It must be a single-family house, (v) It must be a non-smoker household, (vi) Occupants must cook daily, and (vii) There must be no pets/birds in each household. The measured particles were classified into four different size ranges: quasi-ultrafine (qUFP: 250 nm to 500 nm), sub-fine (500 nm to 1 µm), fine (1.0 to 2.5 µm), and coarse particles (2.5 to 10 µm) (Yadav et al., 2022). The data was further classified into daytime (06:00 AM to 10:00 PM) and nighttime (10:00 PM to 06:00 AM) (Sankhyan et al., 2022). The collected data were analysed using R studio software (version 4.4.0), especially the open-air package (Carslaw, 2019). The data were visualized through Origin Software (Origin 2024b).

3.5 PNC measurements using SMPS

A scanning mobility particle sizer (SPMS +C) with condenser was used to measure the ambient nanoparticles. GRIMM Aerosol Technik GmbH & Co (Fig 3.5). was the manufacturer of the SMPS+C instrument. The instrument's serial number is 54031801 (Figs 3.7, 3.8). The device is made up of a condensed particle counter, a neutralizer, and a differential mobility analyzer. The device measures particles with a wavelength range of 10 nm to 1090 nm using a Vienna type L-DMA. After passing through a diffusion drier to help maintain the air sample's relative humidity, the air is passed through a neutralizer composed of radioactive material (Am-241). After that, the air passes through a 0.35-meter-long DMA. The DMA has an outer diameter of 0.026 m and an inner diameter of 0.040 m. The ideal DMA pressure is 101300 Pa and the ideal temperature is 20° C. The effective length of the sample probe without losses is 0.38 meters, and the instrument's

slip factor is 2.83. The particles of various sizes are dispersed among 45 distinct size-segregated channels, and a full measuring cycle takes around 7 minutes.

The Winklmayr et al. (1991) 9(d) equation serves as the foundation for the size distribution computation of the various size bin calculations, which adhere to ISO 15900 standards (Eqn.1).

$$N_c(D) = \left(\frac{Q_a}{Q_{sh}}\right).\sum_{i=1}^{\infty}[\alpha(D,i).\Psi(D).F(D)]_{D=D_i} \quad - \quad (1)$$

where $N_c(D)$ – Total number concentration measured in CPC

D- Diameter of single charged particle that corresponds to voltage of DMA.

D_i- Diameter of the particle with i charges that correspond to voltage of DMA.

Q_a – Volume flow rate of the sample airflow.

Q_{sh} – Volume flow rate of the sheath airflow.

i- Number of elementary charges carried by the particle.

α (D_i, i)- probability of the particle to carry i elementary charges (Fuchs-Wiedensohler values).

ψ D_i – function converts diameter interval into mobility interval.

F(D)- Number size distribution at the inlet of DMA (https://www.grimm-aerosol.com/).

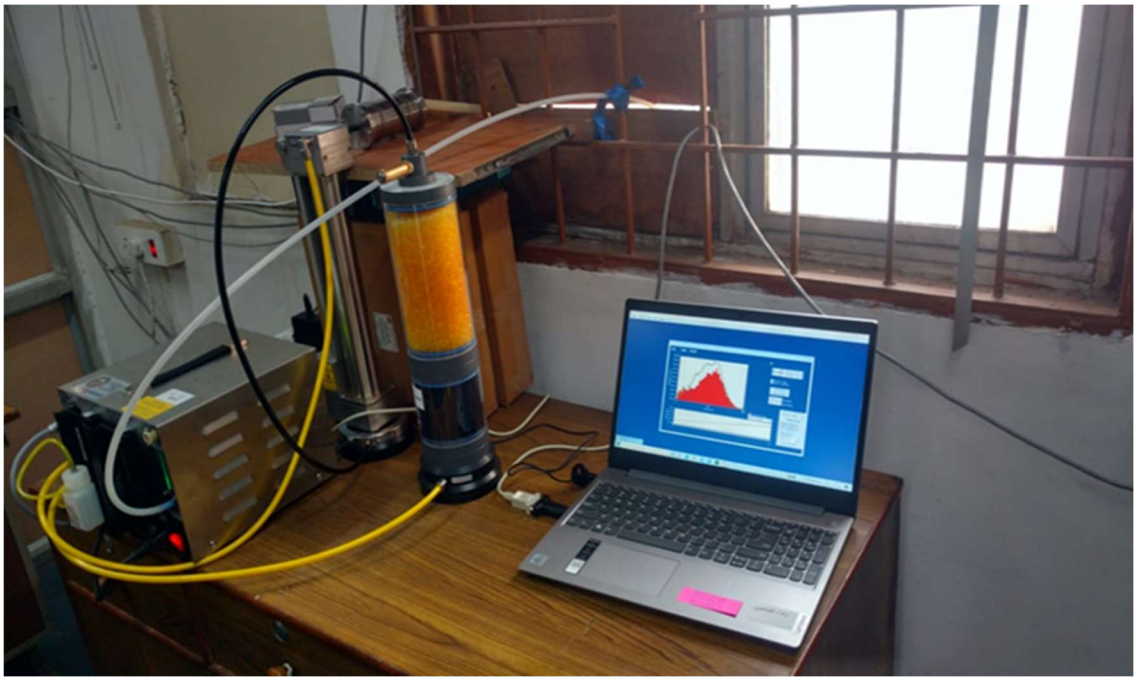

Figure 3.5 Pictorial view of the GRIMM SMPS instrument.

3.6 Meteorological measurement

The meteorological parameters, such as Temperature (T) and Relative Humidity (RH), were measured through a real-time HOBO sensor (MX 1101) (Fig 3.6). The optimum working temperature of the sensor is -20 to 70 ℃ with an accuracy of ± 0.21°C from 0° to 50°C and a drift of 0.1°C/ year.

Figure 3.6 Pictorial view of the HOBO sensor.

3.7 Data analyzing and visualization

Numerous software programs, including R, Origin, and MATLAB, are used for data analysis, and mathematical and computational models are used for health impact assessments.

3.7.1 R software

One of the most popular computer languages for statistical research and data visualization is R software (version 5.12.8) (Fig. 3.7 and 3.8). This program is open source and publicly accessible under a broad public license. Excellent data mining, calculation, graphical data display, and concurrent management of various data sets are all features of the software. This software contains a large number of libraries, each of which is used for a variety of purposes. The open-air package is the most used library for analyzing data on air pollution. This software has a strong community following and is compatible with a variety of operating systems. The software offers a variety of resources to help with learning and problem-solving.

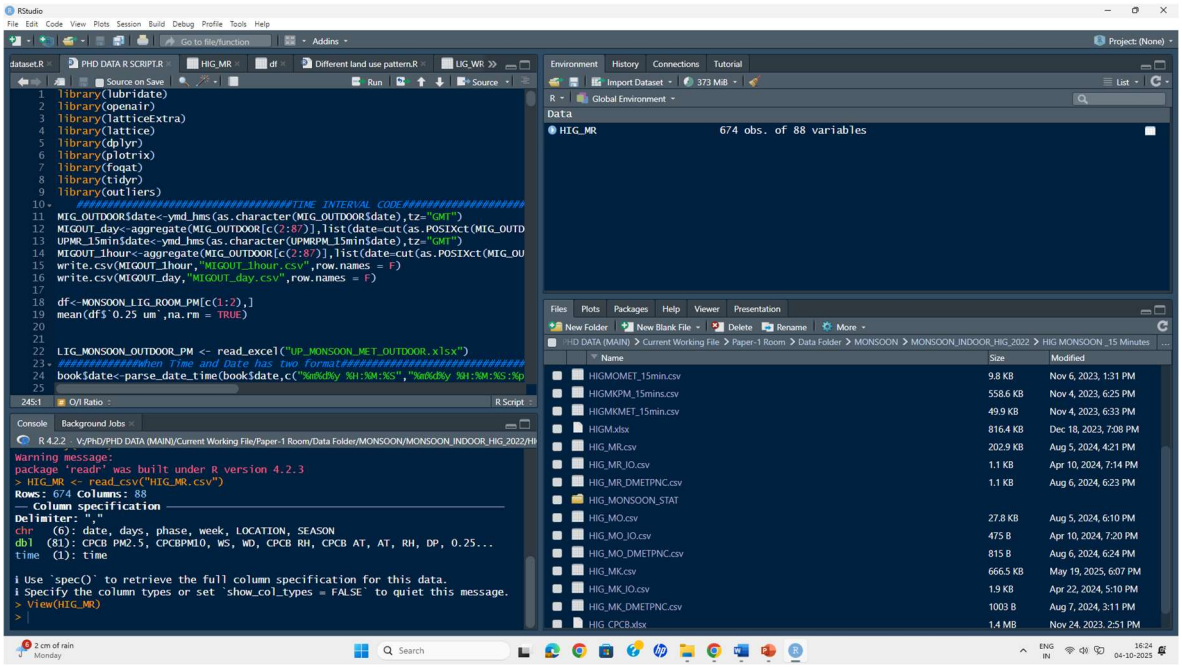

Figure 3.7 Pictorial representation of R software platform.

3.7.1.1 Open-air package

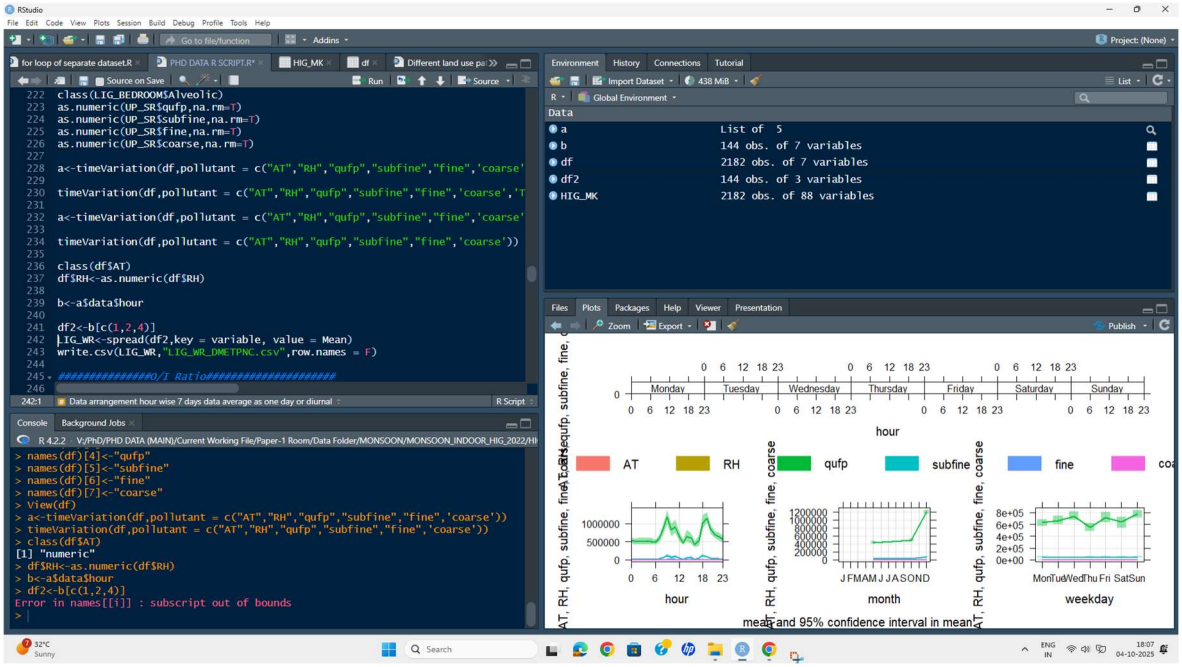

Figure 3.8 Data visualization in the R platform.

3.7.2 ORIGIN software

Origin Lab Corporation created the data analysis and graphing program Origin (Fig 3.9) for both 2D and 3D plotting. This Origin software has been used for data analysis tasks like curve fitting, signal processing, and statistical analysis. This software uses the Levenberg-Marquard algorithm for curve fitting. Programming languages like Python and R functions, as well as scripting languages like Lab Talk, are enabled in Origin. Various data formats, including ASCII text formats, Excel, and Net CDF, are used in origin. JPEG, PNG, and TIFF files are among the formats in which the output of the origin can be saved. The Origin 2022 version has been used for analysis in this study (Fig. 3.10).

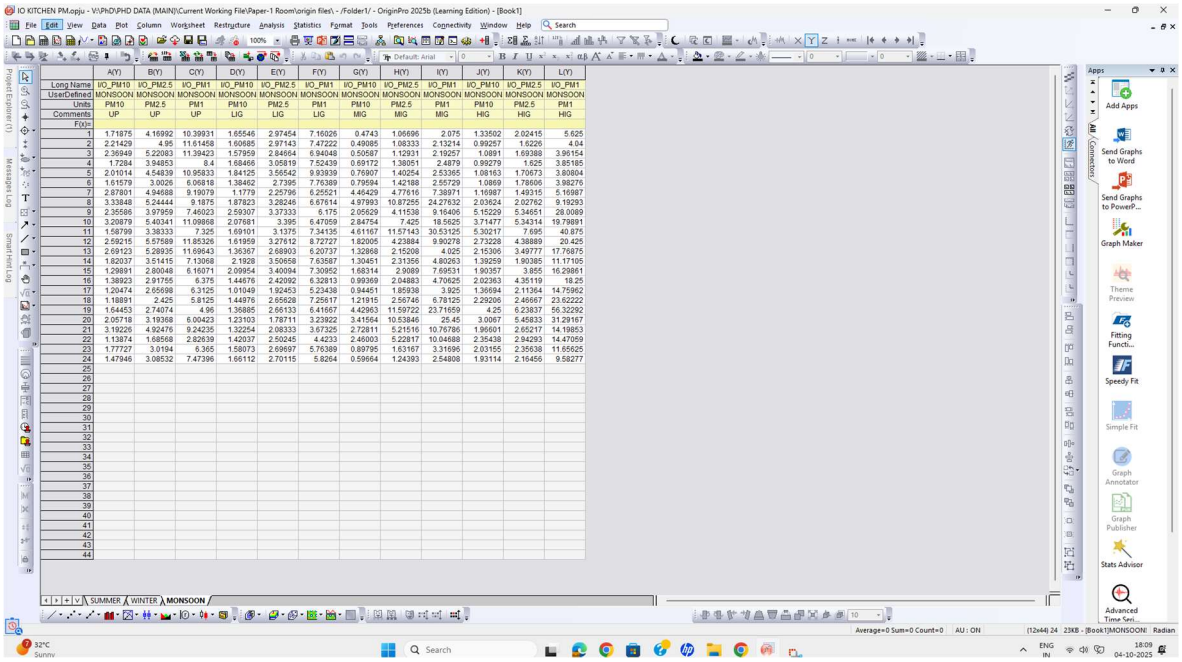

Figure 3.9 Pictorial view of data feeding platform in the origin software.

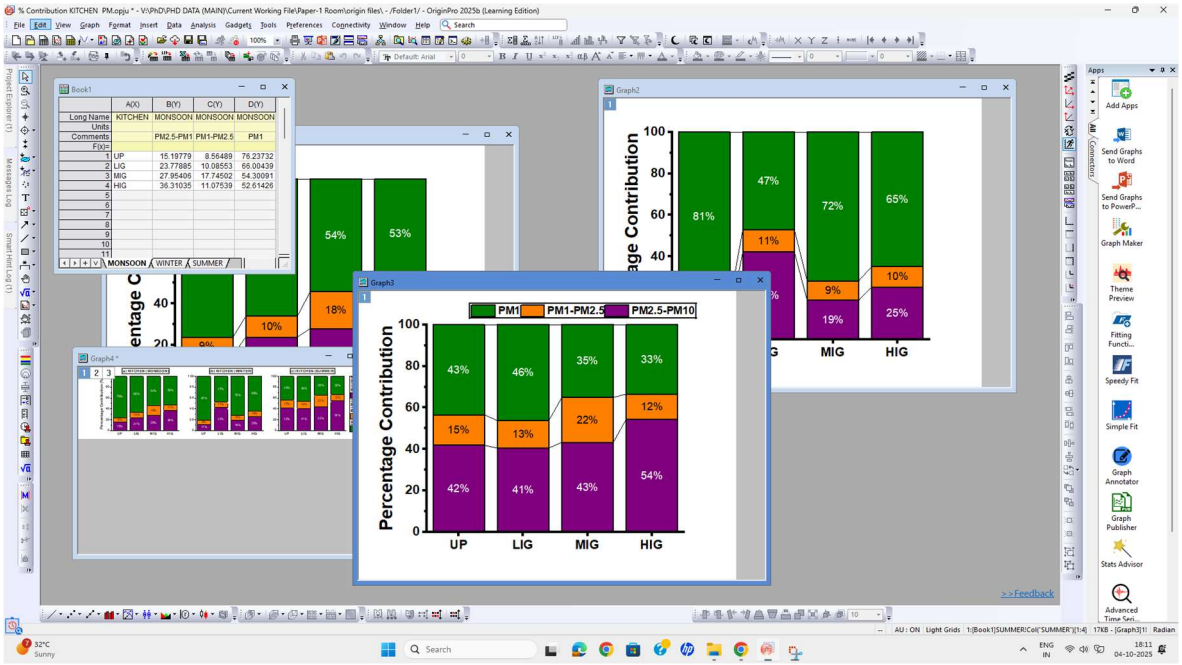

Figure 3.10 Output of the data visualization in the Origin software.

3.7.3 Multiple Path Particle Dosimetry (MPPD) model

The deposition of the particles in the human respiratory tract was done using a Multiple Path Particle Dosimetry (MPPD) model (Fig. 3.11), is one of the widely used models for exposure analysis. This model is extensively utilized in research and education about the deposition of nanoparticles in the human respiratory system, and it has been thoroughly validated (Khan et al., 2022; Manojkumar and Srimuruganandam, 2021b, 2022b). Because of its features and updated functionalities, this model is regarded as one of the best models available for dosimetry investigations. Particle characteristics like size and density, followed by lung characteristics like breathing frequency (BF), tidal volume (TV), upper respiratory tract volume (URT), and the various exposure condition orientations, comprise the model's primary input parameters.

Figure 3.11 MPPD model home page.

In accordance with the recommendations of several international studies, this model also makes use of specific assumptions and constants (Fig. 3.12). The model allows for the analysis of nanoparticle deposition in the pulmonary, tracheobronchial, and alveolar parts of the respiratory system. They deposit in the bronchiole, bronchus, and alveoli. One of the model's shortcomings is that its input uses size-segregated measurements for increased accuracy. Another drawback of this model is that, although it employs theoretical and computational functions to analyze deposition, but the actual deposition in the respiratory tract may differ.

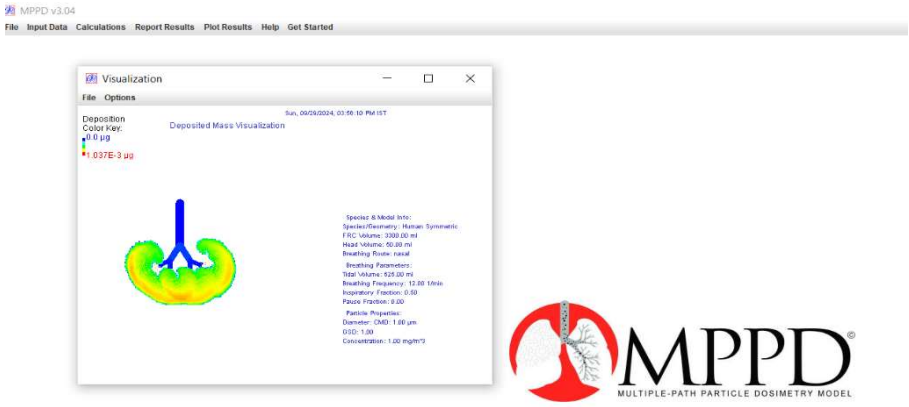

Figure 3.12 MPPD model result output.

The step-by-step model execution is provided in Figure 3.13, and the basic assumptions and functions of the model are also provided in the schematic diagram.

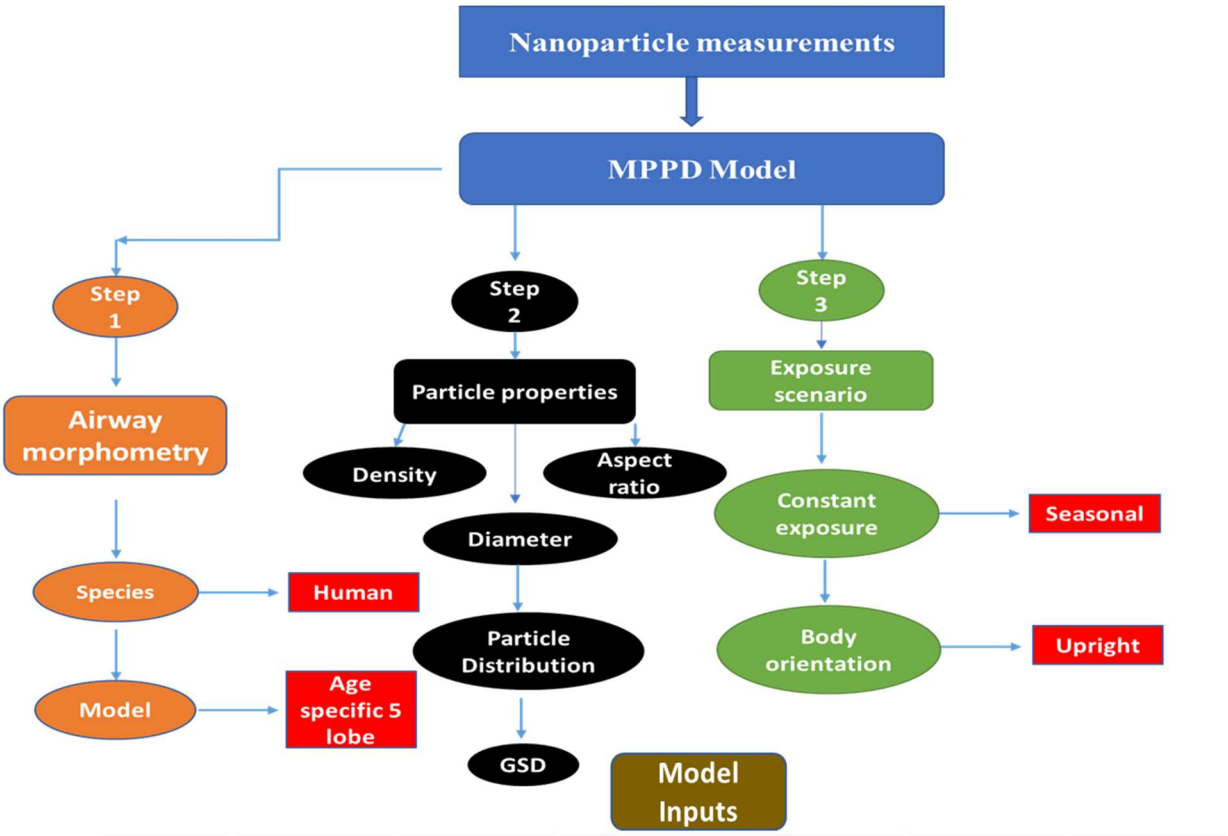

Figure 3.13 Process flow diagram of the MPPD model.

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3.7.4 Inductively Coupled Plasma Mass Spectrometry (ICP-MS)

Inductively Coupled Plasma Mass Spectrometry (ICP-MS) is an analytical technique used for elemental determinations, and it can characterize more than 20 elements at once (Fig. 3.14). In this study, collected samples were chemically analyzed using Inductively Coupled Plasma Mass Spectrometry (ICP-MS 7900). Collected particles were digested using Concentrated HCl: 6 mL and Concentrated HNO_3: 2 mL (3:1 ratio) through Microwave Digestion to dissolve the metals into an aqueous solution using the Microwave Reaction System (Anton Paar make model: Multiwave PRO, 30 min/6 cycles). The volume of the makeup sample was 40 ml of MilliQ water with a 0.2-µm membrane for filtration. The prepared aqueous solution was later introduced into an ICP-MS instrument (Agilent technologies 7900). The flow of Nebulizer and Auxillary gas flow was ~1 L/min and Plasma gas flow of ~15 L/min.

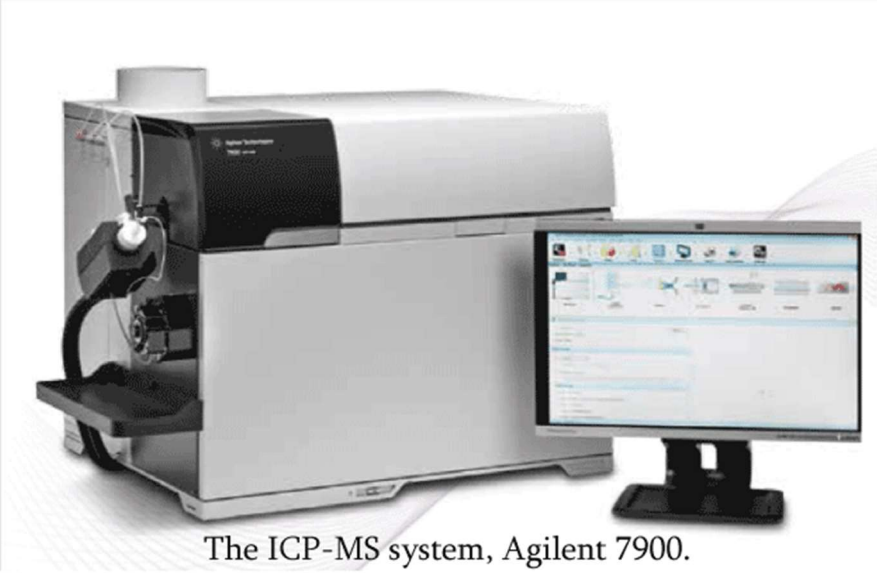

Figure 3.14 Pictorial view of the ICP-MS system used for the study.

3.8 Summary

This chapter provides a detailed discussion of the methodologies used in the study, including the study area, criteria for selecting households, types of instruments employed, and their working methodology, to create a clear picture of indoor monitoring. The statistical tools and models used for data analysis and data interpretation are described in this chapter, while the detailed results and discussions are presented in the subsequent chapter.

Chapter – 4

RESULTS AND DISCUSSION

4.1 Introduction

The particulate matter concentration (PM_{10}, $PM_{2.5}$, and PM_1) and meteorological variables (T and RH) observed in both indoor and outdoor environments exhibit significant seasonal variations. The average temperature and RH of the outdoor environment of each household ranged from (13 - 36 °C) and (39 - 88 %) during different seasons. In contrast, indoor mean temperature and RH varied from 19 to 33 °C and 51 to 92% in bedrooms, 17 to 36 °C, and 33 to 83 % in kitchens. During winter and monsoon, the temperature in outdoor was found to be lower, whereas the relative humidity was found to be higher. However, in summer, the RH in indoor was higher compared to the outdoors. RH variation during different seasons ranged from 33 to 92 % (summer); 47 to 87% (winter), and 65 to 85% (monsoon).

Table 4.1 Household information collected through a questionnaire survey of UP, LIG, MIG, and HIG households selected for the study.

Characteristics of the house	**Urban poor (UP)**	**Low-Income Group (LIG)**	**Middle-Income Group (MIG)**	**High-Income Group (HIG)**
No of occupants	5	5	4	4
Total no of rooms (excluding kitchen)	1	1	2	3
Cooking in a Day (times)	3	3	3	3
Separate Kitchen	No Separate Kitchen	Kitchen attached to bedroom	Separate	Separate
Kitchen ventilation	No	Yes (Window (1) + Door (1))	Yes (Window (1) +Door (1) + Exhaust fan (1))	Yes (Window (1) +Door (2) +Hood (1))
Bedroom ventilation	Door (1)	Window (1) + Door (1)	Window (1) + Door (1)	Window (1) + Door (1)

Fuel used for cooking	LPG	LPG	LPG	LPG

4.2 Temporal variation of particulate matter in different seasons

The seasonal mean concentration of particulates in the monsoon season was less than other seasons in all three different microenvironments (bedroom, kitchen, outdoor), followed by summer and winter (winter>summer>monsoon) (Table 4.2).

Table 4.2 Statistical summary of PM_{10}, $PM_{2.5}$, and PM_1 during monsoon, summer, and winter in (a) UP, (b) LIG, (c) MIG, and (d) HIG in different study environments.

SEASON	INCOME GROUP	SITE	BEDROOM			KITCHEN			OUTDOOR		
		PARAMETERS	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	PM_1 (µg/m³)	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	PM_1 (µg/m³)	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	PM_1 (µg/m³)
MONSOON	UP*	Min	6	6	5	11	8	7	16	7	3
		Max	1472	1435	879	512	485	412	61	30	16
		Mean ±SD	56±116	47±112	39±79	59±57	49±46	44±40	30±10	13±5	6±3
	LIG*	Min	3	3	2	8	7	6	26	11	4
		Max	472	301	274	603	304	234	129	50	24
		Mean± SD	61±49	34±29	28±25	67±56	49±39	42±32	42±18	17±6	6±3
	MIG*	Min	10	8	7	10	9	8	22	10	4
		Max	430	394	363	1674	1605	1060	65	23	10
		Mean± SD	63±63	46±55	38±50	80±133	59±124	45±90	45±10	16±3	6±2
	HIG*	Min	14	13	12	3	3	3	22	9	3
		Max	2941	2649	1316	1926	942	631	50	23	12
		Mean± SD	148±311	128±286	102±198	70±119	42±64	34±49	31±6	13±2	6±2
WINTER	UP*	Min	81	70	64	62	57	54	85	71	62
		Max	2015	891	592	3440	1361	927	503	476	412
		Mean± SD	196±133	162±87	146±66	214±248	177±134	151±80	184±91	160±77	142±69
	LIG*	Min	36	23	15	40	30	15	50	21	16
		Max	566	320	292	1017	537	415	207	128	114
		Mean± SD	131±64	80±38	64±34	182±109	98±59	78±49	90±27	58±27	50±25
	MIG*	Min	41	21	15	30	25	21	55	40	35
		Max	3290	2301	1037	7900	7630	2452	3048	383	161
		Mean± SD	181±241	130±158	106±104	247±469	200±428	156±207	218±400	90± 46	75±29
	HIG*	Min	49	48	47	44	29	20	94	59	51
		Max	1311	1275	1055	1301	1211	777	243	153	136
		Mean± SD	156±129	145±123	135±107	132±125	97±100	81±73	128±22	107±20	99±20
SUMMER	UP*	Min	23	13	7	22	15	7	29	17	11
		Max	1668	350	196	2361	903	515	551	226	178
		Mean± SD	134±125	73±46	53±36	155±200	78±81	54±51	123±93	47±26	28±18
	LIG*	Min	22	13	8	36	19	12	35	20	9
		Max	395	285	259	610	365	323	546	326	97
		Mean± SD	110±66	67±43	56±38	137±79	83±55	65±47	93±54	49±30	32±20
	MIG*	Min	2	2	2	2	2	2	14	10	4
		Max	580	429	338	1692	1173	277	64	22	11
		Mean± SD	44±73	33±62	24±43	30±83	17±60	9±18	35±11	14±3	6±1
	HIG*	Min	13	9	7	7	5	4	34	17	8
		Max	1283	1262	982	1781	420	332	142	74	58
		Mean± SD	66±111	54±108	47±91	148±191	45±50	32±40	67±21	33±12	21±11

Note: UP*- urban poor, LIG*- Low income group, MIG* Middle income group, and HIG* High income group

The analysis revealed that the concentration observed in the kitchen was higher than in the bedroom. The highest concentration of particulate matter was found in the MIG kitchen during the winter season with a concentration of 247µg/m^3, 200 µg/m^3, and 156 µg/m^3 (Fig 4.1, Table 4.2) for PM_{10}, $PM_{2.5}$, and PM_1, respectively.

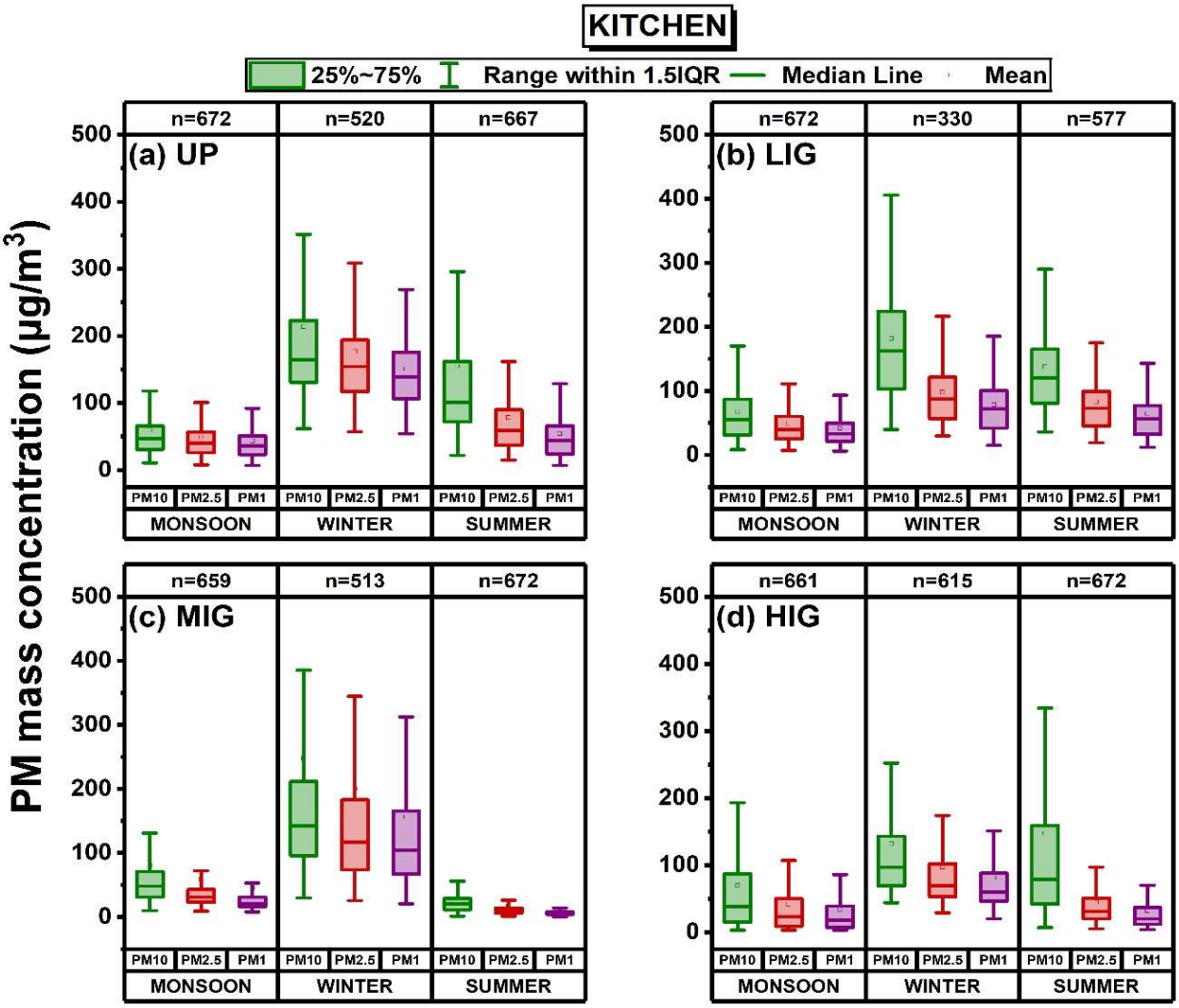

Figure 4.1 Box whisker analysis of PM_{10}, $PM_{2.5}$, and PM_1 during monsoon, summer, and winter in (a) UP, (b) LIG, (c) MIG, (d) HIG in kitchen. (The data represents 15-minute interval data for 7 days plotted using a box whisker plot in which '□' represents the mean concentration in each size bin. The center line of each box corresponds to the median value, and the box's boundaries correspond to the lower and upper quartile values. The '–' at the top and the bottom of each box denote the maximum and minimum values, respectively. The '+' symbols in red denote the outliers (data points scattered from the quartile values).

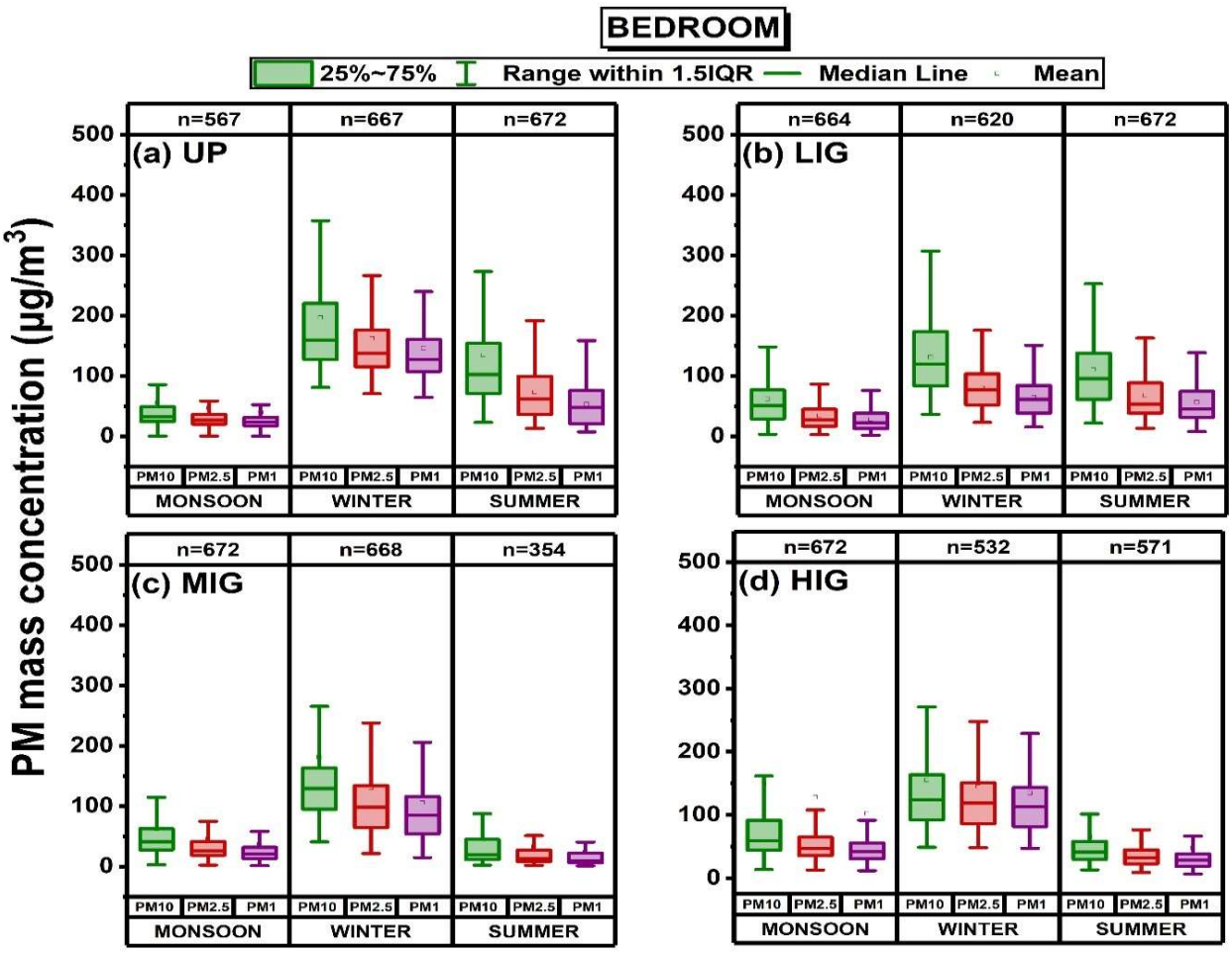

Figure 4.2 Box whisker analysis of PM_{10}, $PM_{2.5}$, and PM_1 during monsoon, summer, and winter in (a) UP (b) LIG (c) MIG (d) HIG in bedroom.

However, during summer, the concentration in MIG household was observed to be the lowest, i.e., 30 µg/m^3, 17 µg/m^3 and 9 µg/m^3 (Fig.4.2). In the bedroom, the maximum concentration of PM_{10} was found in UP households (196 µg/m^3) during winter, whereas the minimum concentration (44 µg/m^3) was found in MIG during summer (Table 1). Fine particulate matter ($PM_{2.5}$) and sub-fine (PM_1) particle concentration also followed a similar pattern as of PM_{10}, having a higher concentration in UP (162 µg/m^3 and 146 µg/m^3) and lowest in the MIG households (33 µg/m^3 and 24 µg/m^3) (Fig. 4.2).

During monsoon, the order of PM_{10} concentration in different households in kitchen was MIG> HIG> LIG> UP. Similarly, in winter, it was MIG> UP> LIG> HIG, and in summer the order was UP> HIG> LIG> MIG. The winter PM_{10} concentration in the UP ranged from 184 to 214 µg/m^3 in all three different microenvironments (Fig 4.3).

Similarly, in bedroom, during winter and summer seasons, the higher concentrations of PM_{10} were found to be 196 µg/m^3 and 134 µg/m^3 (Fig 4.3).

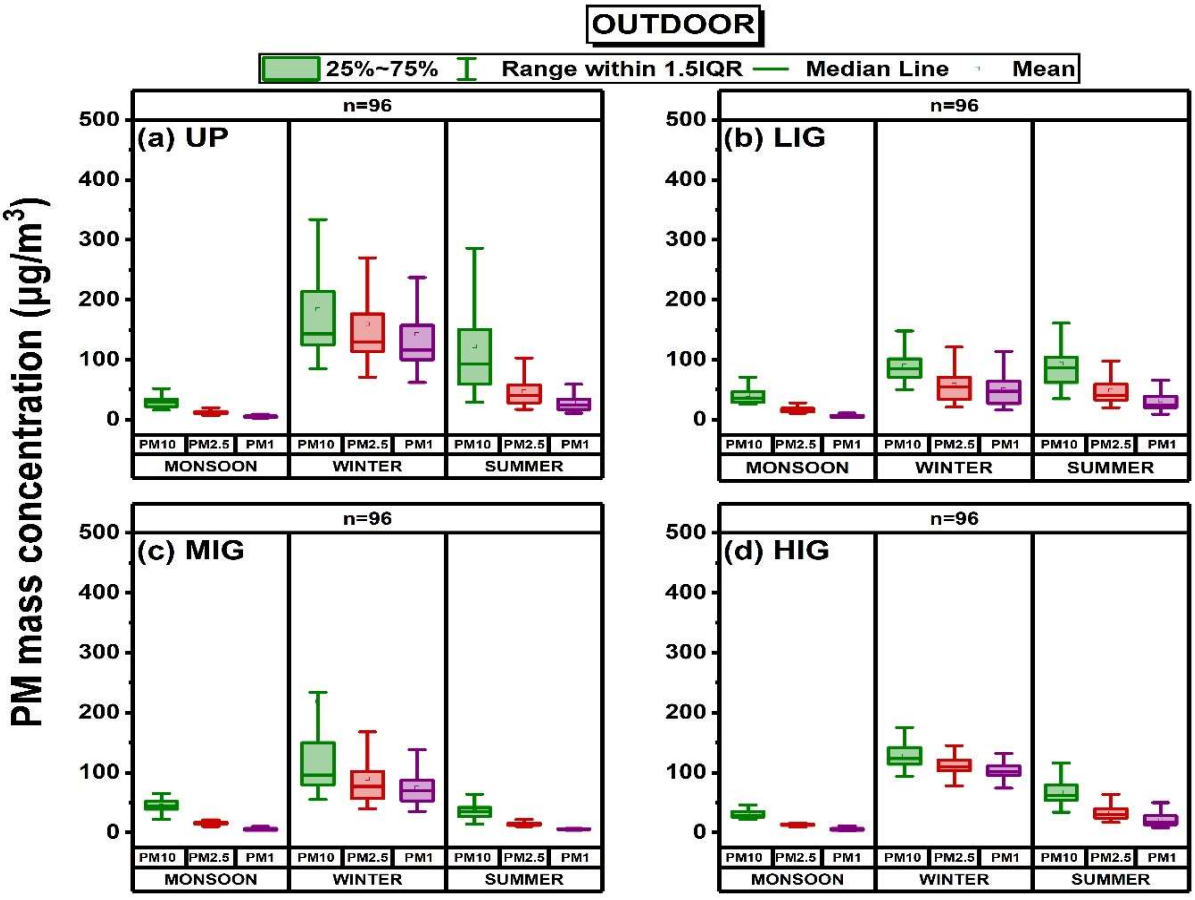

Figure 4.3 Box whisker analysis of PM_{10}, $PM_{2.5}$ and PM_1 during monsoon, summer and winter in (a) UP (b) LIG (c) MIG (d) HIG in outdoor.

During the monsoon, $PM_{2.5}$ concentrations ranged from 40 µg/m^3 to 60 µg/m^3 in all four socio-economic strata. On the other hand, in winter and summer, it was ~100 µg/m^3 to 200 µg/m^3, and ~20 µg/m^3 to 90 µg/m^3, respectively. The overall mean $PM_{2.5}$ concentration followed the same seasonal pattern of winter>summer>monsoon in both indoor and outdoor environments. In indoor environment, the bedroom concentration was lower than in the kitchen, but in terms of exposure, people spend more time (6 to 10 hrs) in bedroom compared to kitchen (< 4 hrs), which poses a serious threat to human health. The differences in exposure times to pollution in the same household but in different environs is a new insight that needs to be taken into account when assessing the health impact.

4.3 Temporal variation of particulates during day and night

We classified the temporal concentrations into daytime and nighttime to highlight variations in PM levels associated with household activities. PM_{10} concentration in kitchen was found to be high (320 µg/m^3) in MIG during day time in winter (Fig.4.4, 4.5, 4.6, Table 4.3).

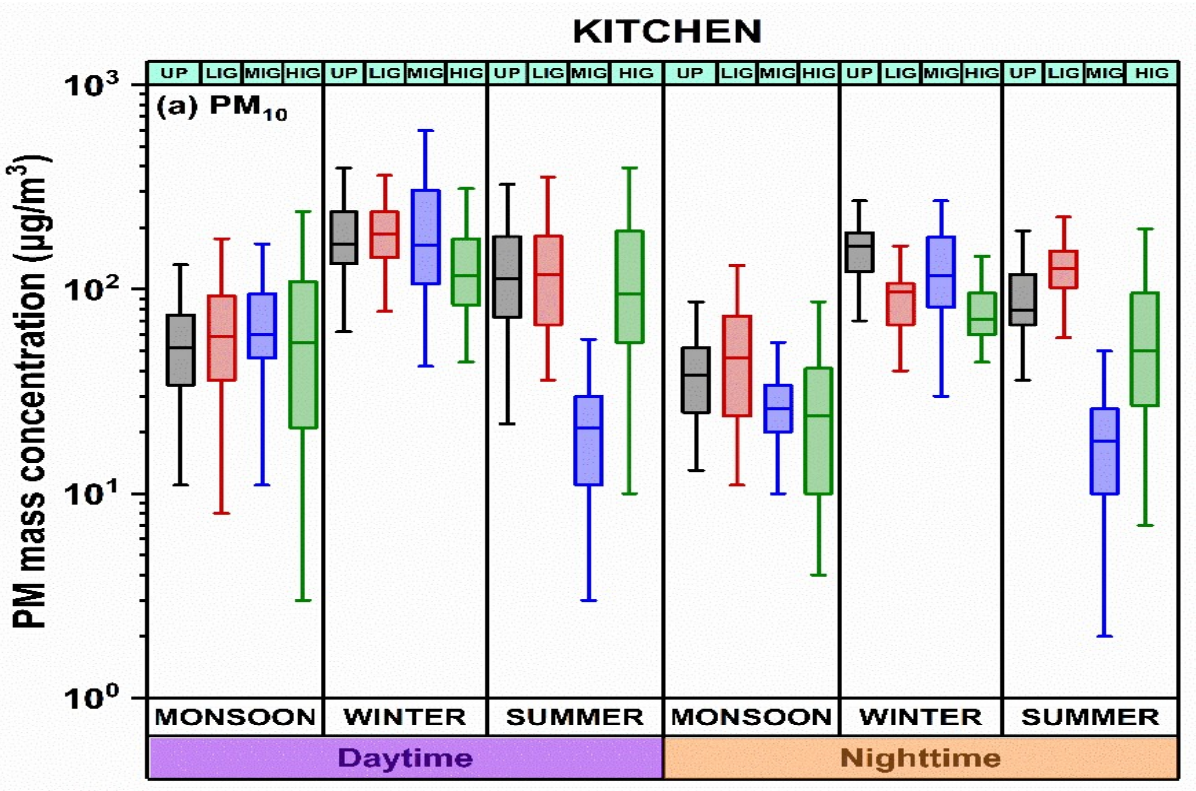

Figure 4.4 Box whisker analysis of (a) PM_{10} concentrations in kitchen during daytime (06:00 AM to 10:00 PM) and nighttime (10:00 PM to 06:00 AM) in monsoon, winter, and summer.

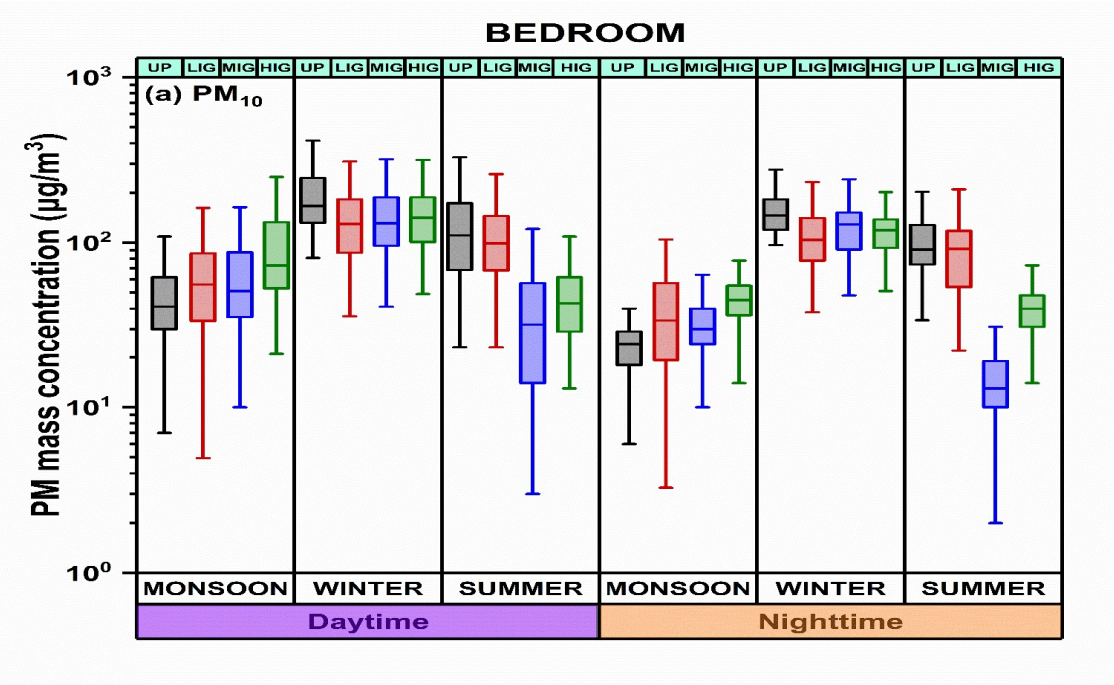

Figure 4.5 Box whisker analysis of (a) PM_{10} concentrations in bedroom during daytime (06:00 AM to 10:00 PM) and nighttime (10:00 PM to 06:00 AM) in monsoon, winter, and summer.

This is due to the high intensity of indoor sources like cooking/worshiping, which took place in the kitchen. Compared to other income groups, frequency of cooking activities and prayer (use of incense sticks) occurred in the MIG kitchen, lighting incense sticks during prayers was also observed in HIG (200 µg/m^3) during the monsoon season in the bedroom environment. During summer, the concentration of PM_{10} in the UP bedroom (146 µg/m^3) and kitchen (173 µg/m^3) was high due to poor ventilation inside the households (Fig. 4.7, 4.8, and Table 4.3). Similarly, in UP, the PM_{10} concentration during nighttime in bedroom was found to be higher in winter (166 µg/m^3) followed by summer (109 µg/m^3). Due to lack of space (as no major room demarcation as kitchen and bedroom exists) in UP and LIG households, particulate matter concentration was found to be high at night compared to well-structured households (MIG and HIG) (Fig. 4.8, 4.9) The concentration trends of $PM_{2.5}$ and PM_1 were similar to PM_{10} concentration. The day and nighttime concentration analysis revealed that during daytime, the concentration was almost two times higher than at night due to the contribution of the intensity of sources (Fig. 4.10, 4.11, Table 4.4). Similar to changes in concentration during the peak and non-

peak hours of the urban road environment, indoor concentrations also vary based on the intensity of sources during the day and nighttime (Fig. 4.12, Table 4.5).

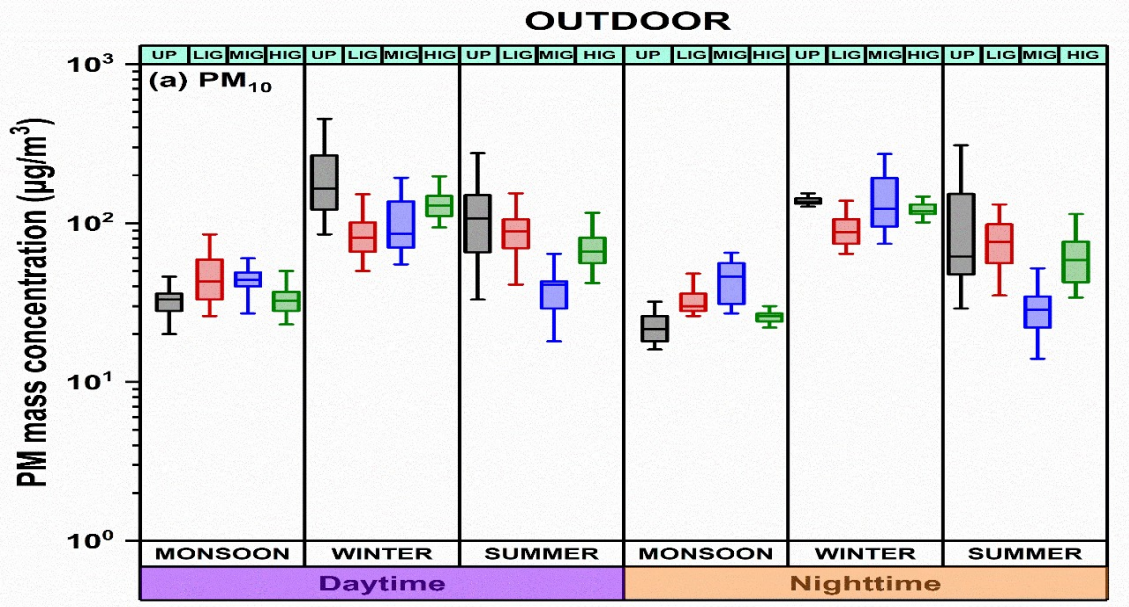

Figure 4.6 Box whisker analysis of (a) PM_{10} concentrations outdoor during daytime (06:00 AM to 10:00 PM) and nighttime (10:00 PM to 06:00 AM) in monsoon, winter, and summer.

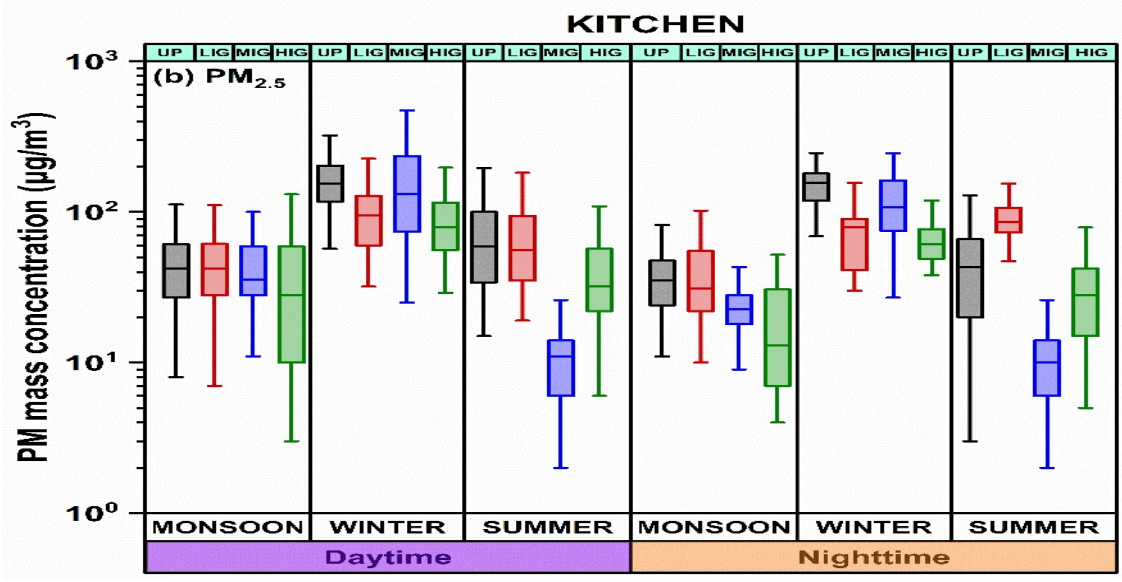

Figure 4.7 Box whisker analysis of (a) $PM_{2.5}$ concentrations in kitchen during daytime (06: 00 AM to 10:00 PM) and nighttime (10:00 PM to 06:00 AM) in monsoon, winter, and summer.

Table 4.3 Statistical summary of PM_{10}, $PM_{2.5}$, and PM_1 during day and nighttime in monsoon for UP, LIG, MIG, and HIG.

Season	Income Group	Phase	Site Parameter	BEDROOM			KITCHEN			OUTDOOR		
				$PM_{2.5}$ (µg/m^3)	PM_1 (µg/m^3)	PM_{10} (µg/m^3)	$PM_{2.5}$ (µg/m^3)	PM_1 (µg/m^3)	PM_{10} (µg/m^3)	$PM_{2.5}$ (µg/m^3)	PM_1 (µg/m^3)	PM_{10} (µg/m^3)
MONSOON	UP	Day	min	7	6	5	11	8	7	20	9	4
			max	1472	1435	879	512	485	412	61	30	16
			mean± SD	72±139	60±136	49±95	68±66	55±54	48±47	33±10	15±6	7±3
			median	41	30	26	52	42	37	33	13	6
		Night	min	6	6	5	13	11	10	16	7	3
			max	168	149	143	116	114	107	32	17	8
			mean± SD	24±13	22±12	21±12	40±19	38±18	35±17	22±5	10±3	4±1
			median	24	23	21	38	35	33	22	9	4
	LIG	Day	min	5	4	3	8	7	6	26	12	4
			max	472	301	274	603	304	234	129	50	24
			mean± SD	68±53	36±31	29±27	74±62	52±42	44±34	49±21	20±7	8±4
			median	56	28	23	59	42	35	43	18	7
		Night	min	3	3	2	11	10	10	26	11	4
			max	180	98	77	242	222	206	54	22	8
			mean± SD	42±30	29±20	24±18	53±37	42±31	37±27	33±6	14±3	5±1
			median	34	20	17	46	31	27	30	14	4
	MIG	Day	min	10	8	7	11	11	9	22	10	4
			max	430	394	363	1674	1605	1060	65	18	8
			mean± SD	78±71	56±64	46±59	107±157	77±149	58±109	44±9	14±2	5±1
			median	51	32	25	60	36	25	44	15	5
		Night	min	10	8	7	10	9	8	27	12	5
			max	85	70	62	103	89	82	65	23	10
			mean± SD	33±13	25±9	21±8	28±12	24±9	19±8	45±12	19±3	8±1
			median	30	23	19	26	23	17	46	20	8
	HIG	Day	min	21	17	15	3	3	3	23	9	3
			max	2941	2649	1316	1926	942	631	50	23	12
			mean± SD	200±370	172±341	135±235	88±141	51±75	40±57	33±6	13±3	5±2
			median	73	53	46	55	28	22	33	13	5
		Night	min	14	13	12	4	4	3	22	11	5
			max	91	69	59	175	98	86	30	14	8
			mean± SD	45±15	39±12	36±11	34±31	24±23	20±20	26±2	13±1	6±1
			median	45	40	36	25	13	12	26	13	6

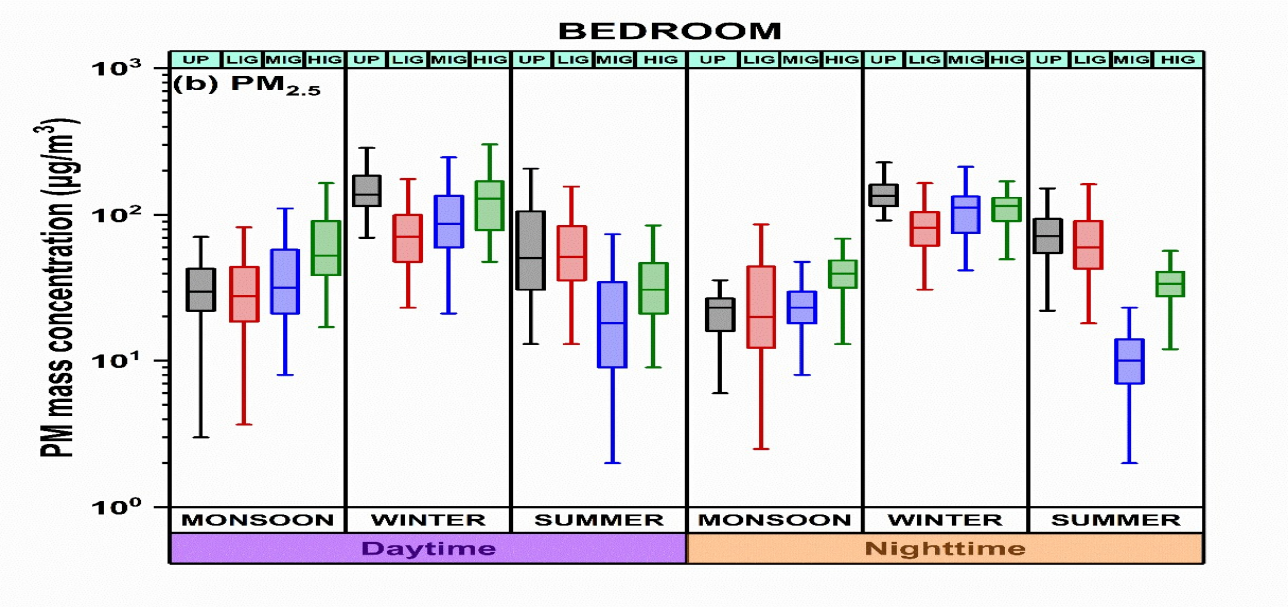

Figure 4.8 Box whisker analysis of (a) $PM_{2.5}$ concentrations in the bedroom during daytime (06: 00 AM to 10:00 PM) and nighttime (10:00 PM to 06:00 AM) in monsoon, winter and summer.

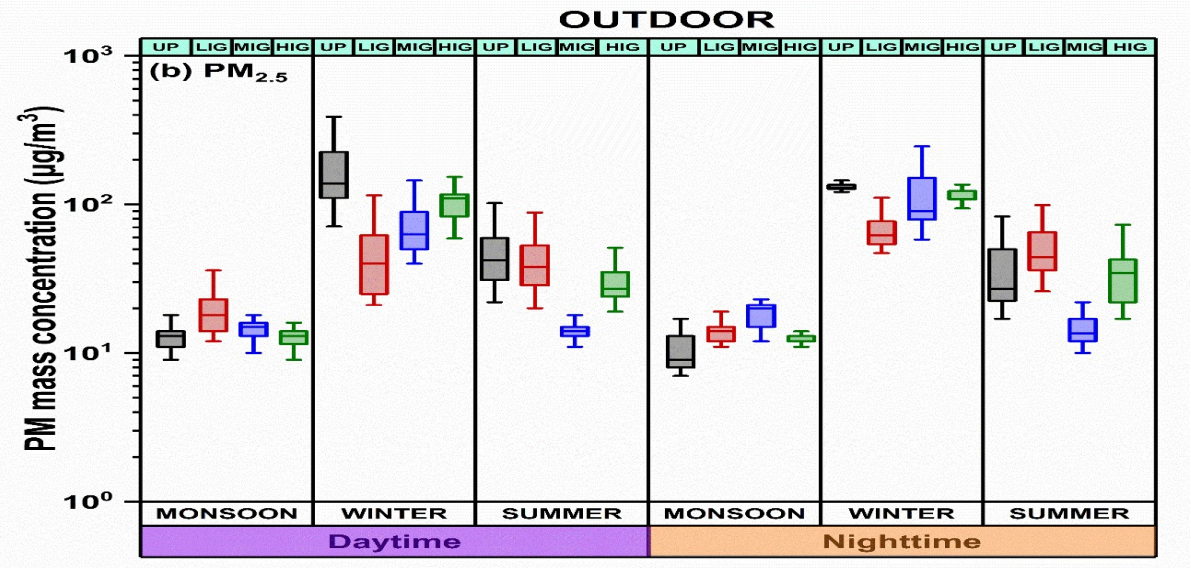

Figure 4.9 Box whisker analysis of (a) $PM_{2.5}$ concentrations in outdoor during daytime (06: 00 AM to 10:00 PM) and nighttime (10:00 PM to 06:00 AM) in monsoon, winter and summer.

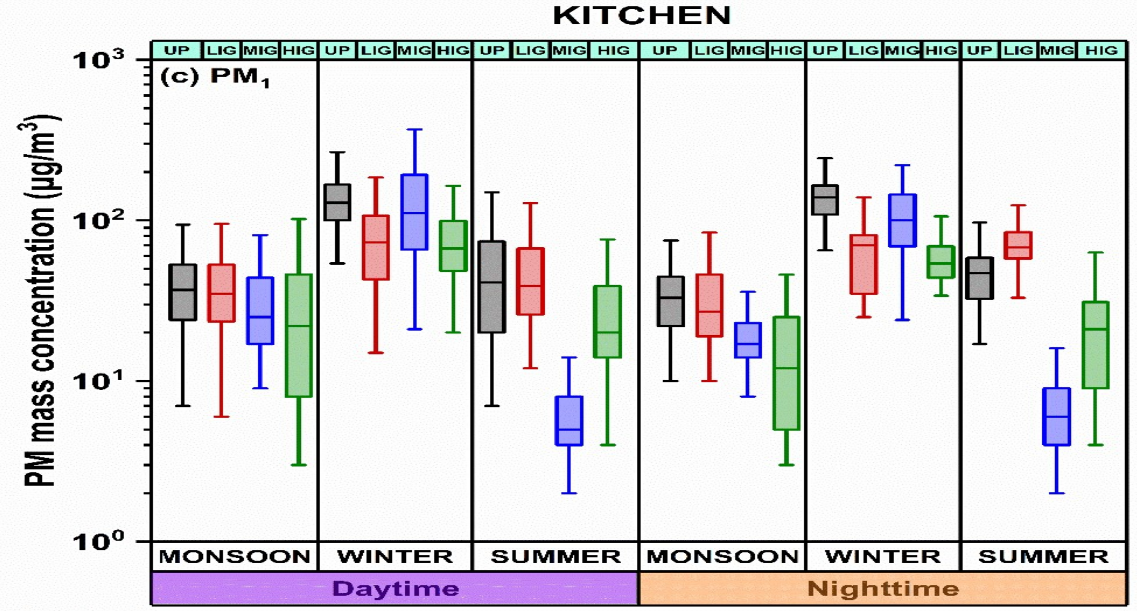

Figure 4.10 Box whisker analysis of (a) PM_1 concentrations in kitchen during daytime (06:00 AM to 10:00 PM) and nighttime (10:00 PM to 06:00 AM) in monsoon, winter and summer.

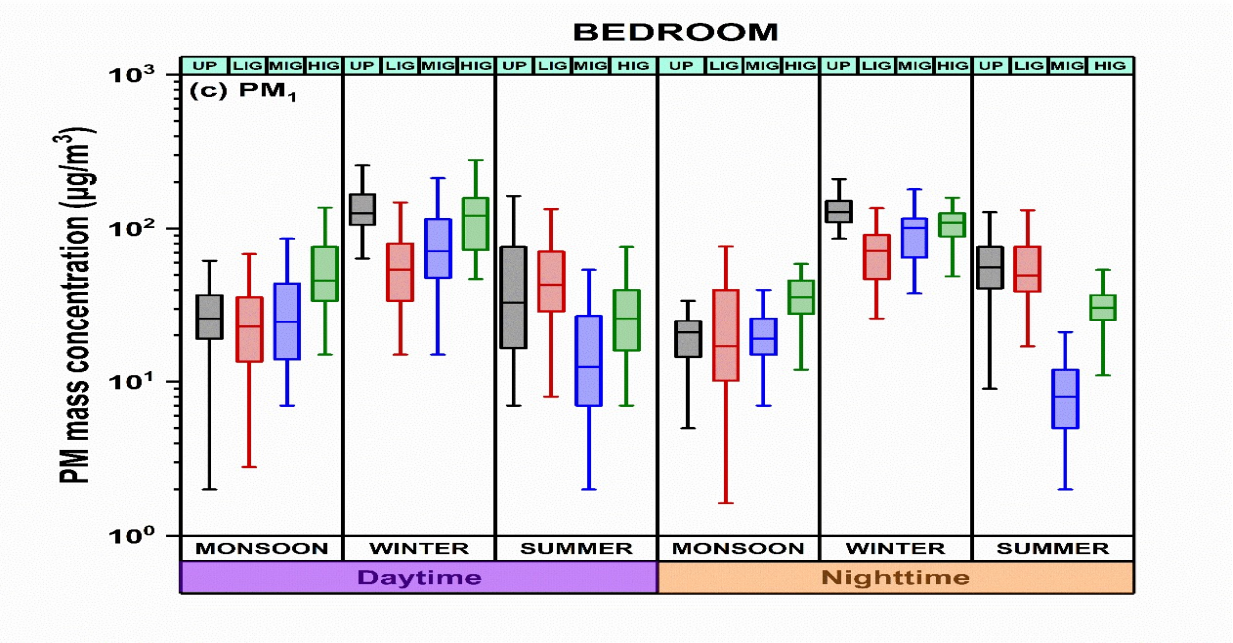

Figure 4.11 Box whisker analysis of (a) PM_1 concentrations in bedroom during daytime (06: 00 AM to 10:00 PM) and nighttime (10:00 PM to 06:00 AM) in monsoon, winter and summer.

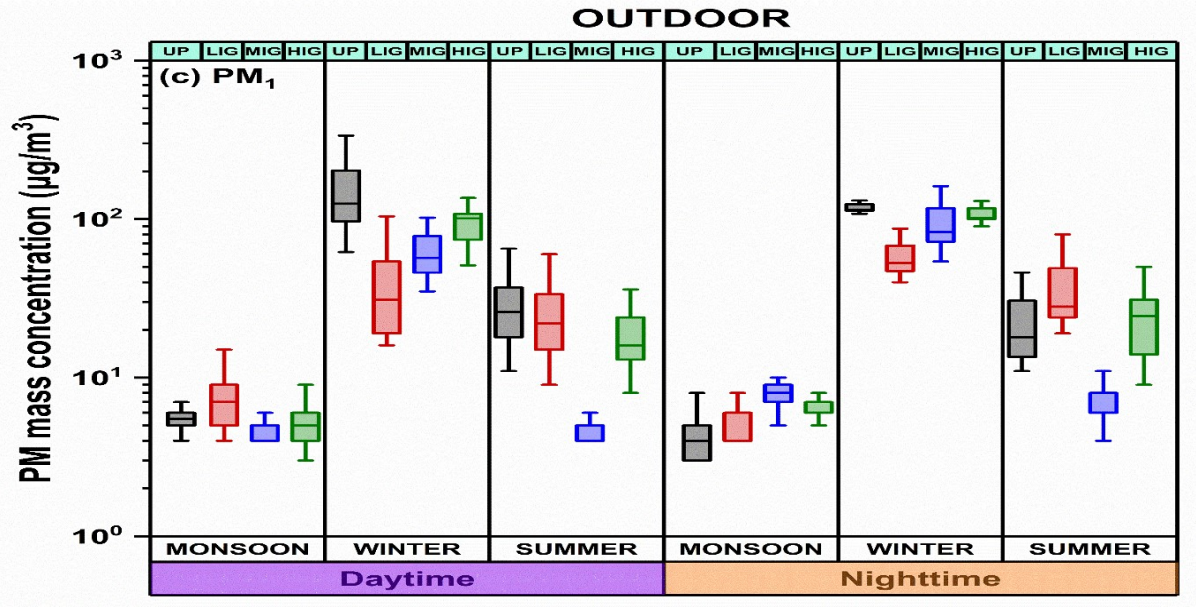

Figure 4.12 Box whisker analysis of (a) PM_1 concentrations in outdoor during daytime (06: 00 AM to 10:00 PM) and nighttime (10:00 PM to 06:00 AM) in monsoon, winter and summer.

Table 4.4 Statistical summary of PM_{10}, $PM_{2.5}$, and PM_1 during day and nighttime in winter for UP, LIG, MIG, and HIG.

Season	Income Group	Phase	Site Parameter	BEDROOM			KITCHEN			OUTDOOR		
				PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	PM_1 (µg/m³)	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	PM_1 (µg/m³)	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	PM_1 (µg/m³)
WINTER	UP	Day	min	81	70	64	62	57	54	85	71	62
			max	2015	891	592	3440	1361	927	503	476	412
			mean± SD	211±150	167±96	148±72	240±297	189±158	157±92	202±102	171±89	152±80
			median	167	138	126	167	154	140	165	138	125
		Night	min	97	92	86	70	69	65	127	121	108
			max	773	594	511	486	447	407	162	153	143
			mean± SD	166±81	152±64	142±53	161±59	152±52	139±46	138±9	132±7	118±8
			median	146	135	128	162	156	139	136	130	115
	LIG	Day	min	36	23	15	78	32	15	50	21	16
			max	566	320	292	1017	537	415	207	128	114
			mean± SD	138±67	79±41	62±36	210±108	104±61	81±51	89±32	51±31	43±29
			median	130	71	54	187	95	73	81	40	31
		Night	min	38	31	26	40	30	25	64	47	40
			max	289	165	136	407	307	269	138	113	104
			mean± SD	116±54	83±30	70±26	120±84	84±52	71±44	91±19	67±16	59±16
			median	104	82	72	97	79	70	88	62	53
	MIG	Day	min	41	21	15	42	25	21	55	40	35
			max	3290	1525	1010	7900	7630	2452	2049	189	102
			mean± SD	198±253	134±156	107±115	320±580	251±533	186±254	189±357	74±31	62±18

			median	131	87	72	164	131	111	86	63	57
		Night	min	48	42	38	30	27	24	74	58	54
			max	2419	2301	1037	271	245	221	3048	383	161
			mean± SD	149±214	124±162	103±80	126±59	115±53	106±49	268±461	117±54	97±31
			median	129	112	101	118	108	101	123	90	83
	HIG	Day	min	49	48	47	44	29	20	94	59	51
			max	1311	1275	1055	1301	1211	777	243	153	136
			mean± SD	174±151	160±145	147±126	161±148	114±121	93±88	131±25	104±24	94±22
			median	137	129	121	118	79	67	129	110	101
		Night	min	51	50	49	44	38	34	101	94	90
			max	761	688	597	191	156	139	147	136	130
			mean± SD	125±73	119±65	113±56	80±28	66±22	60±21	123±11	114±10	107±11
			median	119	115	110	72	61	54	119	109	102

Table 4.5 Statistical summary of PM_{10}, $PM_{2.5}$, and PM_{1} during day and nighttime in summer for UP, LIG, MIG and HIG.

Season	Income Group	Phase	Site Parameter	BEDROOM			KITCHEN			OUTDOOR		
				PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	PM_{1} (µg/m³)	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	PM_{1} (µg/m³)	PM_{10} (µg/m³)	$PM_{2.5}$ (µg/m³)	PM_{1} (µg/m³)
SUMMER	UP	Day	min	23	13	7	22	15	7	33	22	11
			max	1668	350	196	2361	903	515	551	226	178
			mean± SD	146±144	71±51	49±38	173±226	84±92	57±58	130±96	50±27	31±20
			median	111	51	33	113	59	41	107	42	26
		Night	min	34	22	9	36	26	17	29	17	11
			max	515	153	136	890	432	199	366	96	46
			mean± SD	109±62	76±30	60±27	104±84	64±38	48±23	105±84	39±22	22±10
			median	91	72	56	79	60	47	62	27	18
	LIG	Day	min	23	13	8	58	47	33	41	20	9
			max	395	282	254	448	362	323	3502	326	97
			mean± SD	116±67	66±45	55±40	134±53	94±39	77±35	126±307	47±34	29±20
			median	99	52	43	127	86	68	89	38	22
		Night	min	22	18	17	58	47	33	35	26	19
			max	360	285	259	448	362	323	131	99	80
			mean± SD	99±62	70±39	60±33	134±53	94±39	77±35	79±27	51±20	37±18
			median	92	60	50	127	86	68	76	44	28
	MIG	Day	min	3	2	2	3	2	1	18	11	4
			max	463	429	338	1692	1173	277	64	19	6
			mean± SD	54±78	41±72	30±50	32±93	19±71	10±22	39±10	14±2	5±1
			median	31	18	13	21	11	5	41	14	5
		Night	min	2	2	1	1	1	1	14	10	4
			max	580	237	108	805	210	52	52	22	11
			mean± SD	21±55	14±23	10±11	26±58	13±17	8±7	30±9	15±3	7±2
			median	13	10	8	18	10	6	29	14	6
	HIG	Day	min	13	9	7	10	6	4	42	19	8
			max	1283	1262	982	1781	420	332	142	74	57
			mean± SD	79±134	64±131	55±111	171±206	51±58	37±46	70±20	32±11	20±10

			median	43	31	26	95	32	20	66	27	16
		Night	min	14	12	11	7	5	4	34	17	9
			max	75	63	55	1165	143	108	114	73	58
			mean± SD	41±14	35±11	31±10	98±145	31±20	23±16	61±20	35±13	24±11
			median	40	34	31	50	28	21	59	35	25

4.4 Contribution of different-sized particulates to PM_{10}

Based on the type and intensity of sources, the percentage contribution of smaller-size particulates to PM_{10} varied during different seasons in all the households. Due to cooking activities, the contribution of PM_1 was found to be higher in kitchen environment (Fig.4.13) in all the income groups. In the indoor environment, the order of PM_1 concentration was UP>LIG>MIG>HIG, except for LIG in winter (Fig.4.13). Despite using LPG as a cooking fuel in all households, the infrastructure and ventilation also influence indoor pollution concentrations. Due to the influence of ventilation in kitchen, the contribution of PM_1 in summer was reduced twice when compared to winter and monsoon (Fig. 4.13). The contribution of particles in the size range of PM_1-$PM_{2.5}$ to PM_{10} was observed between 10 to 20 % in monsoon, ~<10 % in winter, and 12 to 22 % during summer.

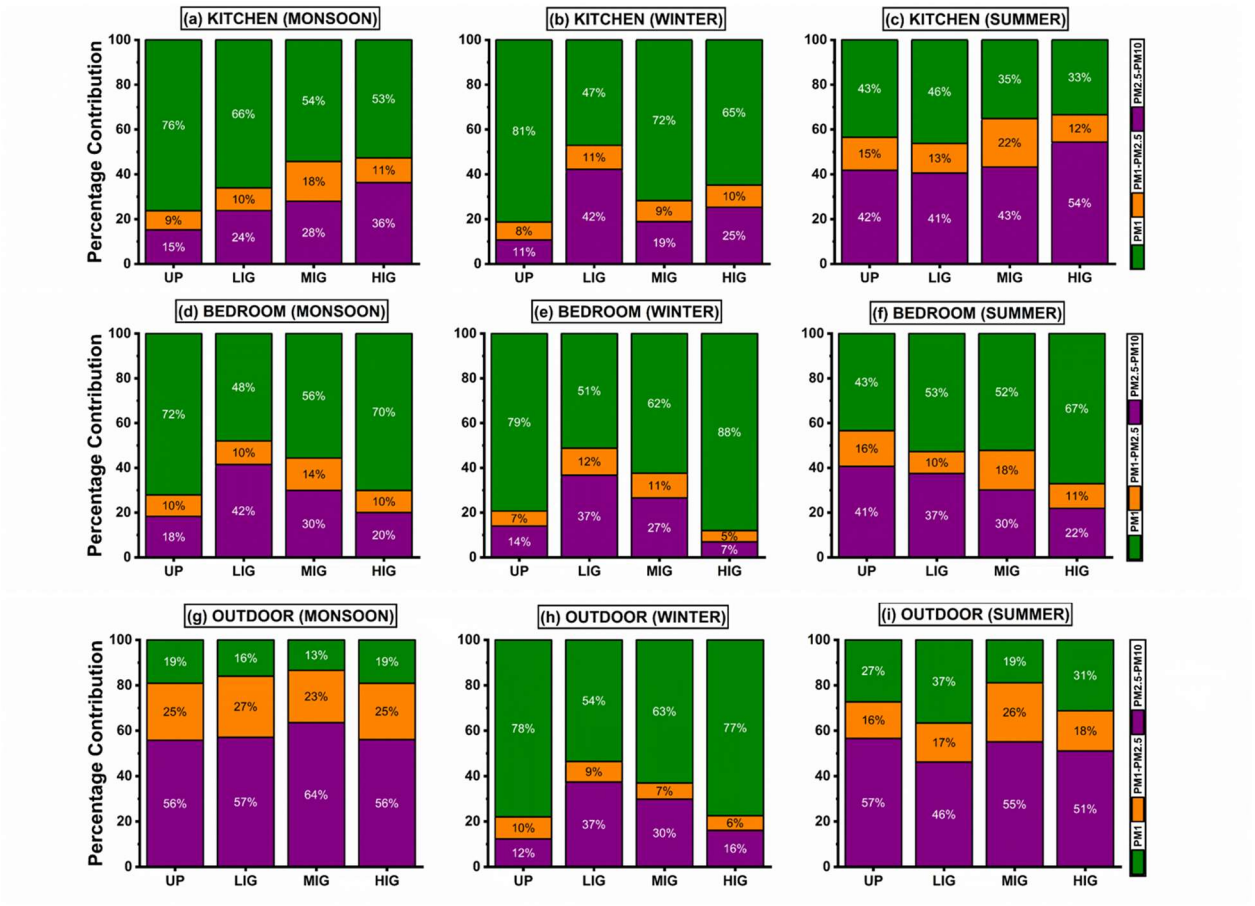

Figure 4.13 Percentage contribution of the different size ranges of PM concentrations to PM_{10} in kitchen, bedroom, and outdoor during monsoon, winter, and summer.

In bedroom microenvironment, PM_1 contribution reached a maximum of about 70 to 80% due to the influence of indoor sources in monsoon and winter in UP and HIG. The higher contribution of PM_1 in UP was due to poor ventilation, whereas in HIG, despite having good ventilation, a strong source (Incense stick usage) contributed for PM_1. During summer, the concentration of PM_1 in UP and LIG households was lower than in winter and monsoon seasons. Similar to PM concentrations in kitchen, the concentrations found in the bedroom were also in the order of UP> LIG> MIG> HIG. In indoor environments, irrespective of seasons, PM_1 concentration was found to be high. During summer, the PM_1 contribution in bedrooms of MIG and HIG was high (50 %) compared to the kitchen, despite having air-conditioned systems (in bedrooms of MIG and HIG) the higher concentration of PM_1 was found due to their occupants' behavior (worshiping) (Fig.4.13). In the outdoor environment, coarse particles contributed more than fine particles, except

during the winter season, when PM1 contributions were higher in both indoor and outdoor environments. In the kitchen, PM_1 contribution ranged from ~ 50 to 80% in selected households during different seasons. Particulate matter such as PM_1 and $PM_{2.5}$, known for their toxicity, which may cause severe human health impacts, were found to be high in the kitchens of UP and LIG households, where the building infrastructure was poor with no mechanical ventilation system and a separate space for kitchen and living (Table 4.5). The study in the kitchen and bedroom showed that in UP and LIG households, the proportion of kitchen concentration was similar to that of the bedroom, suggesting that kitchen sources directly influenced bedroom concentrations as well, when compared to MIG and HIG households.

4.5 Diurnal variation of particulate matter in Kitchen and Bedroom

The diurnal behavior concentration in the kitchen environment coincided with the cooking behavior of the residents (Fig. 4.14, Table 4.6)). In almost all income groups, the concentration of particulate matter was observed to be higher during cooking hours than non-cooking hours.

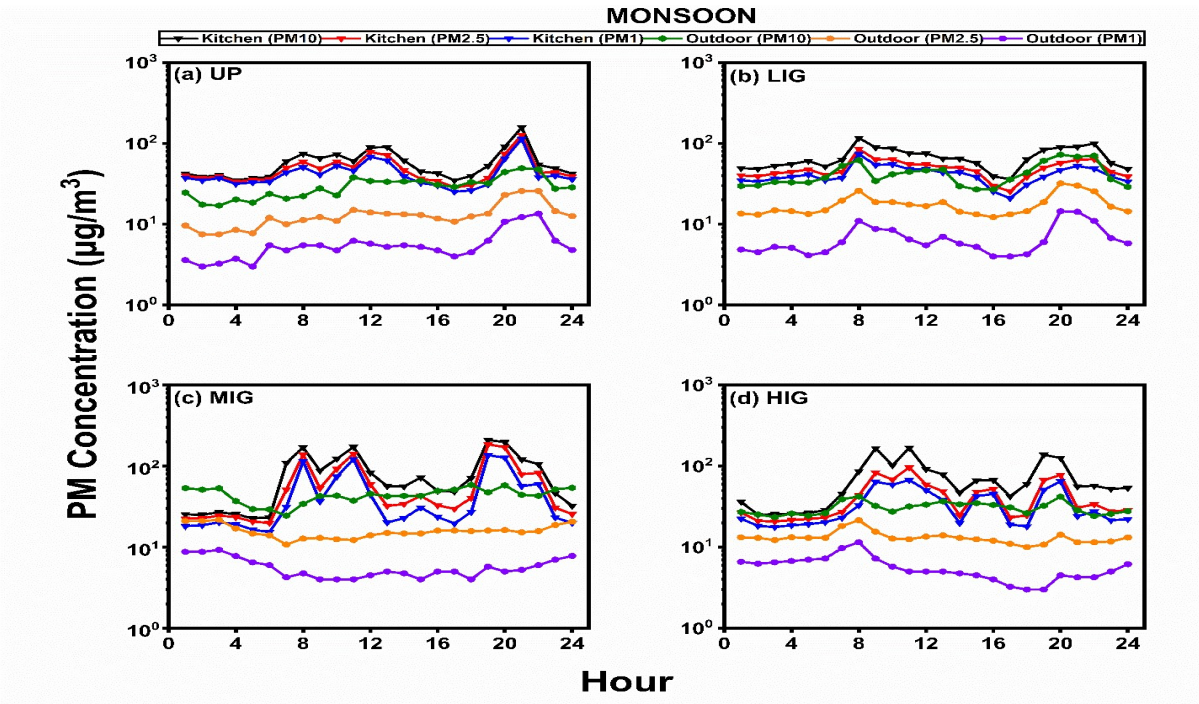

Figure 4.14 Diurnal variation analysis of PM_{10}, $PM_{2.5}$, and PM_1 in the kitchen & outdoors of selected households (a) UP (b) LIG (c) MIG (d) HIG during monsoon season.

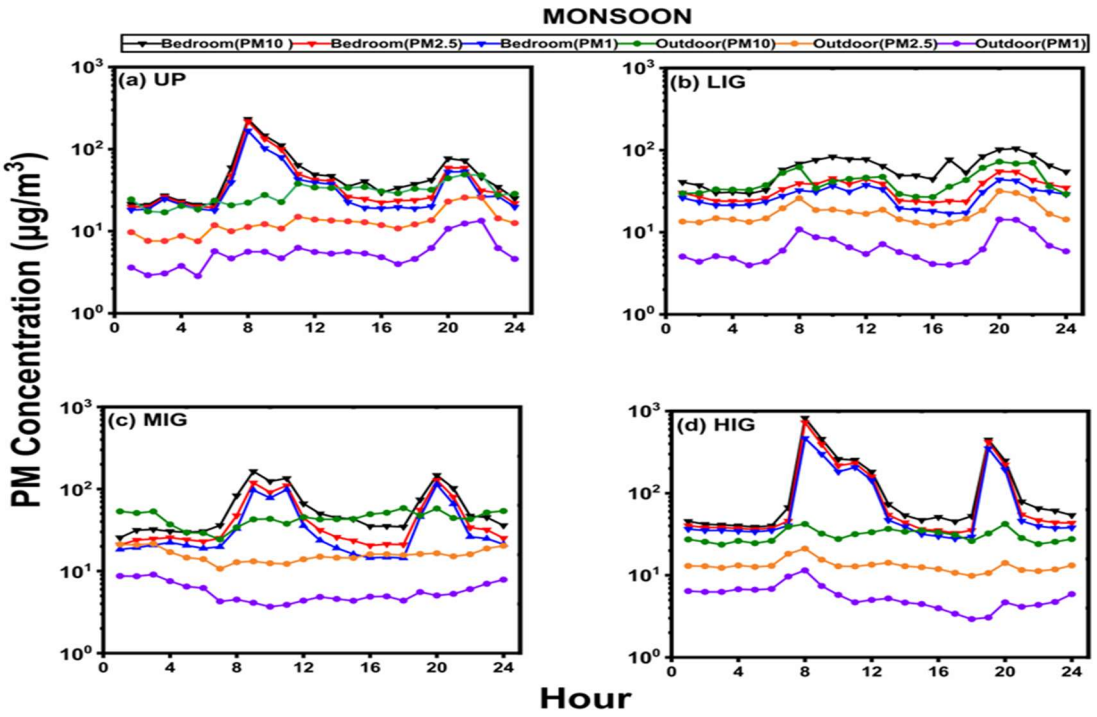

Figure 4.15 Diurnal variation analysis of PM_{10}, $PM_{2.5}$ and PM_1 in bedroom & outdoor of selected households (a) UP (b) LIG (c) MIG (d) HIG during monsoon season.

During the monsoon season, the cooking hour concentration in UP and LIG was found to be lower than in MIG and HIG (Fig. 4.15). During monsoon, the concentration of pollutants was higher in the bedroom than in the kitchen during morning and evening hours (Fig. 4.16). The higher concentration in the bedroom was due to house cleaning and worship activities. The outdoor diurnal concentration clearly showed that during cooking hours, the influence of outdoor concentration on indoor concentration was less. Diurnal concentration during winter in UP and LIG showed no significant changes during the cooking hours. During winter, bedrooms of all households were highly influenced by outdoor environment.

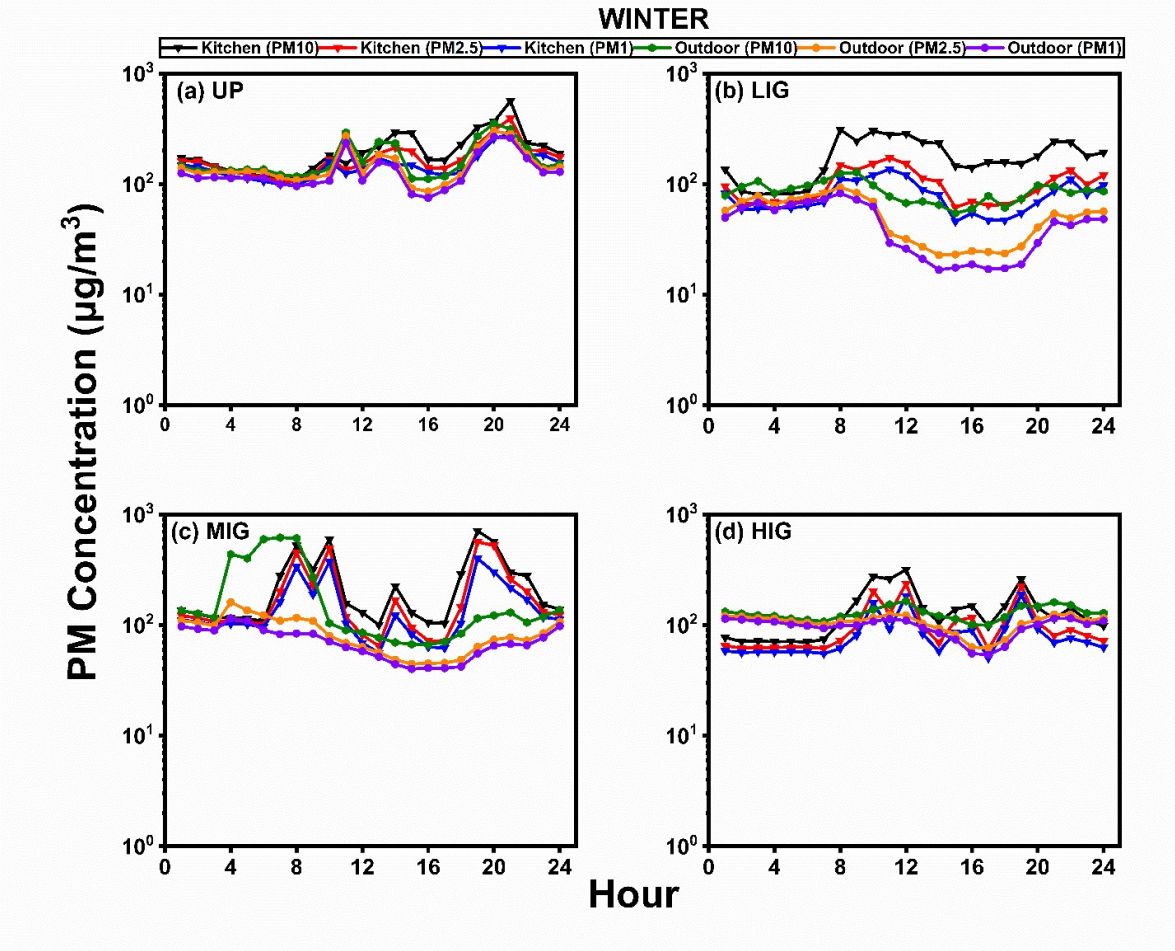

Figure 4.16 Diurnal variation analysis of PM_{10}, $PM_{2.5}$, and PM_1 in the kitchen & outdoors of selected households (a) UP (b) LIG (c) MIG (d) HIG during the winter season.

The household infrastructure also played a major role in UP and LIG for higher concentrations of particulate matter during the winter season. Even though the MIG and HIG were well structured, the existing baseline concentration influenced their indoor concentration during the winter period (Fig 4.17, Table 4.7). Compared to the winter and monsoon seasons, in summer, the diurnal concentration of particulate matter in UP and LIG indoors are comparable to outdoor concentration in both kitchen and bedrooms (Fig 4.19). The ventilation (door and window) effect during summer in UP and LIG caused the infiltration of outside concentration in households, and resulted in a similar pattern of concentration in both outdoor and indoor environments (Fig 4.19).

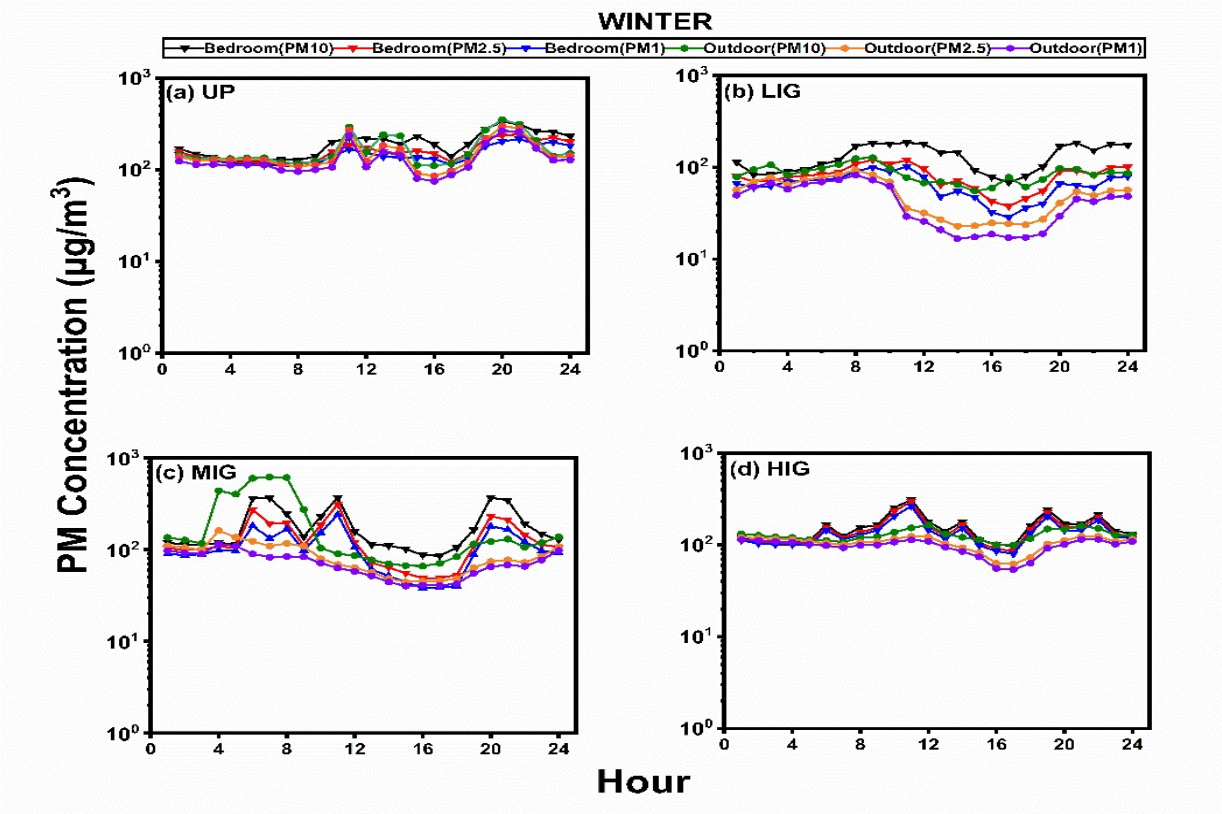

Figure 4.17 Diurnal variation analysis of PM_{10}, $PM_{2.5}$ and PM_1 in bedroom & outdoor of selected households (a) UP, (b)LIG (c) MIG (d) HIG during winter season.

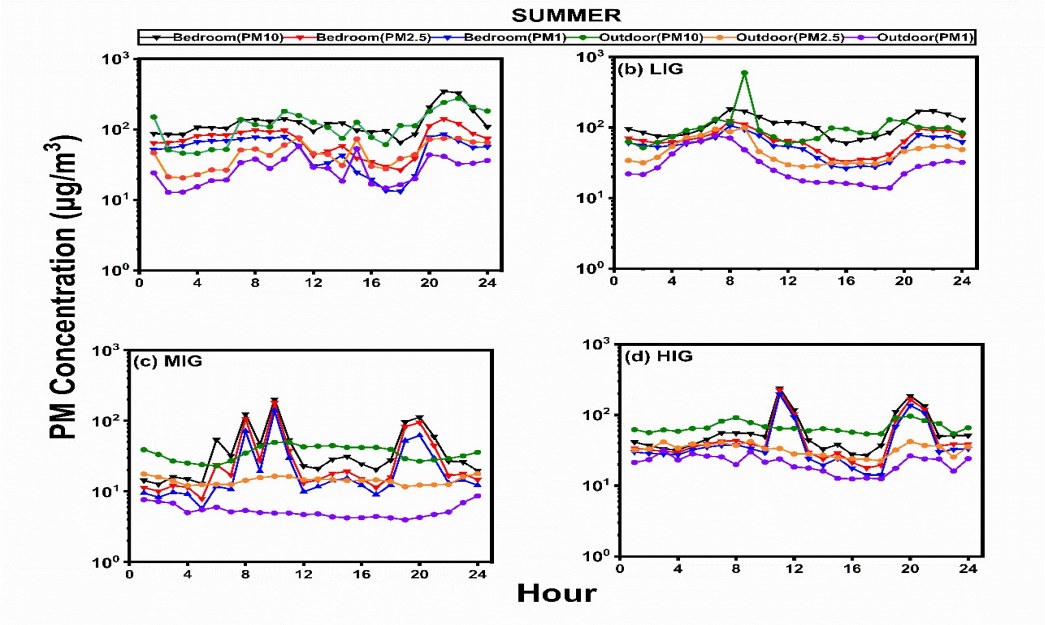

Figure 4.18 Diurnal variation analysis of PM_{10}, $PM_{2.5}$ and PM_1 in bedroom & outdoor of selected households (a) UP (b) LIG (c) MIG (d) HIG during summer season.

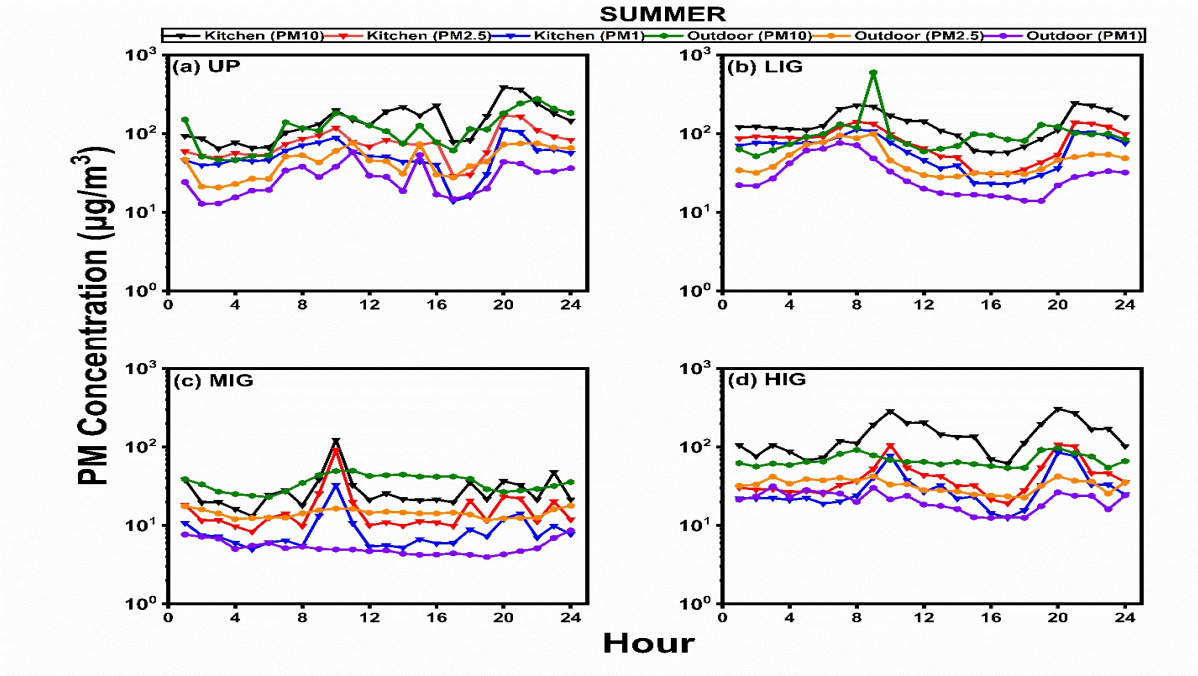

Figure 4.19 Diurnal variation analysis of PM_{10}, $PM_{2.5}$, and PM_1 in the kitchen & outdoor of selected households (a) UP (b) LIG (c) MIG (d) HIG during summer season.

Table 4.6 Statistical summary of Kruskal-Wallis test.

Season	**Microenvironment**	**Parameter**	**chi-square**	**df**	**P value**
Monsoon	Kitchen	qUFP	423.28	3	<0.05
Winter	Kitchen	qUFP	426.5	3	<0.05
Summer	Kitchen	qUFP	1735.9	3	<0.05
Monsoon	Bedroom	qUFP	522.56	3	<0.05
Winter	Bedroom	qUFP	753.77	3	<0.05
Summer	Bedroom	qUFP	622.69	3	<0.05
Monsoon	Outdoor	qUFP	222.22	3	<0.05

Winter	Outdoor	qUFP	145.6	2	<0.05
Summer	Outdoor	qUFP	386.28	3	<0.05

Table 4.7 Statistical summary of Shapiro-Wilk test.

Season	**Microenvironment**	**Parameter**	**W distribution**	**P value**
Monsoon	Kitchen	qUFP	0.71732	<0.05
Winter	Kitchen	qUFP	0.92325	<0.05
Summer	Kitchen	qUFP	0.76723	<0.05
Monsoon	Bedroom	qUFP	0.57642	<0.05
Winter	Bedroom	qUFP	0.94954	<0.05
Summer	Bedroom	qUFP	0.81423	<0.05
Monsoon	Outdoor	qUFP	0.85626	<0.05
Winter	Outdoor	qUFP	0.81403	<0.05
Summer	Outdoor	qUFP	0.77892	<0.05

33

4.6 Indoor/Outdoor ratio

The indoor-to-outdoor pollution (I/O) ratios are derived to quantify the influence of outdoor pollutants on the indoor concentrations. If the I/O ratio is > 1, then it indicates that indoor sources are more dominant than outdoor sources and vice versa. I/O ratios were analyzed diurnally to determine the role of different activities, such as cooking, dusting, and worship/prayers (Fig. 4.20). I/O ratios of PM_{10}, $PM_{2.5}$, and PM_1 significantly varied in the kitchen based on cooking hours. The mean indoor and outdoor ratios showed that outdoor pollutants influenced both indoor environments (bedroom and kitchen) more

during the winter season. The I/O ratio of all PM_{10}, $PM_{2.5}$, and PM_1 during winter in bedroom and kitchen ranged from 1.1 to 1.8 and 0.8 to 2.2 (Fig. 4.20, Table 4.8).

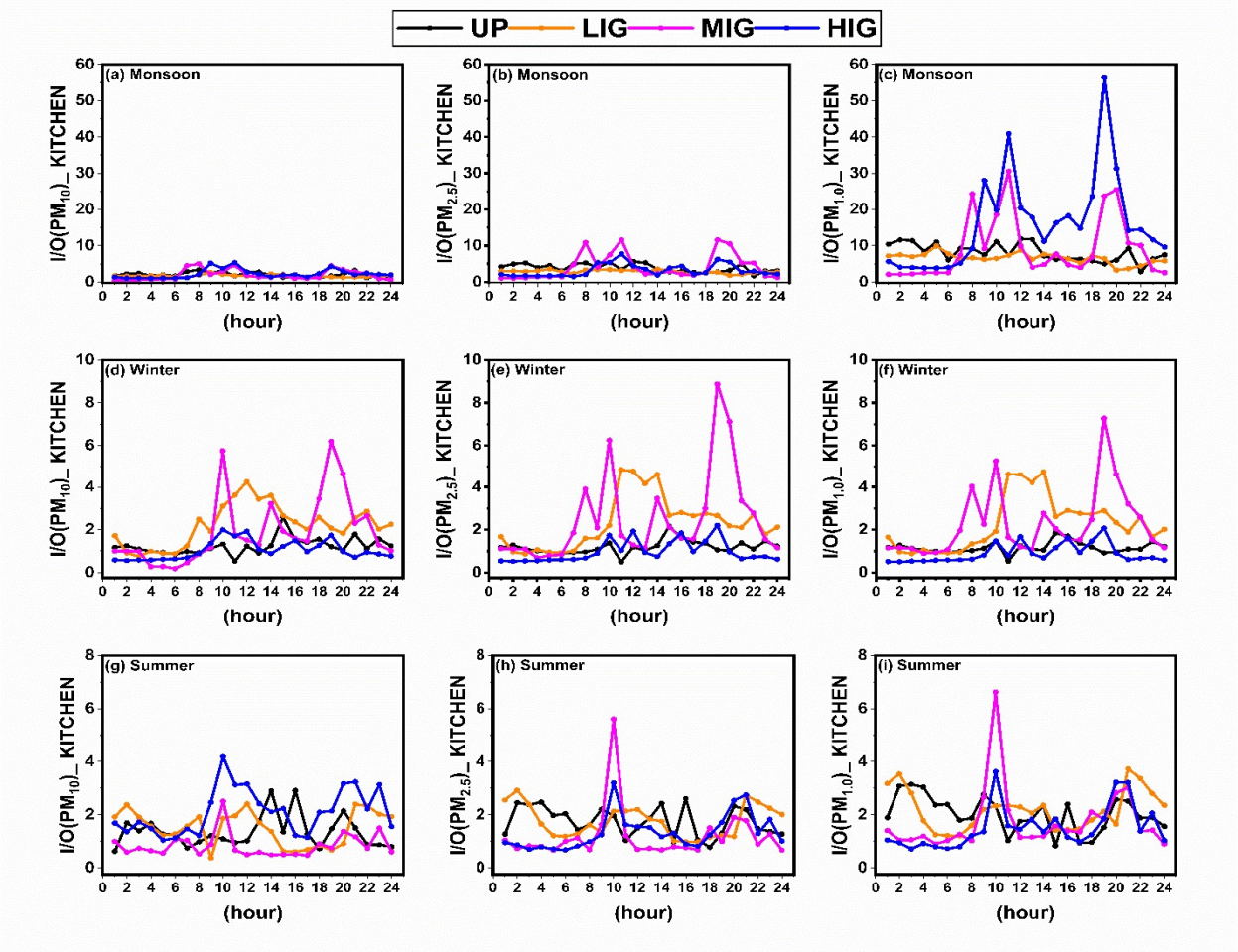

Figure 4.20 Diurnal I/O (kitchen vs outdoor) ratio analysis of PM_{10}, $PM_{2.5}$, and PM_1 during (a-c) monsoon, (d-f) winter, (g-i) summer in UP, LIG, MIG, and HIG households in urban region. Note: The Y-axis in each of the three seasonal panels has a different scale.

During winter, MIG households experienced a high I/O ratio (Fig. 4.20), and peak I/O was obtained twice a day during the morning and evening cooking hours for all three size (PM_{10}, $PM_{2.5}$, and PM_1) fractions. Similarly, in bedroom, the I/O ratio was extremely high for PM_1 during monsoon season in HIG due to the higher indoor source intensity (Fig 4.20). During winter, the I/O ratio of PM_{10}, $PM_{2.5}$, and PM_1 was also found high in LIG, and MIG compared to UP and HIG (Fig. 4.21 d-f). In summer, the I/O ratio of all the households in bedroom and kitchen ranged from 0.9 to 5.0 and 0.9 to 2.5 (Fig. 4.21).

During monsoon, the I/O ratio of $PM_{2.5}$ and PM_1 was found to be high compared to PM_{10}. The I/O ratio for PM_{10} and $PM_{2.5}$ were found to be less than 10 during monsoon. In the case of PM_1, the ratio was high, i.e.,>10 for UP and LIG, 30 for MIG, and ~60 for HIG, especially during the cooking hours (Fig. 4.21).

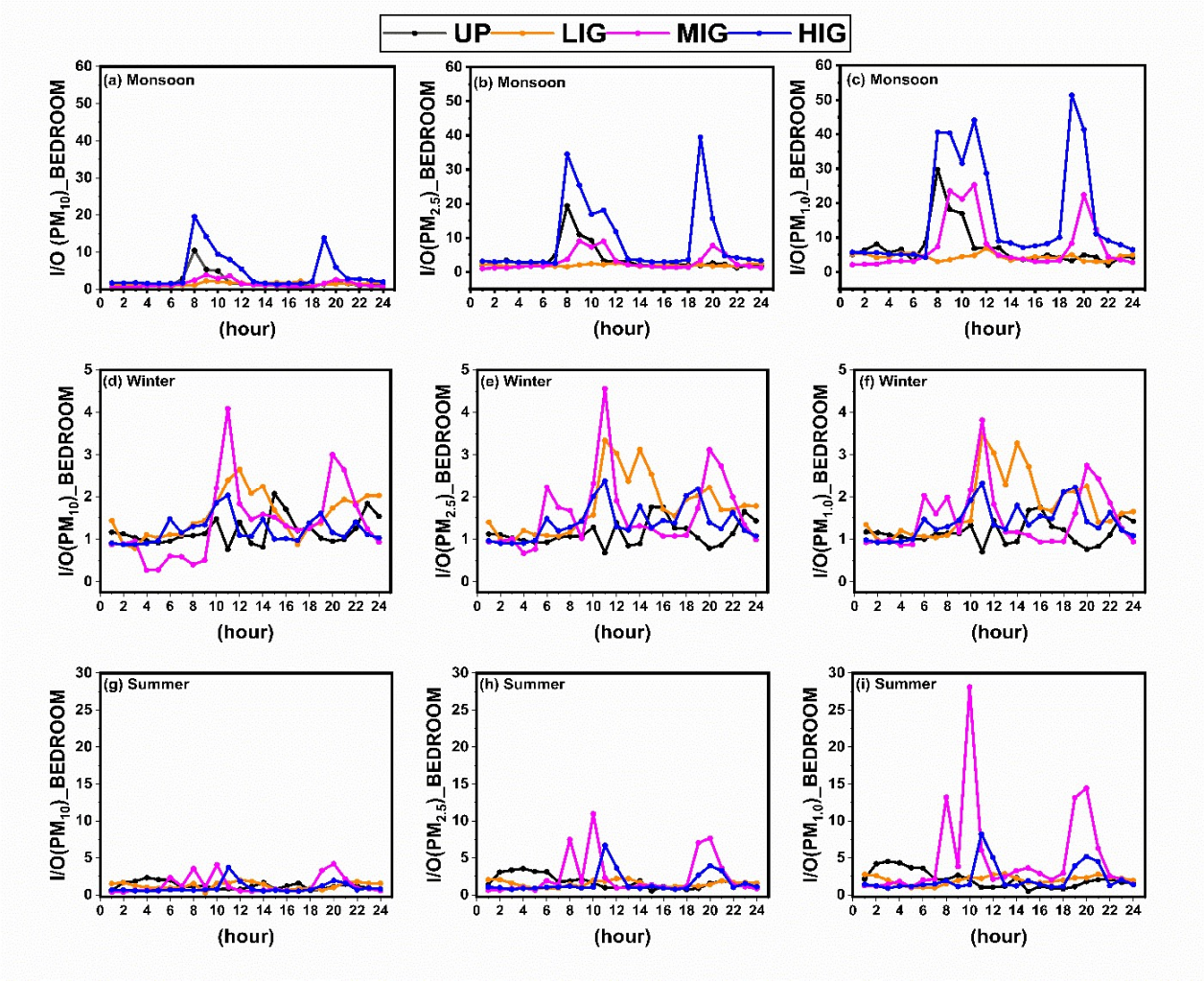

Figure 4.21 Diurnal I/O (bedroom vs outdoor) ratio analysis of PM_{10}, $PM_{2.5}$, and PM_1 during (a-c) monsoon, (d-f) winter, (g-i) summer in UP, LIG, MIG, and HIG households in urban region.

Table 4.8 Statistical summary of meteorological parameters (T and RH) in indoor (bedroom & kitchen) and outdoor environments during different seasons in studied households.

SEASON	INCOME GROUP	SITE	BEDROOM		KITCHEN		OUTDOOR	
		PARAMETERS	T (°C)	RH (%)	T (°C)	RH (%)	T (°C)	RH (%)
MONSOON	UP	Min	28	72	29	74	30	67
		Max	34	91	34	88	32	100
		Mean ±SD	31 ±2	81 ±6	31 ±1	83 ±3	30 ±3	88 ±6
	LIG	Min	27	51	27	63	28	59
		Max	35	85	32	93	34	84
		Mean± SD	32±2	66±7	29±1	78±6	31±2	72±7
	MIG	Min	29	54	31	67	28	58
		Max	37	75	34	76	34	93
		Mean± SD	33±2	65±4	32±1	71±2	31±2	73±10
	HIG	Min	27	49	25	46	28	54
		Max	34	88	36	89	35	96
		Mean± SD	30±1	70±6	29±3	68±11	31±2	75±13
WINTER	UP	Min	15	57	13	57	12	62
		Max	22	86	22	97	22	100
		Mean± SD	19±2	67±6	17±2	73±9	14±2	87±12
	LIG	Min	23	35	20	30	18	45
		Max	31	64	28	67	28	90
		Mean± SD	28±1	51±6	24±2	47±9	22±3	71±14
	MIG	Min	19	39	14	46	5	41
		Max	24	90	25	100	25	95
		Mean± SD	22±1	61±8	19±2	65±10	13±5	76±13
	HIG	Min	17	54	22	37	9	45
		Max	22	72	26	73	22	87
		Mean± SD	19±1	63±4	23±1	48±7	13±3	72±12
SUMMER	UP	Min	26	39	26	33	25	21
		Max	31	62	30	85	34	57
		Mean± SD	28±1	51±5	28±1	57±11	29±3	39±11
	LIG	Min	25	35	32	17	26	20
		Max	33	84	43	55	41	71
		Mean± SD	28±2	63±12	36±2	33±8	32±4	45±14
	MIG	Min	28	62	27	49	29	61
		Max	35	100	36	95	35	98
		Mean± SD	30±1	92±9	33±1	70±8	31±2	79±11
	HIG	Min	29	48	31	29	32	13
		Max	32	62	40	68	53	48
		Mean± SD	30±1	57±3	34±2	46±9	36±4	35±7

4.7 Diurnal variation of particulate matter and meteorological variables in indoor and outdoor

The particulate matter concentrations (PM_{10}, $PM_{2.5}$, and PM_1) and meteorological variables (AT and RH) observed in both indoor and outdoor environments exhibit significant seasonal variations (Fig.4.22).

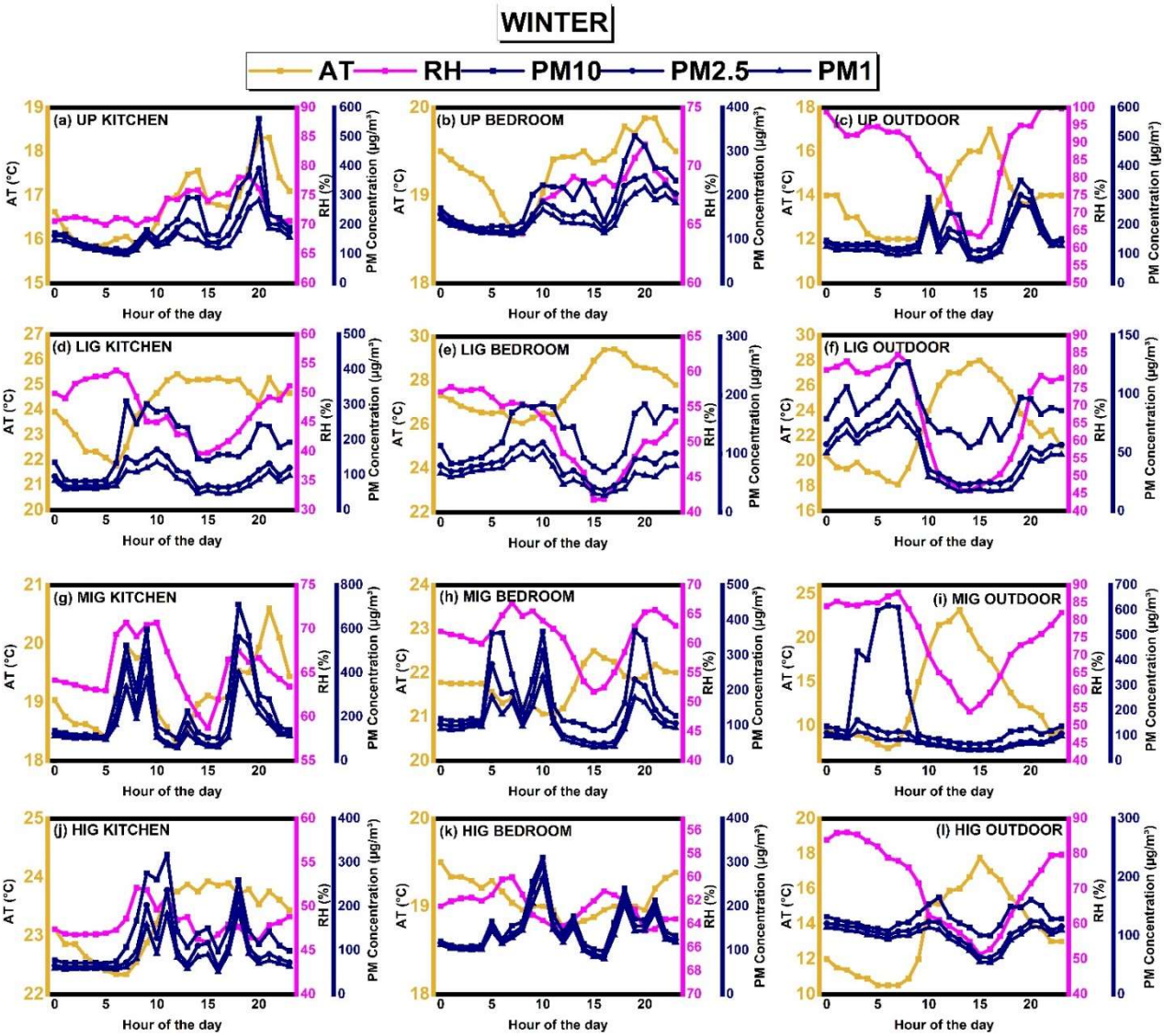

Figure 4.22 Diurnal variation of PM (PM_{10}, $PM_{2.5}$, and PM_1), AT and RH during winter season (a-c) UP, (d-f) LIG, (g-i) MIG and (j-k) HIG households in urban region. Note: The Y-axis in each of the three seasonal panels has a different scale.

The average temperature and RH of the outdoor environment of each household ranged from (13 - 36 °C) and (39 - 88 %) during different seasons. In contrast, indoor mean temperature and RH varied from 19 to 33 °C and 51 % to 92% in bedrooms, 17 to 36 °C, and 33 % to 83 % in kitchens (Fig 4.23).

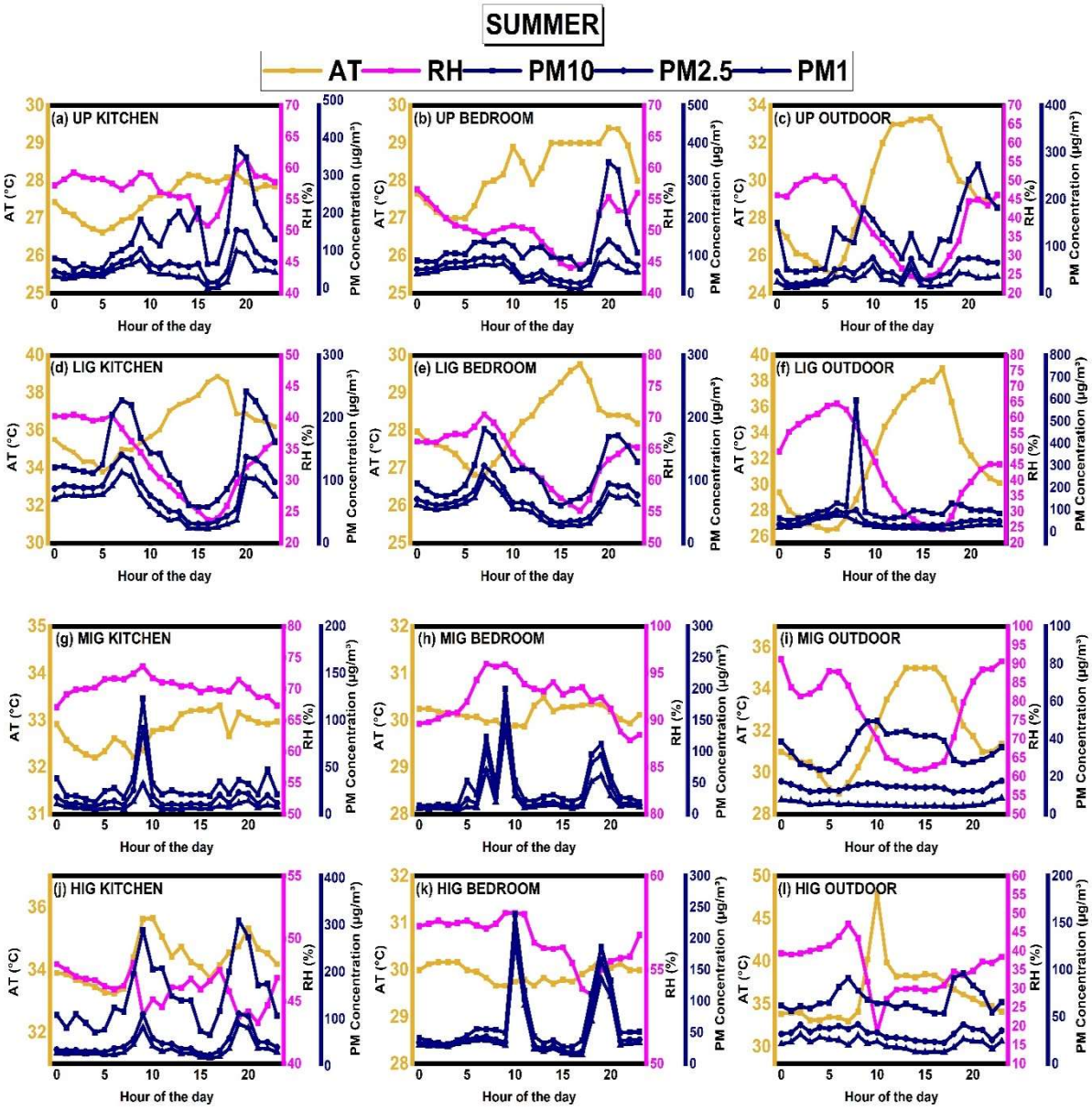

Figure 4.23 Diurnal variation of PM (PM_{10}, $PM_{2.5}$, and PM_1), AT and RH during summer season (a-c) UP, (d-f) LIG, (g-i) MIG and (j-k) HIG households in urban region. Note: The Y-axis in each of the three seasonal panels has a different scale.

During winter and monsoon, the temperature in outdoor was found to be lower, whereas the relative humidity was found to be higher. However, in summer, the RH in indoor was higher compared to the outdoors. RH variation during different seasons ranged from 33 to 92 % (summer); 47 to 87% (winter), and 65 to 85% (monsoon) (Fig 4.24).

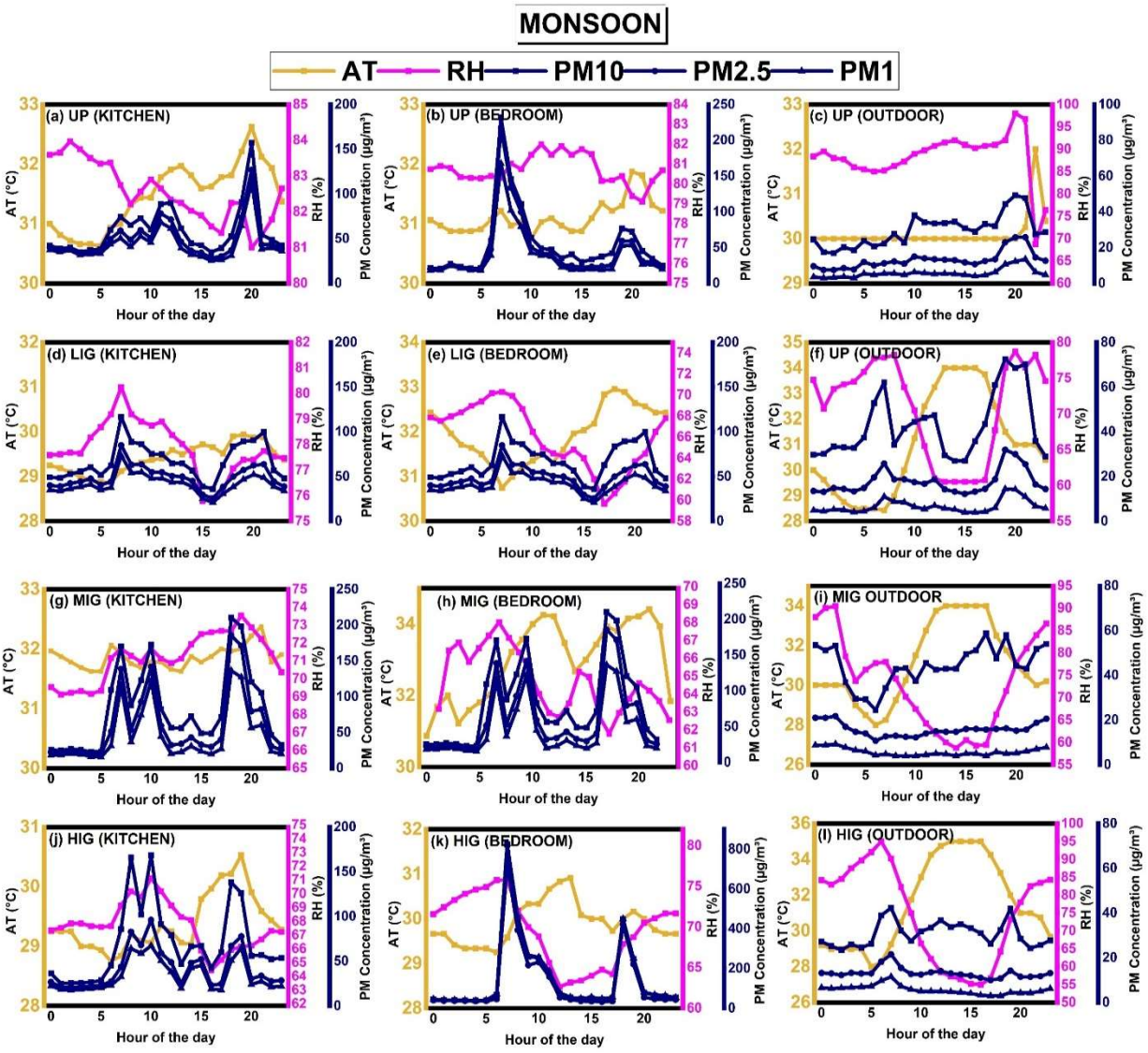

Figure 4.24 Diurnal variation of PM (PM_{10}, $PM_{2.5}$, and PM_1), AT and RH during monsoon season (a-c) UP, (d-f) LIG, (g-i) MIG and (j-k) HIG households in urban region. Note: The Y-axis in each of the three seasonal panels has a different scale.

4.8 Temporal analysis of different sizes of particles

The number concentration of qUFP was found to be higher than all other size fractions in all selected microenvironments. The cooking activities in the kitchen contributed to the maximum concentration of PNCs in all households (Fig. 4.25). The highest concentration of qUFP in the kitchen was observed in UP (monsoon and winter) and LIG (summer) households. The overall maximum observed concentration of qUFP in the kitchen was 2.1×10^{6} #cm^{-3} (Fig. 4.25, Table 4.9, 4.10, 4.11); whereas similar studies have

reported that during cooking, number concentrations can increase by 20 to 40% in the kitchen and up to 10 times in the living room (Kuye & Kumar, 2023). Both UP and LIG households exhibited less ventilation in the kitchen environment, resulting in higher PNCs. HIG and MIG households, with good natural and mechanical ventilation systems in the kitchen, experienced lower concentrations of PNCs across all seasons compared to UP and LIG households (Fig. 4.26, Table 4.12, 4.13, 4.14). In the bedroom, when the intensity of sources increased, HIG households experienced a higher concentration of qUFP (1.1×10^6 #cm^{-3}) irrespective of their household infrastructure (Fig. 4.27, Table 4.15, 4.16, 4.17). The order of mean concentration of qUFP in the kitchen was UP>LIG>MIG>HIG, while in the bedroom, it was HIG>UP>LIG>MIG. Socioeconomic conditions influenced the concentration of the qUFP in the kitchen, and the change in order in the bedroom was attributed to an episodic event. The findings imply that the intensity of the sources and the home's infrastructure, including the ventilation system and the distinct separation between the kitchen and the bedroom, affect the concentration of indoor pollutants.

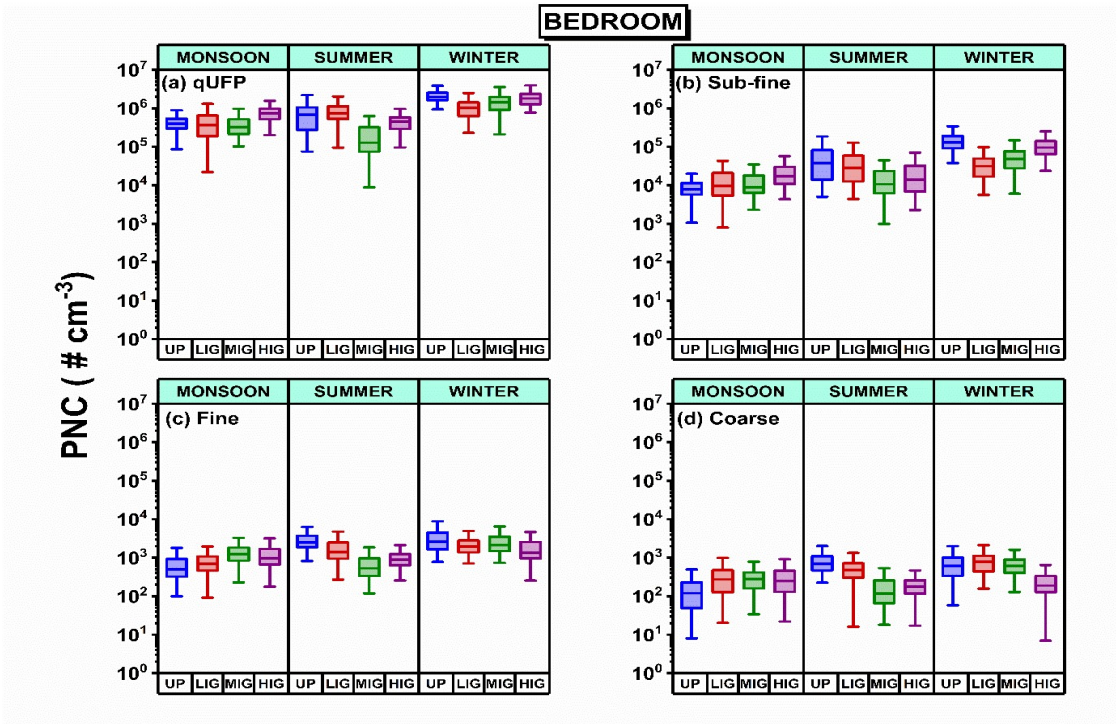

Figure 4.25 Particle number concentrations of (a) qUFP, (b) sub-fine, (c) fine, and (d) coarse particles in the bedroom during the monsoon, summer, and winter seasons in the study area.

Table 4.9 Statistical summary of Tukey quartile test during monsoon in bedroom.

Category	Season/ bedroom	Diff	Low-Q	Up-Q	P adj	Conf. int	Parameter
LIG-HIG	Monsoon	-681997.8	-78700.7	-576995	0.00	95%	qUFP
MIG-HIG	Monsoon	-577304.9	-68458.7	-470029	0.00	95%	qUFP
UP-HIG	Monsoon	-565468.4	-67884.8	-452088	0.00	95%	qUFP
MIG-LIG	Monsoon	104692.8	6970.1	208622	0.04	95%	qUFP
UP-LIG	Monsoon	116529.4	6247.9	226810	0.03	95%	qUFP
UP-MIG	Monsoon	11836.5	-10061.1	124284	0.02	95%	qUFP

Table 4.10 Statistical summary of Tukey quartile test during winter in bedroom.

Category	Season-bedroom	Diff	Low-Q	Up-Q	P adj	Conf. int	Parameter
LIG-HIG	Winter	-891702.7	-100899	-774409	0.00	95%	qUFP
MIG-HIG	Winter	-453847.8	-567241	-340453	0.00	95%	qUFP
UP-HIG	Winter	-216757.5	104920.5	328594.5	0.04	95%	qUFP

MIG-LIG	Winter	437854.9	329065.6	546644.1	0.00	95%	qUFP
UP-LIG	Winter	1108460.2	1001294.8	1215625.6	0.00	95%	qUFP
UP-MIG	Winter	670605.3	567721.7	773488.7	0.00	95%	qUFP

Table 4.11 Statistical summary of Tukey quartile test during summer in bedroom.

Category	**Season/ bedroom**	**Diff**	**Low-Q**	**Up-Q**	**P adj**	**Conf. int**	**Parameter**
LIG-HIG	Summer	281817.8	204462.6	359173.0	0.00	95%	qUFP
MIG-HIG	Summer	-318446.0	-414047	-222844.3	0.00	95%	qUFP
UP-HIG	Summer	141974.8	64639.82	219309.8	0.01	95%	qUFP
MIG-LIG	Summer	-600263.8	-690454	-5100732	0.00	95%	qUFP
UP-LIG	Summer	-139843.0	-210379	-69306.8	0.02	95%	qUFP
UP-MIG	Summer	460420	370247.5	550594.1	0.00	95%	qUFP

In the indoor environment, the concentration of qUFP particles ranged between 10^6–10^5 #cm^3, followed by sub-fine particles at 10^5–10^4 #cm^{-3} and fine particles at 10^4 #cm^{-3}–10^2 #cm^{-3} (Table 4.18). Similarly, during cooking, an increase in PNCs from 10^3 to 10^5 was observed (Sun & Singer, 2023b). The number concentration of coarse particles remained low throughout the monitoring period, not exceeding 1100 (10^3 #cm^{-3} to 10^2 #cm^{-3}). The monsoon season was found to have lower concentrations than the winter and summer seasons in all three microenvironments. The seasonal mean concentration of particle

numbers for all size fractions was found to be in the order winter>summer >monsoon, in the kitchen and bedroom, except for HIG (in the bedroom). During the monsoon period, HIG households used more number of incense sticks for prayers (worship of the Durga Pooja festival), which contributed to PNCs and resulted in an indoor episodic pollution event.

Throughout the monitoring period, the number concentration of particles was consistently lower outdoors compared to indoors. In UP and HIG, the qUFP concentration in the outdoors was ~30% less than indoors, while in LIG and MIG, it was ~ 50% lower. The mean average concentration of qUFP outdoors ranged from 10^5 #cm^{-3} followed by sub-fine (10^4 #cm^{-3}), fine (10^3 #cm^{-3}), and coarse (10^2 #cm^{-3}). The maximum mean concentration of qUFP was found to be 1.9×10^6 #cm^{-3} during winter outdoors in UP. The analysis of outdoor and indoor pollution concentration analysis revealed that the indoor environment is more polluted than the outdoor environment, highlighting the necessity to reduce emissions indoors, particularly in the urban regions of developing nations.

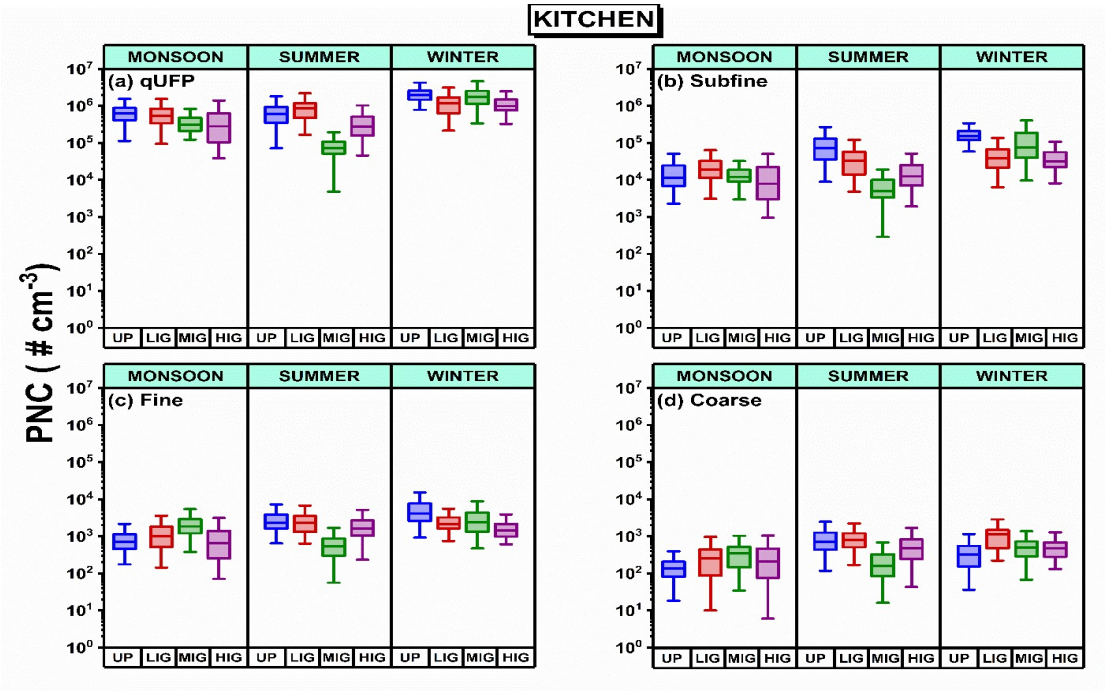

Figure 4.26 Particle number concentrations of (a) qUFP, (b) sub-fine, (c) fine, and (d) coarse particles in the kitchen during the monsoon, summer, and winter seasons in the study area.

Table 4.12 Statistical summary of Tukey quartile test during monsoon in kitchen.

Category	Season/ Kitchen	Diff	Low-Q	Up-Q	P adj	Conf. int	Parameter
LIG-HIG	Monsoon	167056.2	87930.8	246181.5	0.04	95%	qUFP
MIG-HIG	Monsoon	52146.5	-27031.1	131324.1	0.03	95%	qUFP
UP-HIG	Monsoon	235135.3	156216.9	314053.8	0.00	95%	qUFP
MIG-LIG	Monsoon	-114909	-194087	-35732.02	0.00	95%	qUFP
UP-LIG	Monsoon	68079.1	-10839.3	146997.6	0.00	95%	qUFP
UP-MIG	Monsoon	182988.8	104017.9	261959.7	0.01	95%	qUFP

Table 4.13 Statistical summary of Tukey quartile test during winter in kitchen.

Category	Season/ Kitchen	Diff	Low-Q	Up-Q	P adj	Conf. int	Parameter
LIG-HIG	Winter	52762.2	-95914.7	201438.8	0.04	95%	qUFP
MIG-HIG	Winter	678156.1	548020.7	808291.6	0.00	95%	qUFP
UP-HIG	Winter	924029.4	794375.4	1053683.5	0.00	95%	qUFP
MIG-LIG	Winter	625394.1	471626.9	779161.3	0.00	95%	qUFP
UP-LIG	Winter	871267.4	717907.4	102462.7	0.00	95%	qUFP
UP-MIG	Winter	245873.3	110412.1	381334.5	0.00	95%	qUFP

Table 4.14 Statistical summary of Tukey quartile test during summer in kitchen.

Category	**Season/ Kitchen**	**Diff**	**Low-Q**	**Up-Q**	**P adj**	**Conf. int**	**Parameter**
LIG-HIG	Summer	533975.3	4653126.0	602634.7	0.00	95%	qUFP
MIG-HIG	Summer	-333584.7	-395666.4	-271502.9	0.00	95%	qUFP
UP-HIG	Summer	306108.9	242557.7	369660.0	0.00	95%	qUFP
MIG-LIG	Summer	-867560.0	-935171.8	-799948.2	0.00	95%	qUFP
UP-LIG	Summer	-227866.5	-296829.9	-158903.0	0.00	95%	qUFP
UP-MIG	Summer	639693.5	577275.6	702111.5	0.00	95%	qUFP

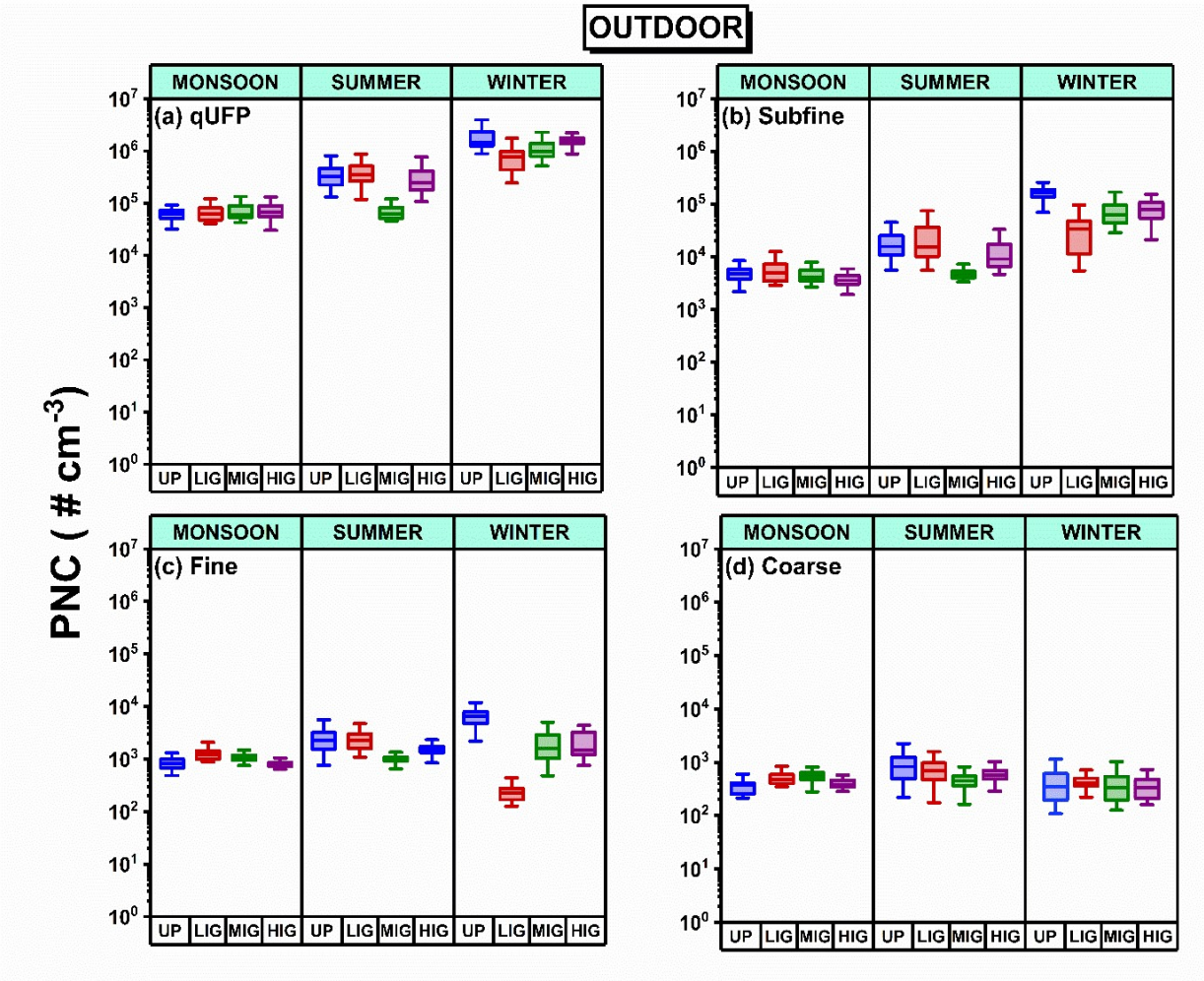

Figure 4.27 Particle number concentrations of (a) qUFP, (b) sub-fine, (c) fine, and (d) coarse-sized particles outdoors during the monsoon, summer, and winter seasons in the study area.

Table 4.15 Statistical summary of Tukey quartile test during monsoon in outdoor.

Category	Season/ Outdoor	Diff	Low-Q	Up-Q	P adj	Conf. int	Parameter
LIG-HIG	Monsoon	218.4	-10326.3	10763.2	<0.05	95%	qUFP

MIG-HIG	Monsoon	-914.12	-12188.9	10360.3	<0.05	95%	qUFP
UP-HIG	Monsoon	-3914.4	-15159.2	7330.3	<0.05	95%	qUFP
MIG-LIG	Monsoon	-1132.6	-11740.6	9475.4	<0.05	95%	qUFP
UP-LIG	Monsoon	-4132.9	-14709.0	6443.1	<0.05	95%	qUFP
UP-MIG	Monsoon	-3000.3	-14304	8303.7	<0.05	95%	qUFP

Table 4.16 Statistical summary of Tukey quartile test during winter in outdoor.

Category	**Season-Outdoor**	**Diff**	**Low-Q**	**Up-Q**	**P adj**	**Conf. int**	**Parameter**
LIG-HIG	Winter	218.4	-10326.3	10763.2	<0.05	95%	qUFP
MIG-HIG	Winter	-914.12	-12188.9	10360.3	<0.05	95%	qUFP
UP-HIG	Winter	-3914.4	-15159.2	7330.3	<0.05	95%	qUFP
MIG-LIG	Winter	-1132.6	-11740.6	9475.4	<0.05	95%	qUFP
UP-LIG	Winter	-4132.9	-14709.0	6443.1	<0.05	95%	qUFP
UP-MIG	Winter	-3000.3	-14304	8303.7	<0.05	95%	qUFP

Table 4.17 Statistical summary of Tukey quartile test during summer in outdoor.

Category	**Season/ Outdoor**	**Diff**	**Low-Q**	**Up-Q**	**P adj**	**Conf. int**	**Parameter**
LIG-HIG	Summer	-468578.7	-573588	-363569.4	0.00	95%	qUFP
MIG-HIG	Summer	-811933.0	-929067	-694798.9	0.00	95%	qUFP
UP-HIG	Summer	-503817.8	-610432	-397203.3	0.01	95%	qUFP
MIG-LIG	Summer	-343354.3	-472426	-214282.5	0.00	95%	qUFP
UP-LIG	Summer	-35239.1	-154846	84367.6	0.00	95%	qUFP
UP-MIG	Summer	308115.5	177734.1	438496.3	0.00	95%	qUFP

Table 4.18 Statistical summary of PNCs in Indoor (Bedroom and Kitchen) and outdoor environments during different seasons in studied households.

Season	Income Group	LOCATION	BEDROOM (#cm^{-3})				KITCHEN (#cm^{-3})				OUTDOOR (#cm^{-3})			
		PARAMETERS	qUFP	Sub-Fine	Fine	Coarse	qUFP	Sub-Fine	Fine	Coarse	qUFP	Sub-Fine	Fine	Coarse
MONSOON	UP	MIN	86778	1062	100	8	113308	2259	175	18	31995	2183	483	213
		MAX	4794815	1891702	226480	3275	4802411	840330	28706	4299	169645	21851	2453	713
		MEAN±SD	562503± 631743	37525± 167392	2462± 15873	181± 249	732330± 548152	26885± 67507	1152± 2219	205± 308	67928± 29294	5871± 4168	940± 441	359± 108
		MEDIAN	402503	8044	498	119	631296	11593	708	137	63503	4719	816	369
	LIG	MIN	21847	794	92	20	93982	3099	143	10	40698	2885	882	348
		MAX	3182291	577742	16046	2392	2991993	439022	22395	4927	266787	29951	3826	1294
		MEAN±SD	448326± 36421	19064± 39509	974± 1178	357± 305	665582± 473885	31711± 45523	1498± 2192	334± 414	72295± 35116	6499± 4701	1339± 511	533± 183
		MEDIAN	364879	9708	695	273	541462	18771	1005	254	62791	4929	1198	474
	MIG	MIN	101936	2297	228	34	122297	2964	378	34	42739	2677	746	279
		MAX	4383100	697917	27037	2281	5204492	2332914	286589	4538	134327	7898	1477	811
		MEAN±SD	554467± 674840	35633± 81982	1864± 2329	334± 277	549209± 733072	55105± 189125	4487± 18700	418± 420	72812± 25402	4473± 1227	1085± 175	551± 114
		MEDIAN	326702	8835	1243	276	314145	12067	1847	347	60766	4079	1076	545
	HIG	MIN	199963	4329	177	22	38382	956	71	6	30347	1923	636	285
		MAX	5523351	2835760	491503	17237	4483812	1368091	134051	16213	154758	10763	1239	572
		MEAN±SD	1125487± 119303	161960± 464823	10344± 41941	524± 1466	496194± 611054	29964± 84396	1763± 6476	382± 840	72993± 27517	4014± 1667	804± 115	400± 72
		MEDIAN	741245	17213	975	251	281094	7840	645	206	68024	3565	781	384
WINTER	UP	MIN	939879	37712	780	58	781627	58547	923	36	885142	70115	2209	108
		MAX	5260606	1558542	126909	31257	5679809	2060567	205795	59995	5269156	922103	32463	2558
		MEAN±SD	2194372± 756344	168062± 148017	4396± 8049	936± 1649	2132582± 893192	188047± 172290	7377± 14710	905± 4023	1961566± 1039020	190067± 113800	6792± 3832	474± 398
		MEDIAN	1969216	131545	2592	613	1967554	153347	4074	316	1467379	167967	6540	346
	LIG	MIN	229132	5669	712	157	214765	6340	745	221	245549	5430	126	222
		MAX	4534179	384344	7862	4538	4144416	813373	45103	8553	1763478	122441	1970	1275

		MEAN±SD	1076346± 570051	38474± 33739	2204± 1085	846± 520	1246931± 722269	60618± 76897	3194± 3763	1155± 838	802580± 416768	36831± 27715	250± 172	440± 140
		MEDIAN	1015119	31284	1944	773	1185727	38185	2125	1124	771177	34193	224	411
	MIG	MIN	210510	6002	93	128	338708	9632	52	67	516306	28470	479	126
		MAX	5184819	2251198	37807	34217	5282110	4025174	146052	21300	2892401	184683	39203	14497
		MEAN±SD	1517625± 849088	112976± 239698	6676± 1705	904± 1827	1874804± 1033610	228074± 456702	16254± 6749	896± 2010	1156575± 500028	72899± 33615	3106± 4704	810± 1621
		MEDIAN	1423452	48307	294	609	1746142	76553	244	496	981121	63795	1571	339
	HIG	MIN	774327	23640	254	7	324400	8111	606	131	883774	21248	753	160
		MAX	5417040	2568090	149293	2458	4630847	1719384	182571	11597	2234107	153862	4398	1493
		MEAN±SD	1965207± 884969	162362± 265012	3736± 10563	263± 264	1202589± 668440	77422± 159033	3983± 12984	619± 792	1581813± 319886	79576± 34665	2087± 1124	360± 180
		MEDIAN	1805892	95196	1363	188	991311	31475	1437	468	1587401	79272	1490	334
SUMMER	**UP**	MIN	74525	5007	821	224	71859	8876	645	117	132260	5573	761	219
		MAX	3530759	273781	27388	16363	5191019	1526317	126395	19375	2063302	290414	16143	4984
		MEAN±SD	732047± 507791	54877± 49806	3165± 2256	1028± 1228	745513± 592442	116359± 160386	4074± 8178	1208± 1719	380774± 235272	23711± 27172	2652± 1745	1050± 832
		MEDIAN	675943	37368	2521	700	609253	73139	2336	703	326454	15725	2283	828
	LIG	MIN	94638	4398	270	16	165661	4798	632	168	118068	5523	1082	176
		MAX	3712049	466180	12039	3054	4371701	536817	23347	6041	1042337	179733	17337	24615
		MEAN±SD	868108± 514075	51016± 65270	1963± 1635	582± 451	964593± 658439	56352± 76307	2896± 2290	936± 575	411872± 225764	32828± 38889	2487± 1440	888± 1758
		MEDIAN	747286	27780	1386	472	859420	33265	2335	804	346596	15460	2305	704
	MIG	MIN	8808	982	118	18	4830	289	56	16	45929	3326	608	163
		MAX	2905013	777109	54493	5420	1497836	582964	151886	31246	142059	9632	1558	820
		MEAN±SD	266407± 386702	36034± 91263	2418± 6770	234± 407	100795± 122896	11599± 36691	1397± 7869	322± 1291	69874± 21626	4964± 1284	1022± 189	453± 136
		MEDIAN	127280	10652	530	117	72155	4939	533	160	62959	4623	1008	449
	HIG	MIN	96129	2262	255	17	45645	1927	232	43	107335	4647	839	287
		MAX	5279343	2282556	166415	1719	3393544	685763	54980	15840	858188	75309	2732	1267
		MEAN±SD	590545± 710715	61406± 211945	2510± 10511	221± 191	433350± 470091	31383± 70228	2754± 4528	700± 931	306484± 164856	14173± 11701	1541± 349	600± 174
		MEDIAN	449268	13915	879	177	279261	12542	1598	475	245462	9081	1470	580

4.9 Seasonal and diurnal variations in PNC

The diurnal variation of the PNCs in both outdoor and indoor environments varied throughout the day. Different sources influenced the concentrations in all three microenvironments (Figs. 4.28 and 4.29). During the monsoon season, the number concentration of particles outdoors was consistently lower than indoors (Figs. 4.28, 4.29). Indoor pollution sources, such as cooking and incense sticks, contributed to higher numbers of qUFP, sub-fine, and fine particles. The diurnal PNC in the kitchen coincided with the cooking hours in UP and LIG households, and kitchen PNC influenced bedroom PNC in these households. During monsoon, the use of incense sticks in the bedroom of HIG households led to higher concentrations of qUFP and sub-fine particles. However, the influence of cooking sources was less pronounced in MIG and HIG kitchens due to their superior infrastructure.

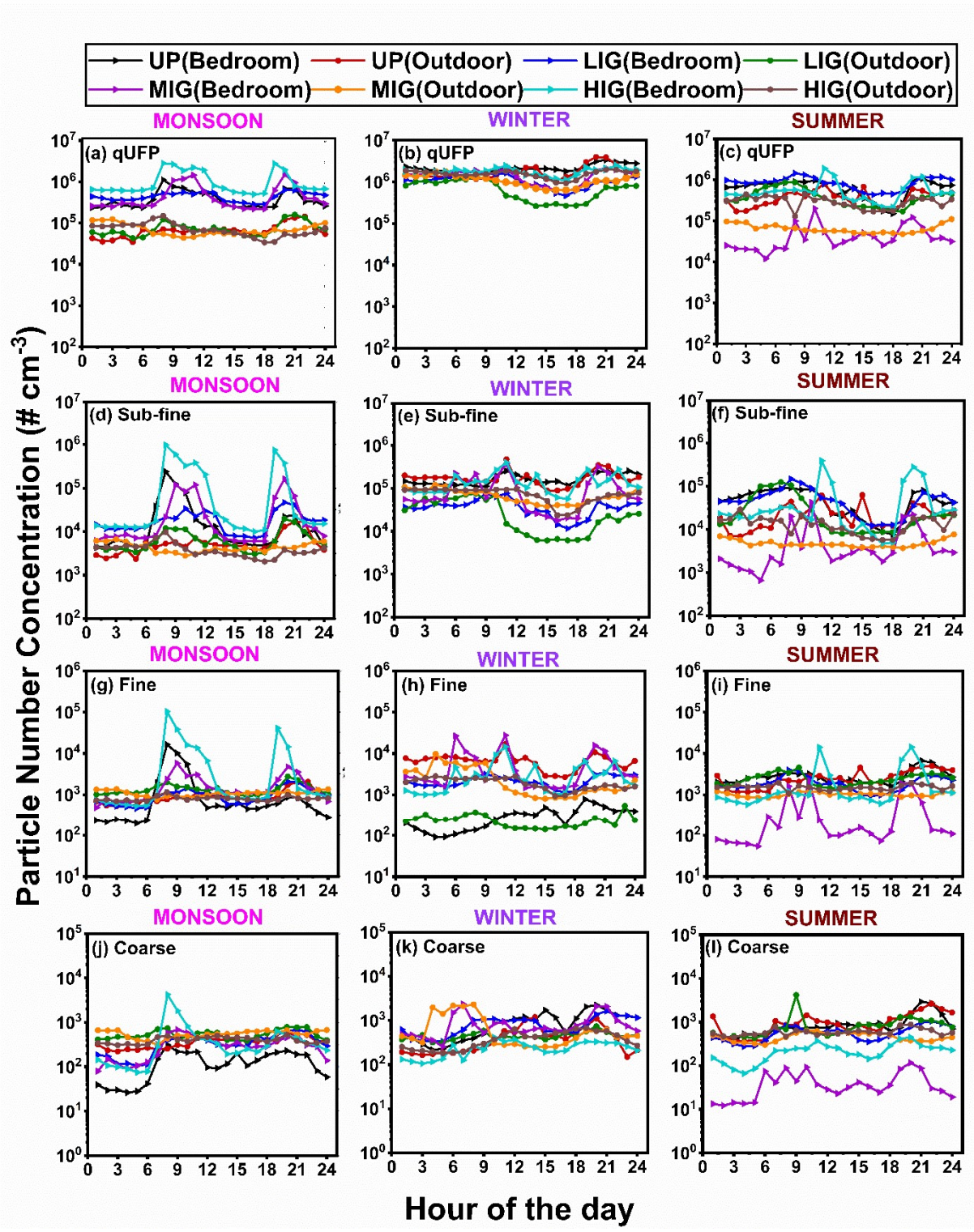

Figure 4.28 Diurnal variation analysis comparison in bedrooms for (a-c) qUFP, (d-f) sub-fine, (g-i) fine, and (j-l) coarse-sized particles during the monsoon, summer, and winter seasons in the study area.

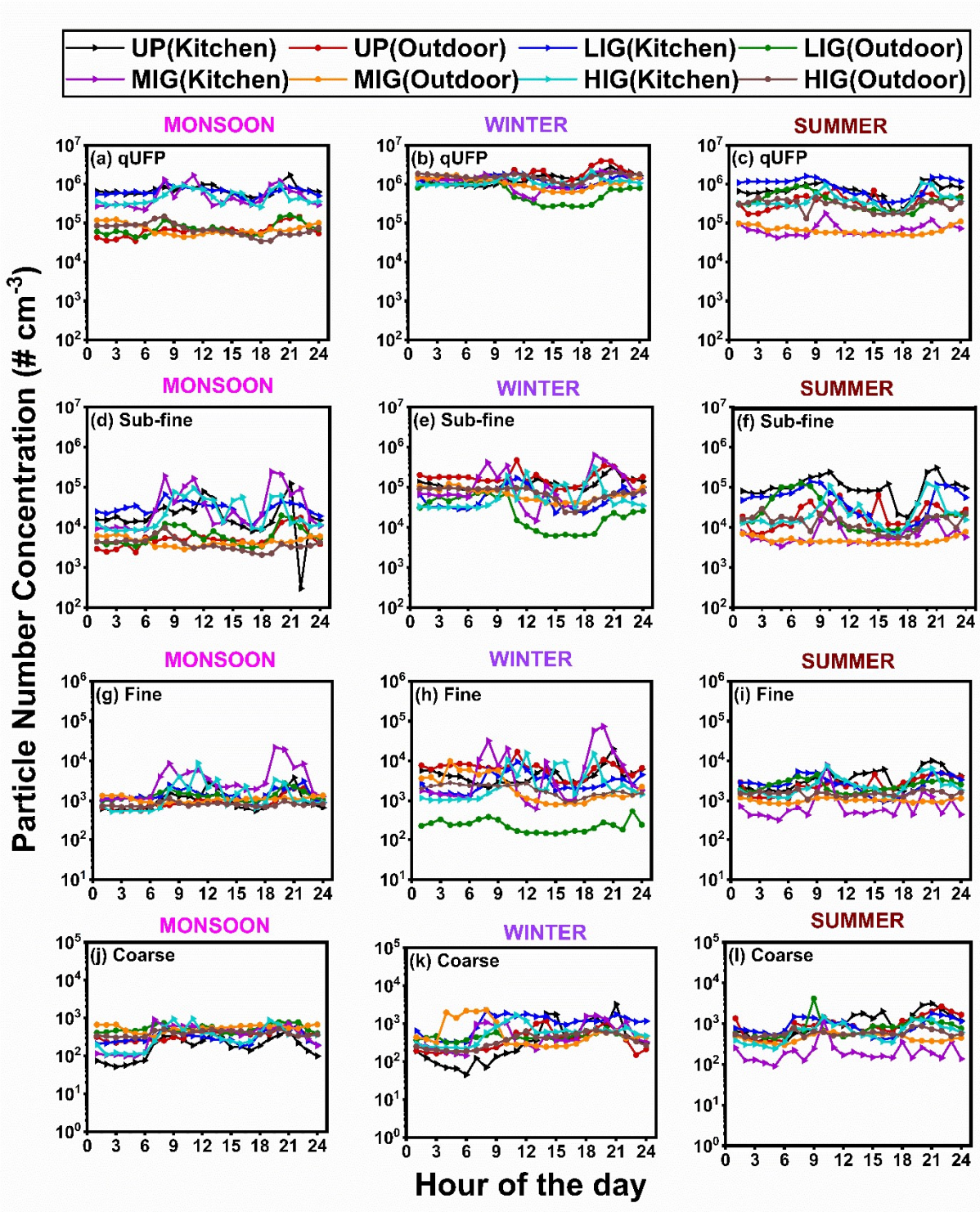

Figure 4.29 Diurnal variation analysis comparison in Kitchen for (a-c) qUFP, (d-f) sub-fine, (g-i) fine, and (j-l) coarse-sized particles during the monsoon, summer, and winter seasons in the study area.

During the winter season, qUFP and sub-fine concentrations in indoor and outdoor microenvironments exhibited a similar trend because of the pre-existing background concentrations in the study region in both the indoor and outdoor environments (Fig. 4. 28). The higher number concentrations of qUFP and sub-fine particles in UP (both indoor and outdoor) during late-night hours in winter were due to heating (Thermal comfort) (Fig. 4.29). In all income groups, the diurnal concentration trend in winter was observed to be similar in both bedrooms and kitchens, as well as in outdoor environments; whereas, in other seasons, the trends diverged. The diurnal PNC trends strictly coincided with source intensity in both indoor and outdoor environments. In the summer season, sub-fine indoor number concentration showed more deviated trends in both the kitchen and the bedroom due to dusting and cleaning activities occurring in both areas. The results revealed that qUFP and sub-fine PNCs were found to be high in indoor environments; whereas coarse particle concentrations were observed to be higher in outdoor environments; however, indoor concentrations of coarse particles were lower than outdoor concentrations.

4.10 I/O ratios in the kitchen and bedroom

The influence of one microenvironment on another was determined using the ratio of two different environments. The I/O ratio indicates the influence of outdoor concentrations on indoor environments, specifically in bedrooms and kitchens (Fig. 4.30). The outdoor coarse PNC influenced kitchen and bedroom PNC more (I/O $\leq$0.5) during the monsoon and summer seasons (Fig 4.30). The sub-fine particles I/O ratio was highest (40) in the HIG household (bedroom) during the monsoon season due to the excessive use of incense sticks during prayer. Similarly, during summer, the I/O ratio of sub-fine particles in MIG was 7.5, which was the highest ratio obtained in the summer season due to indoor dusting and cleaning. In the kitchen, a low I/O ratio was found in summer (<2.5) and higher in the monsoon season, while in winter, the I/O ratio was found in an intermediate range. Seasonal variations in I/O ratio values were mainly due to the influence of indoor or outdoor sources. During the monsoon season, the I/O ratios of the qUFP and sub-fine particles were relatively higher in almost all household kitchens because of the strong influence of cooking sources. Similar results were also reported in a previous study (Thakur & Patel, 2024b). However, during winter, indoor sources predominantly

influenced sub-fine and fine particles. Outdoor sources strongly influenced the I/O ratio in UP bedrooms; whereas in the kitchen, the I/O ratio was influenced by cooking sources (Fig. 4.30). Further, the I/O values revealed that it was not uniform but changed from season to season across all households. The presence of indoor sources also decreased the influence of outdoor sources.

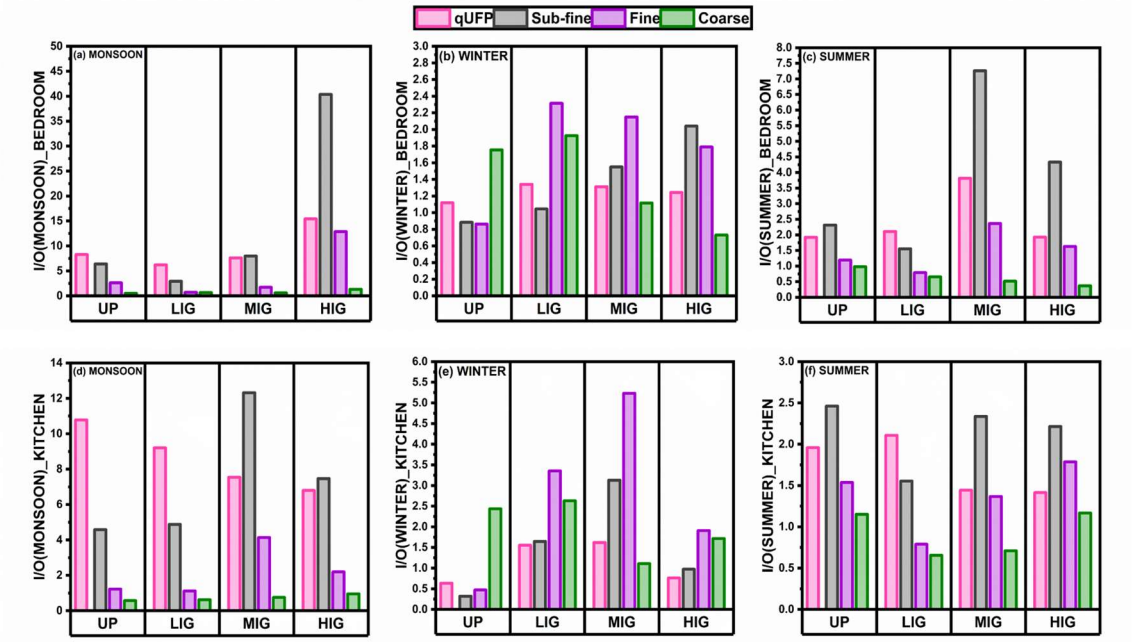

Figure 4.30 Ratios of indoor (bedroom and kitchen) and outdoor locations in selected households during different seasons.

4.11 $C_{Bedroom}/C_{Kitchen}$ ratio

The ratio analysis between two different indoor environments (kitchen and bedroom) revealed how the number concentration of one microenvironment influences the other within a household. The UP household showed a lower $C_{Bedroom}/C_{Kitchen}$ ratio compared to all other households across different seasons. This clearly indicated that the indoor household infrastructure played a significant role in influencing particle number concentration (Fig 4.31). The $C_{Bedroom}/C_{Kitchen}$ ratio was found to be high (qUFP: 5.6, sub-fine: 19, fine: 16, and coarse: 3) in HIG households during monsoon season (Fig. 4.31) due to less influence of the kitchen. For all size ranges of PNC during the monsoon season, the ratio was found to be lower in UP and LIG. During the summer season, due to dusting and cleaning in the bedroom, the sub-fine particle $C_{Bedroom}/C_{Kitchen}$ ratio was

observed to be high. The UP households showed a greater influence of one environment over the other. However, the bedroom of HIG households was least influenced by kitchen emissions due to well-planned infrastructure. A similar scenario was also observed in MIG households. Therefore, well-designed households showed the least influence of one microenvironment on another. UP and LIG households were more susceptible to exposure in both the kitchen and bedroom due to their household infrastructure, compared to MIG and HIG households. The health impacts of indoor pollutants are directly proportional to concentration and exposure duration (Vo et al., 2022).

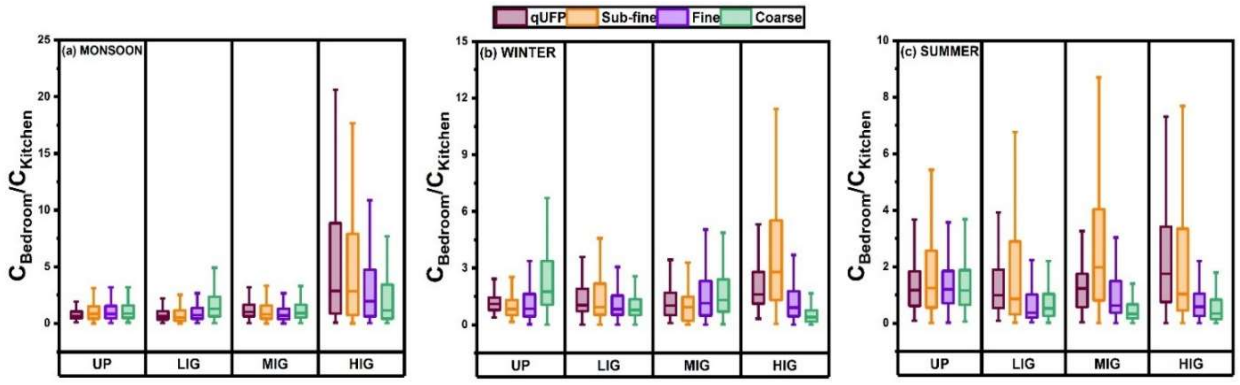

Figure 4.31 Ratios of bedroom and kitchen concentrations in selected households in different seasons.

4.12 Quantifying PNC in bedrooms at night

Occupants spend more time in bedrooms than in kitchens, making it essential to analyse the influence of kitchen concentrations on bedrooms at night (10:00 PM–6:00 AM) across different households. The analysis revealed that, in LIG and UP households, the occupants in the bedroom were exposed to the maximum number of pollutants due to indoor emissions of pollutants emanating from the kitchen (Fig 4.32). Conversely, in MIG and HIG households, the occupants in the bedroom had minimum exposure to emissions from the kitchen (Fig. 4.32 c and d). Throughout the monitoring period, the order of influence of indoor emissions from the kitchen on the bedroom was LIG> UP> MIG> HIG when no cooking activities were occurring. In LIG household, the strong influence of kitchen sources in the bedroom ($R^2 = 0.97$) during the night time was due to the occupant's behaviour (night cooking). The correlations of kitchen and bedroom I/O

revealed that late-night cooking activity (~10 to 11 PM) increased the exposure during sleeping hours for residents in LIG households.

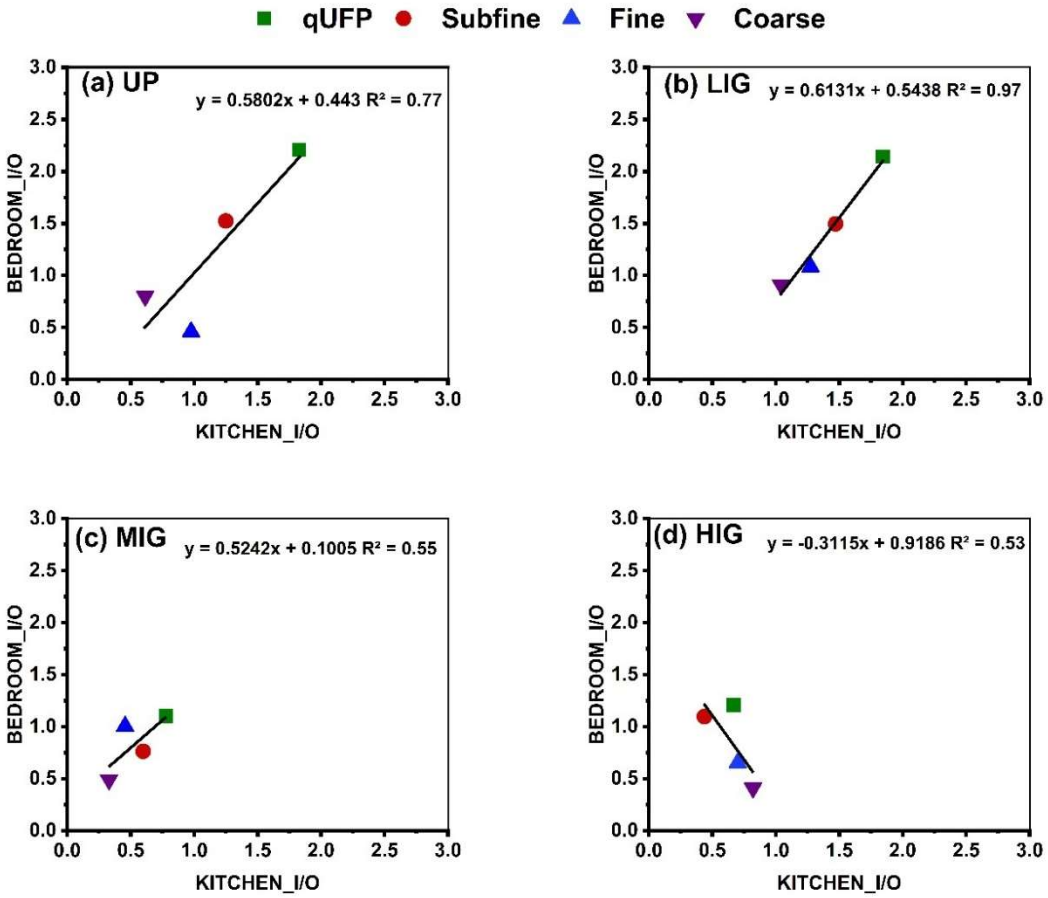

Figure 4.32 Correlations between I/O kitchens and I/O bedrooms in different households at night.

4.13 Temporal variation of PNC during different hours of the day

The qUFP concentrations were analysed from the different hours of the day throughout the year. The results revealed that the qUFP number concentrations in the kitchen and bedroom were not uniform throughout the year. The fluctuation in concentrations were observed during different hours of the day based on the activity (Fig. 4.33). In UP, both bedroom and kitchen were found to have higher concentrations (1.6×10^{6} #cm^{-3}) during the evening hours. The concentration observed in UP was the highest average concentration received throughout the year in all selected households. The UP with a single room infrastructure for both kitchen and bedroom in urban regions was found to

have a greater impact on PNC in an indoor environment. The daily average concentration in UP was found to be in the range of 1 to 1.2×10^6 #cm^{-3} concentration in both kitchen and bedroom. In LIG households, the maximum concentration of the qUFP number concentration was observed during the morning hours, followed by evening hours and night hours.

In LIG, during peak hours, the maximum average concentrations ranged between 0.9 $\times10^5$ to 1.2×10^6 #cm^{-3} particles (Fig. 4.33). The daily average concentration of the LIG households ranged between 7 to 9×10^5 #cm^{-3}. In MIG households, the maximum average concentration was observed in the evening hours which ranged from 1 to 1.1×10^6 cm^{-3}, whereas the daily average concentration ranged between 7 to 9×10^5 #cm^{-3} (Fig. 4.33 c). In HIG, the maximum average concentration was found to be during the morning hours with a range of 1 to 8×10^5 #cm^{-3}. Daily average concentration in HIG ranged between 7.5×10^5 to 13×10^6 #cm^{-3}. The results revealed that the PNC concentration during the nighttime in different households was found to be higher than the daytime, except in the HIG bedroom. In kitchen, the concentration of qUFP gradually decreases in each household based on the kitchen infrastructure and ventilation facility. In the bedroom, the HIG with a separate room and ventilation system received a higher concentration than UP, due to the practice of continuously using incense sticks for a long time. However, the influence of the bedroom activities was not found in the kitchen, where the concentration received was the lowest. In UP and LIG, the influence of kitchen on bedroom and vice versa was found due to the poor infrastructure of households, resulting in nearly the same concentration in kitchen and bedroom environments. In UP and MIG, the maximum concentration was found during the evening hours, whereas in LIG and HIG, it was during the morning hours. These changes are due to the cooking behavior, types of cooking, and variety of cooking practices adopted in the individual households, which are further explored and discussed in the upcoming results sections.

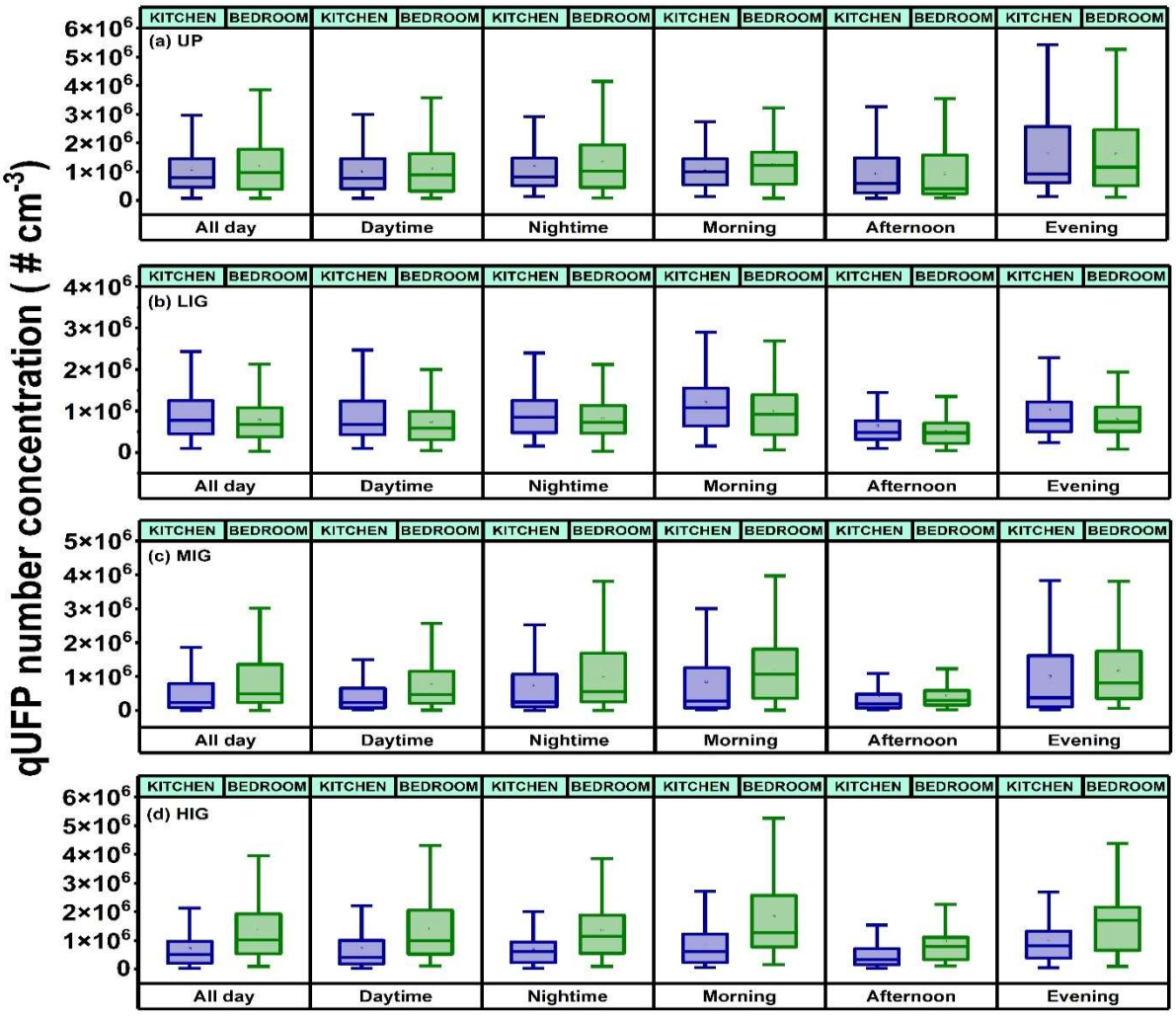

Figure 4.33 Box whisker analysis of qUFP PNC in different households (a) UP, (b) LIG, (c) MIG and (d) HIG during different hours of the day in a year.

Note: The time periods classification are as follows: all day (12:00 am to 12:00 am), daytime (6:00 am to 6:00 pm), nighttime (6:00 pm to 6:00 am), morning (6:00 am to 12:00 pm), afternoon (12:00 pm to 6:00 pm) and evening (6:00 pm to 10:00 pm).

4.14 Diurnal variation of Particle number concentration and Meteorological variables in indoor and outdoor

The particle number concentration (qUFP and Sub-fine) and meteorological variables (AT and RH) observed in both indoor and outdoor environments exhibit significant seasonal variations (Fig.4.34).

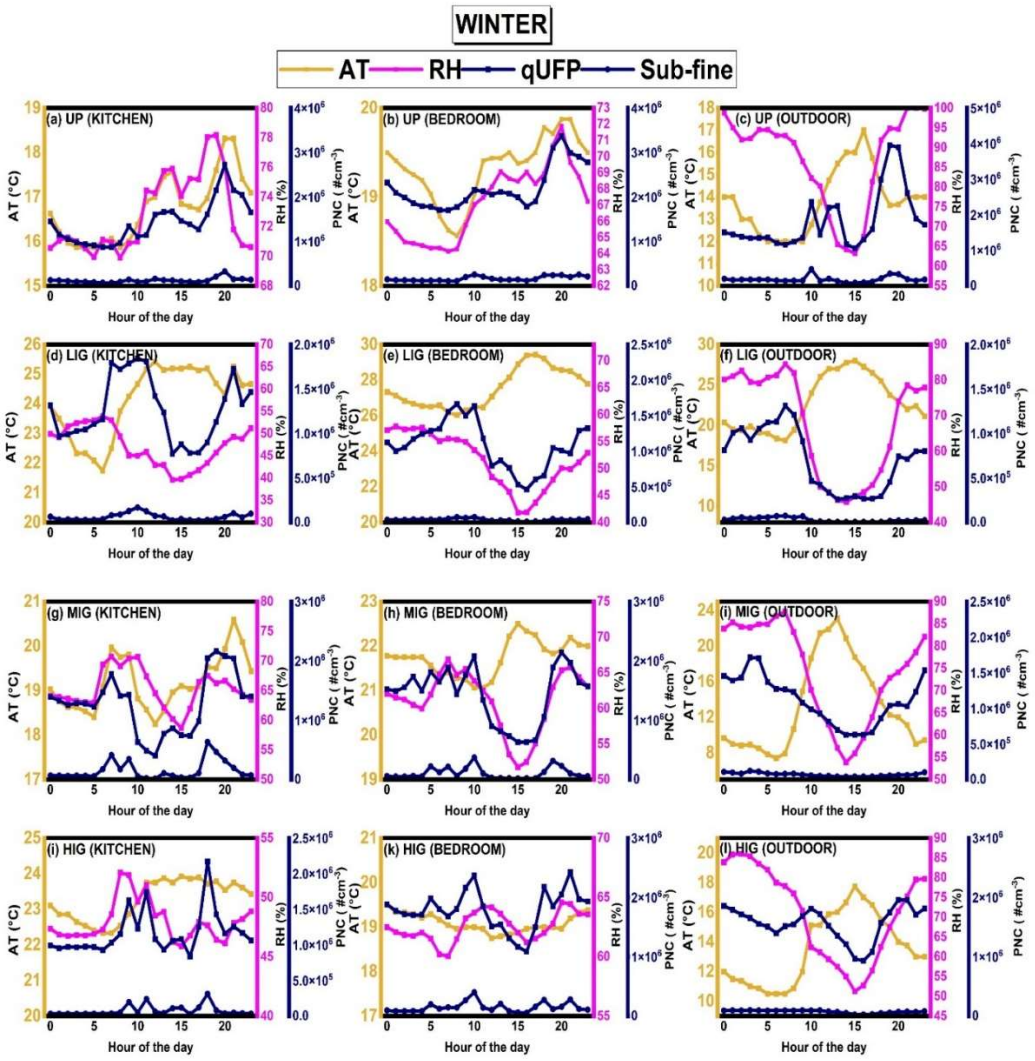

Figure 4.34 Diurnal variation of particle number concentration (qUFP and Sub-fine), AT and RH during winter season (a-c) UP, (d-f) LIG, (g-i) MIG and (j-k) HIG households in urban region. Note: The Y-axis in each of the three seasonal panels has a different scale.

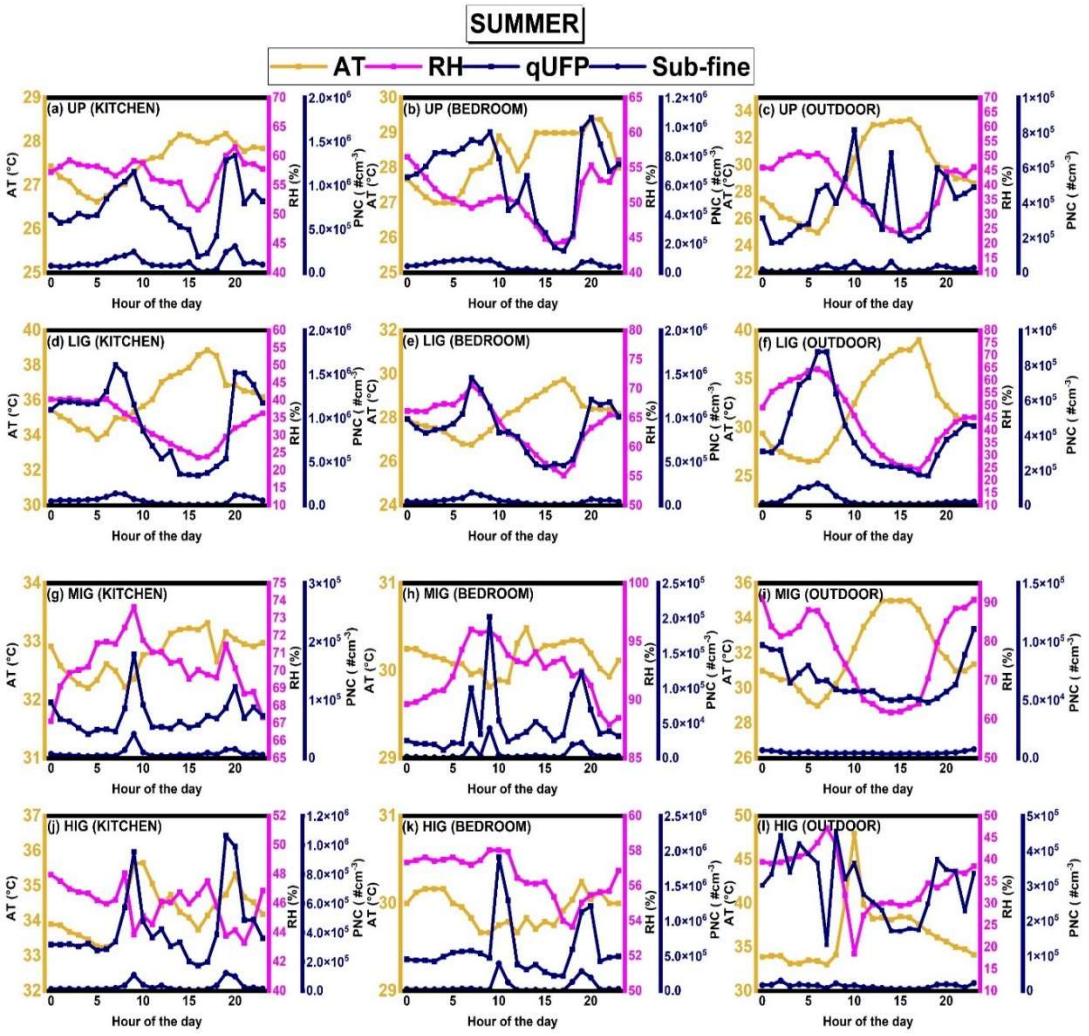

Figure 4.35 Diurnal variation of particle number concentration (qUFP and Sub-fine), AT and RH during summer season (a-c) UP, (d-f) LIG, (g-i) MIG and (j-k) HIG households in urban region. Note: The Y-axis in each of the three seasonal panels has a different scale.

The average temperature and RH of the outdoor environment of each household ranged from 13 - 36 °C and 39 - 88 % respectively, during different seasons. In contrast, indoor mean temperature and RH varied from 19 to 33 °C and 51 % to 92% in bedrooms, 17 to 36 °C, and 33 % to 83 % in kitchens (Fig. 4.35). During winter and monsoon, the temperature in outdoor was found to be lower, whereas the relative humidity was found to be higher. However, in summer, the RH indoors was higher compared to outdoors. RH variation during different seasons ranged from 33 to 92 % (summer); 47 to 87% (winter), and 65 to 85% (monsoon) (Fig. 4.36).

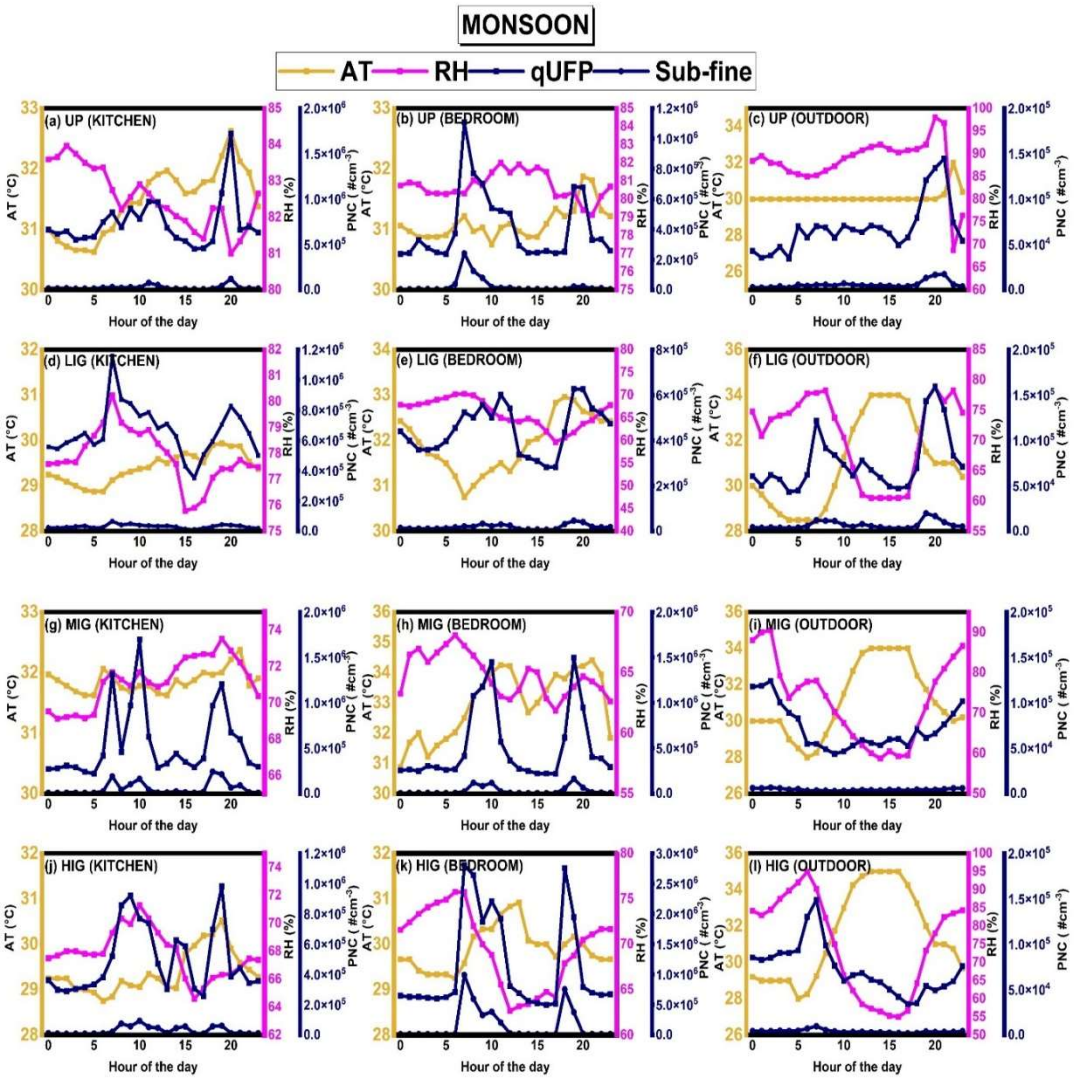

Figure 4.36 Diurnal variation of particle number concentration (qUFP and Sub-fine), AT and RH during monsoon season (a-c) UP, (d-f) LIG, (g-i) MIG and (j-k) HIG households in urban region. Note: The Y-axis in each of the three seasonal panels has a different scale.

4.15 Cooking influence on PNC generation in Kitchen

Cooking activity is one of the most common activities that contribute to the indoor air pollution (Torkmahalleh et al.,2018). The particle number concentrations were analyzed during peak cooking hours in different households across various seasons (Fig. 4.37). During cooking, the concentrations of the qUFP were found to be high in almost all households in all the seasons. During monsoon, the HIG household observed a qUFP

concentration of 4×10^6 #cm^{-3} (Fig. 4.37 a); however, the mechanical ventilation systems helped the peak concentration of particles to decay within 50 minutes (Fig. 4.37). Whereas in UP households, the concentration was ~ 4×106 #cm-3, but it took ~150 minutes for the particle concentration to reach back to its baseline levels. This illustrates the role of the mechanical ventilation system in reducing indoor air pollution. The maximum concentration of particles was observed during the winter cooking period (~ 5.9×10^6 #cm^{-3}) in the UP household.

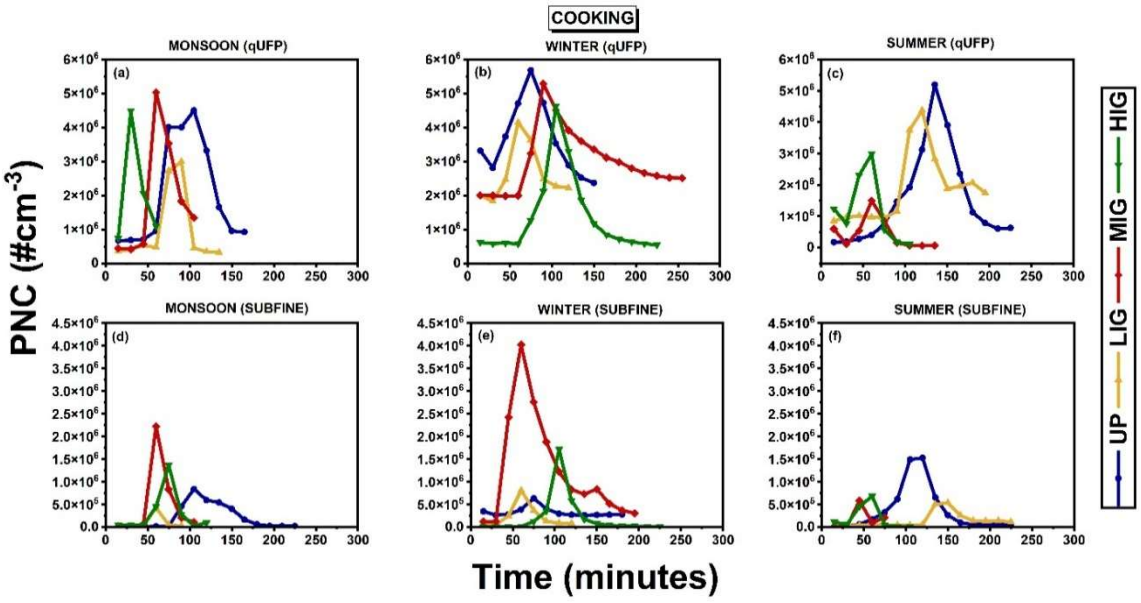

Figure 4.37 Concentration variation of qUFP (a, b, c) and subfine particles (d, e, f) during cooking activity in kitchens of selected households in different seasons.

Winter period cooking was found to have higher concentrations of PNC in almost all the income groups compared to summer and monsoon. The concentration of qUFP during winter exhibits a gradual rise followed by a gradual decline. During summer, the qUFP concentration required upto 250 minutes to come back to its baseline concentration (Fig.4.37 c). The sub-fine concentration was observed to be high in winter in the MIG household (4×10^6 #cm^{-3}) (Fig. 4.37), and for other seasons and income groups, the concentration was found to be < ~2×10^6 #cm^{-3}. In the summer season, sub-fine concentration was found to have a lower concentration than in any other season (Fig. 4.37). The higher concentration in winter for sub-fine concentration was due to the specific type of cooking, which was discussed in the later sections of the study. The

results revealed that the cooking emissions in indoor areas stay for a period of up to 250 minutes in different households. The time depends on the type of ventilation system, the structure of the household, and the existing climatic conditions, which influence the dispersion of particles.

4.16 Dusting associated PNC generation in Bedroom

Dusting activity is one of the major indoor activities after cooking in indoor environments (Fig. 4.38). The qUFP and subfine particles were found have more concentration and more decay time during the winter season. During winter, the concentration of qUFP and subfine particles took around 250 to 300 minutes to come back to its baseline concentration due to dusting activity (Figs. 4.38). The concentration of qUFP ranged between 3 to 5×10^6 #cm^{-3} (Figs. 4.38 a, c) during monsoon and summer in different households, whereas in winter the range was found to be from 4 to 5×10^6 #cm^{-3} (Fig. 4.38). The decay of concentrations during winter was noticed to be gradually decreasing in winter compared to summer and monsoon due to the existing higher background concentrations. The subfine concentrations were found to be ~1.5×10^6 #cm^{-3} in UP during the monsoon (Fig.4.38 d) and in MIG and HIG during winter, while lower concentrations (<1×10^6 #cm^{-3}) were observed in summer due to dusting. The decay of particles due to dusting took less time to come back to its background concentration in monsoon and summer, and in winter, it was vice versa. Ventilation system usage was restricted during winter in the study area due to the existing low temperature and high relative humidity, which resulted in a longer decay time of particles in the bedroom than in other seasons.

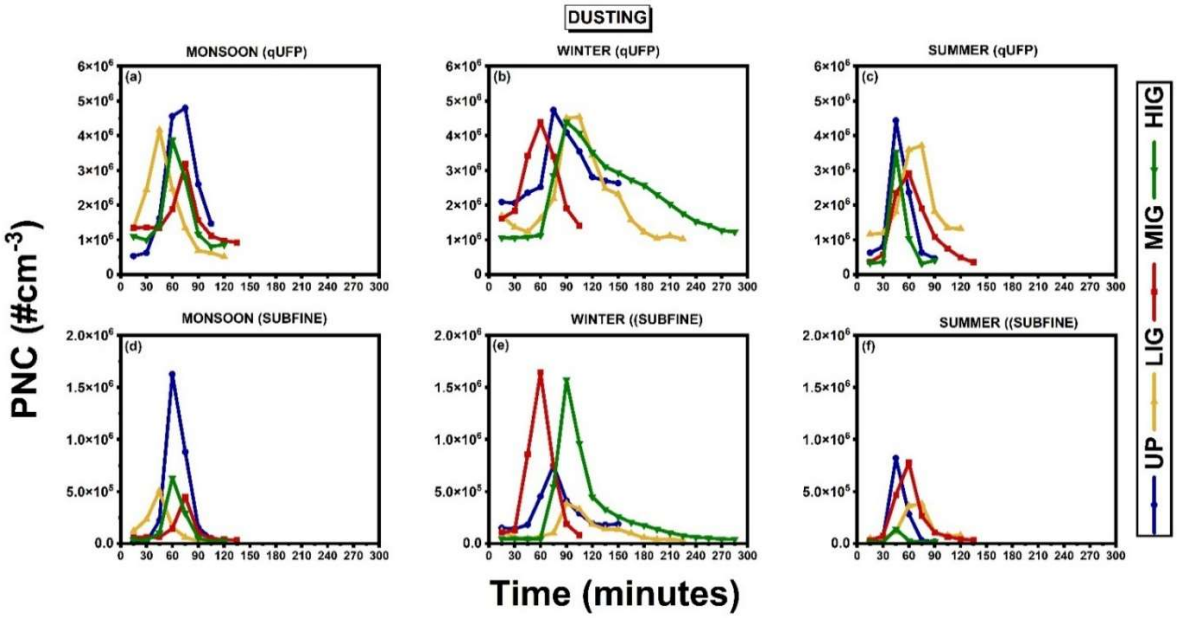

Figure 4.38 Concentration variation of qUFP (a, b, c) and subfine particles (d, e, f) during dusting activity in bedrooms of selected households in different seasons.

4.17 PNC of qUFP and subfine particles during incense stick burning

Incense is a major indoor pollutant being used for aesthetics, religious ceremonies, worship, aromatherapy, and meditation at home and in temples, as well as in spa centers or yoga gymnasiums. The Incense stick usage was observed in almost all selected households (Fig. 4.39). The incense stick emits a wide range of particles, and qUFP were found to be emitted in large numbers compared to subfine particles. The concentration received during the incense stick burning was found to emit particles equivalent to cooking and dusting. In HIG household, the concentration observed due to the usage of incense sticks was 5 to 6 $\times 10^6$ #cm^{-3} (Fig. 4.39) for qUFP particles and ~3$\times 10^6$ #cm^{-3} for subfine particles (Fig. 4.39). In winter, the incense stick usage concentration ranged between 4 to 5 $\times 10^6$ #cm^{-3} and for subfine 1 to 2 $\times 10^6$ #cm^{-3}(Fig. 4.39 e). During summer, the UP household observed concentration of qUFP (5 to 6 $\times 10^6$ #cm^{-3}) and subfine (~2$\times 10^6$ #cm^{-3}) followed a similar trend of winter HIG concentration. This is due to the usage of the incense stick, and suggests that the usage of the Incense stick in different seasons emits particles of similar concentration. The qUFP concentration in all three different seasons was observed to be ~ 5$\times 10^6$ #cm^{-3}. The decay time of incense sticks ranged between 160 to 180 minutes in different households.

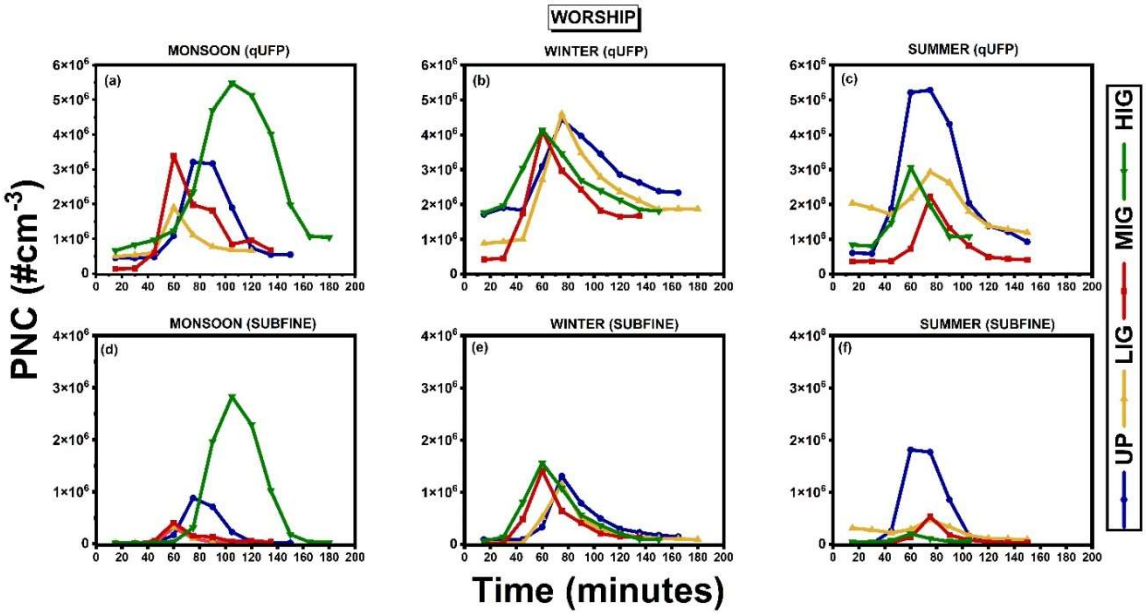

Figure 4.39 Concentration variation of qUFP (a,b, c) and subfine particles (d, e, f) during incense stick burning in the indoors of selected households in different seasons.

The decay time of different-sized particles generated due to the various activities such as cooking, dusting, and incense stick burning in different households revealed that the decay time is concentration-based on the existing meteorology conditions, ventilation status, and intensity of the sources. During an average dusting activity, PNCs were found to have less decay time, followed by incense stick usage and cooking. However, in the winter season with lower temperatures, poor ventilation, and higher relative humidity, it was found to be the season that takes more decay time, causing vulnerable effects to the residents indoors due to the high exposure time.

4.18 Temporal variation of pollutants in the kitchen during different techniques of cooking

The PNC generation in kitchen during various types of cooking methods was analysed, and it revealed that the concentration of the PNC varied based on the type of cooking.

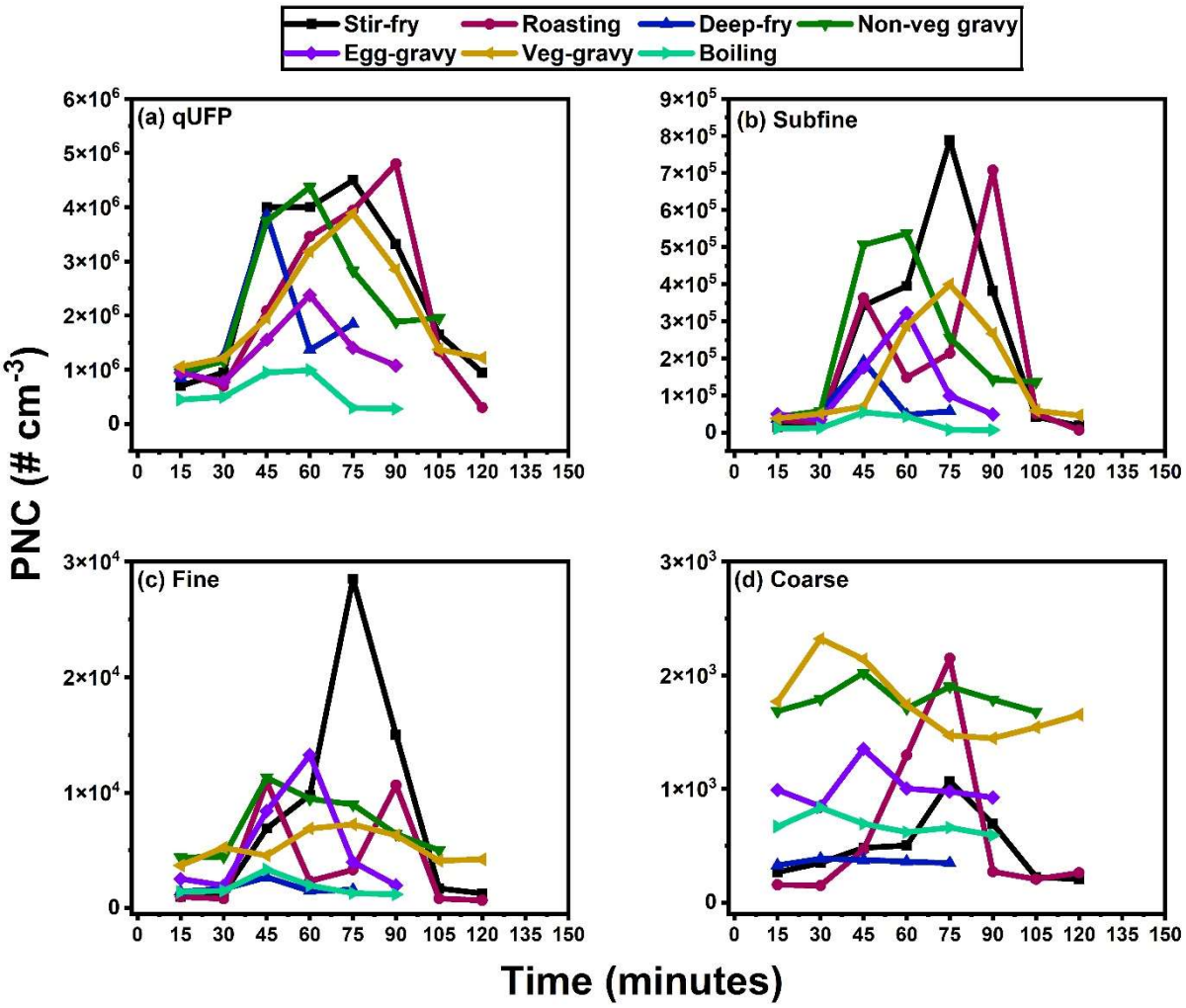

Figure 4.40 PNC variation of (a) qUFP, (b) subfine, (c) fine, and (d) coarse particles generated during different types of cooking in selected households.

The decay period of particles also varied accordingly. The number concentration of particles were found to be high of qUFPs 10^6 #cm^{-3} followed by subfine (10^5 #cm^{-3}), fine (10^4 #cm^{-3}) and coarse (10^3 #cm^{-3}) (Fig. 4.40). The activities such as stir-fry, roasting, gravy making (veg and non-veg) emits a similar range of qUFPs ranged between 4 to 5×10^6 #cm^{-3} (Fig. 4.40). The stir-frying and roasting activity generates a greater number of subfine ranged particles with a concentration of 7 to 8×10^5 #cm^{-3}. During stir- frying, concentration of fine particles (~3×10^4 #cm^{-3}) were emitted whereas due to roasting, coarse particles (~2×10^3 #cm^{-3}) were emitted. The PNC analysis of different-sized particles revealed that the roasting method of cooking is one of the methods that highly emits PNCs. The boiling method of cooking is found to have a lower number

concentration of the particles compared to other cooking techniques for qUFP and subfine particles. In fine and coarse particle size ranges, boiling and deep frying contributed to lower PNCs. Among the different methods of cooking, the boiling method contributed less smaller size particles compared to coarse particles. Different types of gravy preparation found to emit higher number of coarse particles. The results revealed that in different households, apart from the household infrastructure type, cooking methods also play a major role in determining the PNC, especially in kitchen environment.

4.19 Correlation of Total PNC with $PM_{2.5}$ concentration

Correlation of total PNC with the measured $PM_{2.5}$ was analyzed for establishing the relation between the PM and PNC in terms of concentration (Fig 4.41). The concentrations measured during all different seasons were analysed for correlation. During monsoon, the correlation of PNC and PM were found to be linearly related with higher correlation value of r = 0.9 for UP, LIG and HIG and 0.8 for MIG in kitchen and similarly in bedroom the correlation were r = 0.9 for LIG, MIG and HIG and 0.8 for UP. The correlation values during the monsoon season were found to be highly correlated in both kitchen and bedroom, revealing that the sources which were responsible for PNC generation in indoor were also responsible for the $PM_{2.5}$ concentration in both microenvironments. The correlation also suggests that the PNC concentration in indoor is positively correlated with PM concentrations in indoor, which were linearly correlated. This suggests that the increase in PNC concentration in indoor microenvironments also indicates the higher concentration of $PM_{2.5}$ in particular microenvironments in that season.

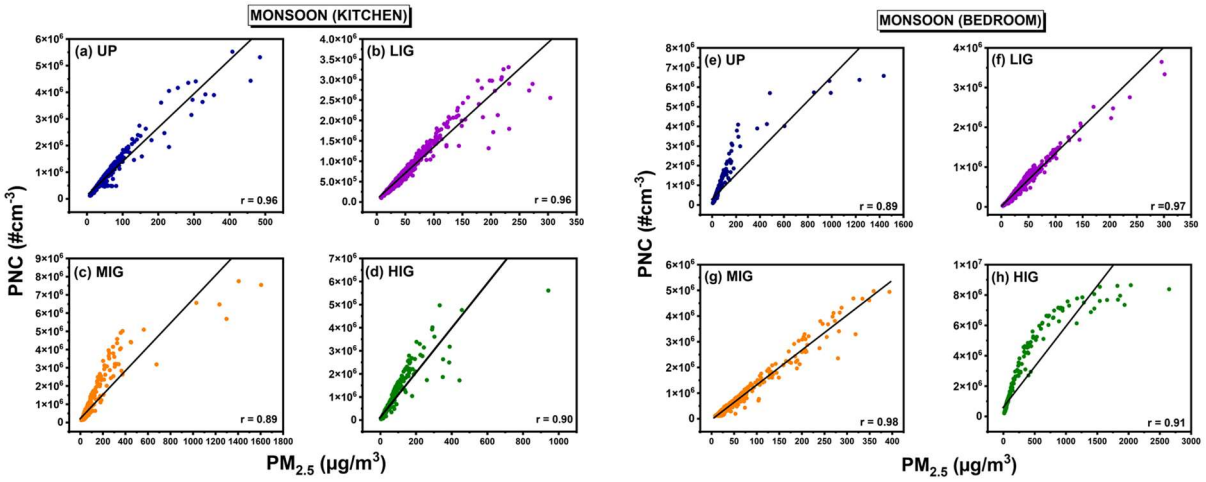

Figure 4.41 Correlation of PNC and $PM_{2.5}$ in different households UP (a,e), LIG (b,f), MIG (c,g), and HIG (d,h) in kitchen and bedroom during monsoon season.

Similar correlation analyses were performed during winter and summer seasons as well (Fig 4.42). During winter, the correlation in UP and MIG kitchen was found to be less (r = 0.7) (Figs. 4.41 a, c) compared to LIG (r = 0.9) (Fig. 4.41 b) and HIG (r = 0.8) (Fig. 4.41 d), whereas in kitchen, it was r = 0.8 for UP and MIG and r = 0.9 for LIG and HIG (Fig 4.43). The results suggest that during winter, the influence of outside sources on $PM_{2.5}$ concentration was found in UP and MIG, and in LIG and HIG, indoor sources had a stronger influence than the outdoor sources in both the kitchen and bedroom microenvironments.

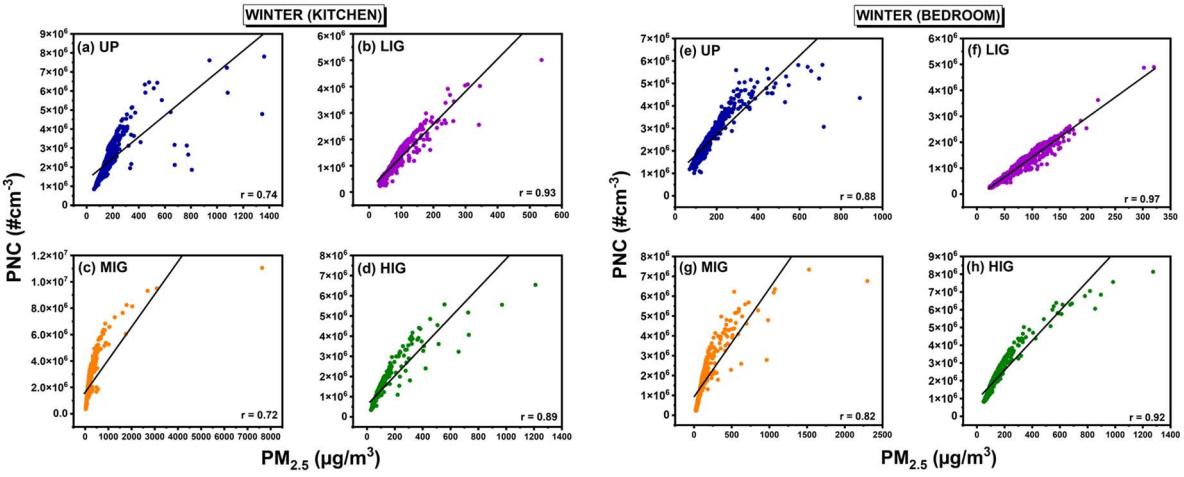

Figure 4.42 Correlation of PNC and $PM_{2.5}$ in different households UP (a,e), LIG (b,f), MIG (c,g), and HIG (d,h) in kitchen and bedroom during winter season.

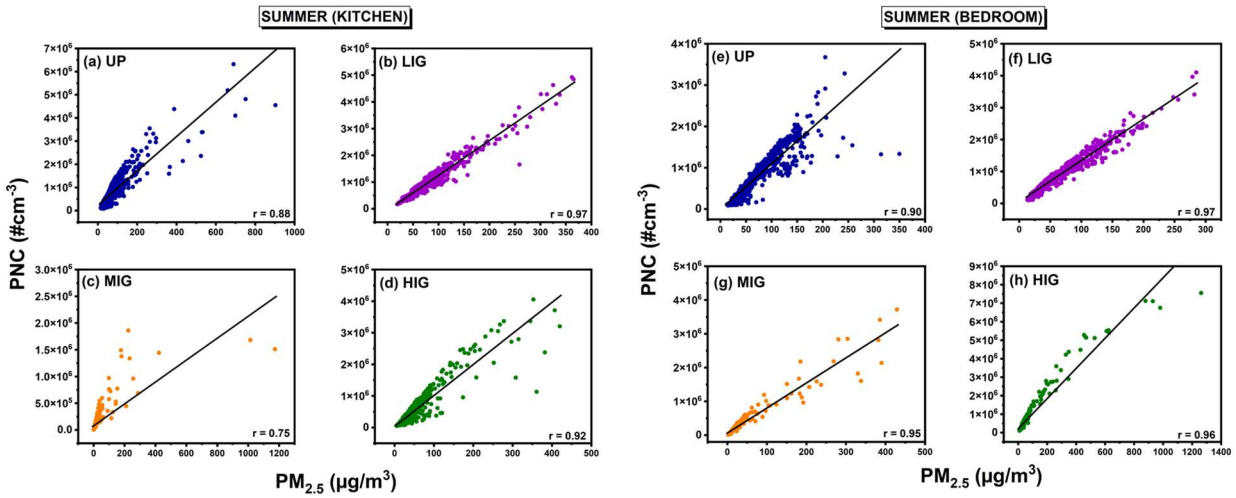

Figure 4.43 Correlation of PNC and $PM_{2.5}$ in different households UP (a,e), LIG (b,f), MIG (c,g), and HIG (d,h) in kitchen and bedroom during summer season.

During the summer season, LIG and HIG kitchen were found to have a strong correlation (r = 0.9) of PNC and $PM_{2.5}$ (Fig 4.43), whereas UP and MIG correlation was r = 0.8 and 0.7 in kitchen environment. In bedroom, the correlation was found to be < 0.9 in all four different households. Results suggest that in bedroom, the concentration was dominated by the indoor sources. All the correlation analyses in different seasons revealed that in the indoor environment, PNC and $PM_{2.5}$ were strongly correlated linearly, irrespective of the season and microenvironment. This also suggests that the majority of the emission sources in indoors were due to the influence of indoor sources in the selected households.

4.20 Temporal variation of different-sized PNC

Temporal analyses of different activities associated with festivals and normal days were analyzed using a wide range of particle concentrations in Delhi. The different size range particles such as N_{nuc} (10 to 30 nm), N_{atk} (30 to 100 nm), N_{acc} (100 to 1000 nm) along with the qUFP (250 to 500 nm), Sub-fine (500 to 1000 nm) were analyzed during the festival period (Diwali) (Figs. 4.44, 4.45). The measurement period consists of different phases such as Before Diwali (BD), During Diwali (DD), After Diwali (AD) and Normal Day (ND). The temporal analysis shows that the different activities (fireworks, dusting, cooking, and worship) contribute to an increase in different-sized particles in the indoor environment.

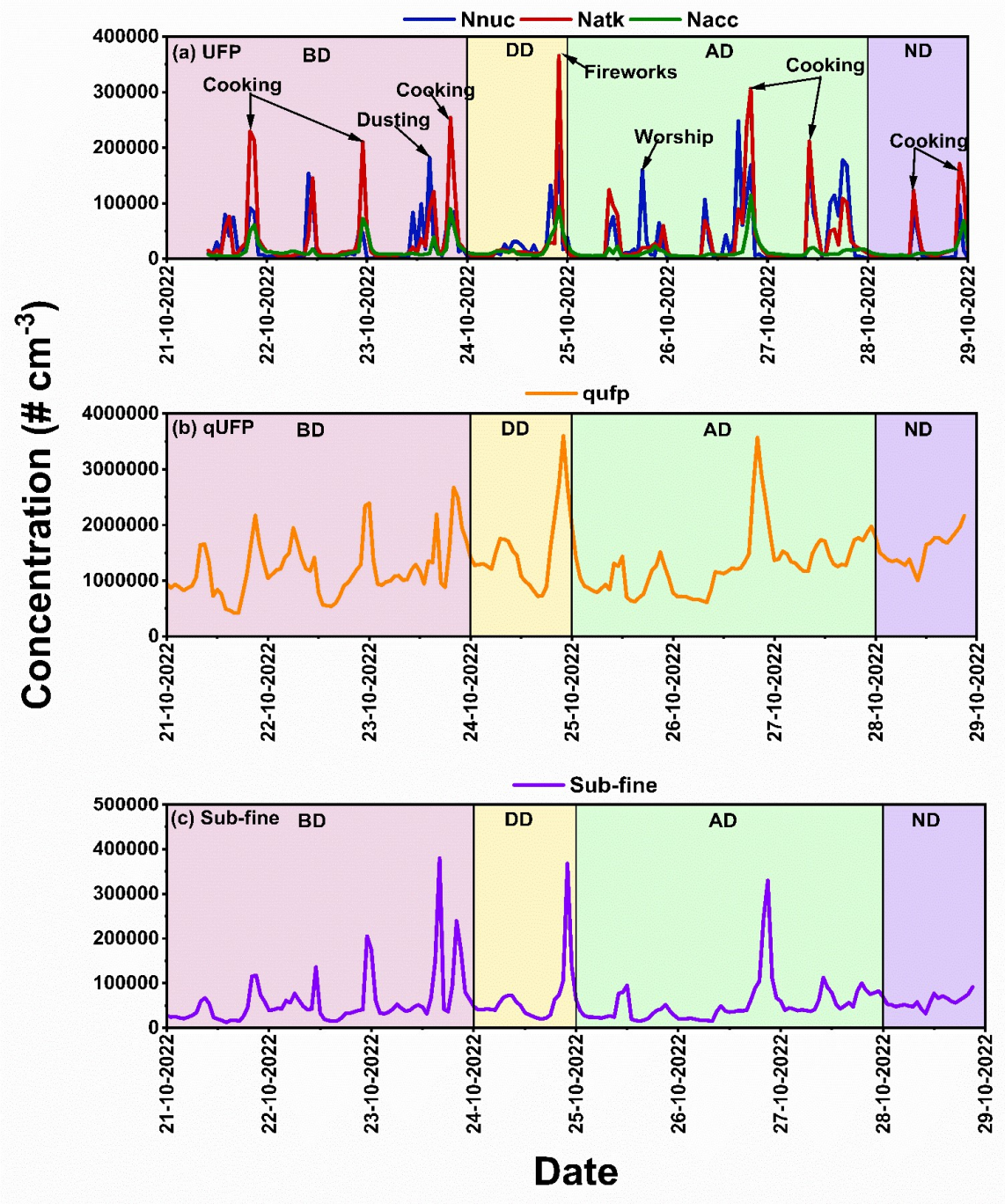

Figure 4.44 Temporal variation of PNC (a) UFP, (b) qUFP and (c) Sub-fine during BD, DD, AD and ND phases of the monitoring period in indoor environment.

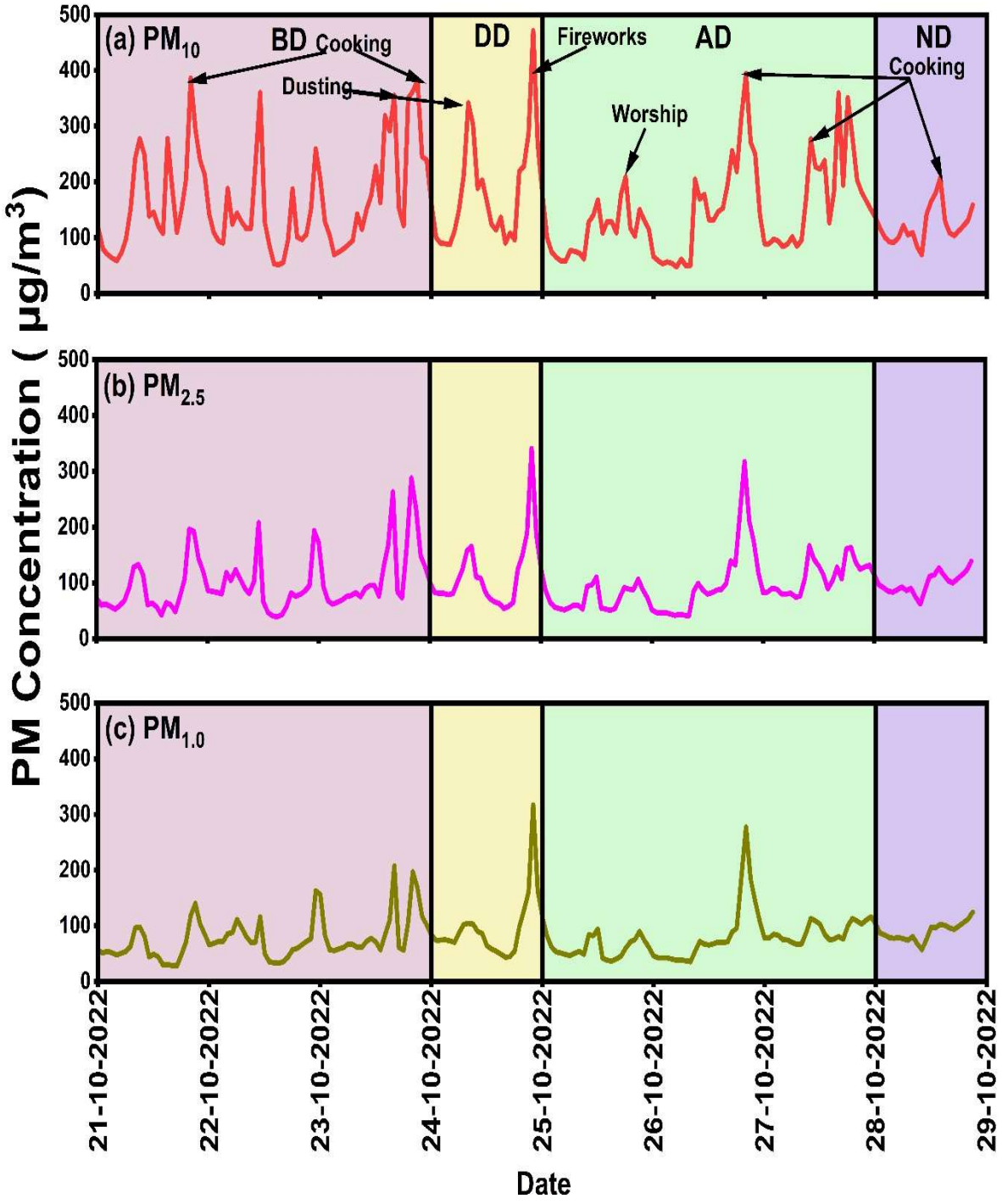

Figure 4.45 Temporal variation of PM_{10}, $PM_{2.5}$ and PM_1 during BD, DD, AD and ND phases of the monitoring period in indoor environment.

The mean concentration of the qUFP particles was found to be higher during the DD phase as a result of fireworks in the study region with a concentration of 1.5×10^6 #cm^{-3} (Table. 4.20). The qUFP concentration is followed by sub-fine and N_{atk}. During the DD

phase, the concentration observed for all the other size fractions in the order of sub-fine (6.4×10^4 #cm^{-3}), followed by N_{atk} (2.7×10^4 #cm^{-3}), N_{nuc} (2.7×10^4 #cm^{-3}), N_{acc} (1.8×10^4 #cm^{-3}) then fine (2.9×10^3 #cm^{-3}) and coarse particles (1.1×10^3 #cm^{-3}) (Fig. 4.44). During the ND phase, the concentrations of the different size ranges were found to be less compared to the DD phase, except for N_{acc} and fine mode particles. Due to the Diwali firecrackers emission influence in indoor environment, the maximum concentration attained was 3.5×10^6 #cm^{-3} for qUFP size range (Fig. 4.44).

The concentration of N_{nuc} and N_{atk} were found to be higher during the AD phase compared to the other phases. Similarly, for the fine particles, the concentration was found to be higher during the ND phase (3.5×10^4 #cm^{-3}). The temporal analysis indicates that the cooking activity creates a prominent peak concentration a little lower than the fireworks. The concentration attained for the qUFP due to cooking in the AD phase was ~ 3.5×10^6 #cm^{-3}, but during the ND phase, the maximum concentration obtained was 1.03×10^6 #cm^{-3} (Table. 4.19). The peak of particle concentration due to the cooking activities were found to prominent in almost all days during all the four different phases. This reveals that the air quality of indoor environments is more vulnerable all the days when cooking activities take place. However, the normal cooking day produces a particle concentration of fine particles around 3.5×10^3 #cm^{-3}. These results suggest that during the Diwali festival, cooking activities (festival cooking) are also a major concern for indoor air quality apart from emissions from fireworks. In an indoor environment, the dusting and worship activities (use of incense sticks) also contribute significantly. The order of concentration of PNC based on different indoor activities is fireworks> cooking> dusting > worship (highest to lowest).

Table 4.19 Statistical summary of the different-sized particles during different phases of the study period.

Phase	**Parameter**	**N_{nuc} (#cm^{-3})**	**N_{atk} (#cm^{-3})**	**N_{acc} (#cm^{-3})**	**qUFP (#cm^{-3})**	**Sub-fine (#cm^{-3})**	**Fine (#cm^{-3})**	**Coarse (#cm^{-3})**
BD	Min	636	4220	3958	419728	12535	971	177
	Max	182339	254414	89809	2673243	379965	20009	4513

	Mean ± SD	26487 ± 39012	36742± 58199	15616± 17323	1195949± 502056	58509± 59099	3950± 4229	1203± 968
	SE	4915	7332	2183	59168	6965	498	114
	Median	7525	12624	9200	1084445	41221	2540	906
DD	Min	961	3802	6230	720825	20033	1224	217
	Max	203034	365516	93611	3599847	367877	11317	3902
	Mean	27848± 46379	27956± 72373	18419± 20536	1518355± 694849	64991± 70082	2978± 2306	1111± 908
	SE	9467	14773	4192	141835	14305	471	185
	Median	12498	12071	10085	1363804	45558	2260	904
AD	Min	202	1788	3761	611453	15481	505	88
	Max	247920	306704	114262	3572964	461578	13415	3309
	Mean ± SD	34277± 55305	33236± 55955	12699± 15004	1282860± 543238	56386± 61832	2920± 2672	875± 736
	SE	6518	6594	1768	64021	7287	315	87
	Median	6321	8742	8314	1242705	39497	1974	753
ND	Min	162	2262	4451	419728	12535	971	177
	Max	96983	171573	68536	2170942	117613	13467	3797
	Mean ± SD	11418± 25149	26019± 46483	13031± 13469	1030648± 457963	39577± 29516	3559± 2890	1343± 890
	SE	5134	9488	2749	93481	6025	590	182
	Median	2097	6716	9485	896200	25878	2918	1206

4.21 Diurnal variation of PNC

The diurnal variation of the different-sized particles shows that few particle concentrations remain constant throughout the day, and few vary drastically due to associated activities in the indoor environment. The N_{nuc} concentration in the morning hours (00.00-6.00) was found to be less, which was < 10^4 #cm^{-3} (Fig. 4.46), and it started to increase gradually and reached the maximum of up to 10^5 cm^{-3}. This indicates that indoor activities were contributing to N_{nuc} and N_{atk} concentration, and it was found less during early morning hours due to the absence of indoor activities (sleeping hours). The qUFP concentration in a day range between 10^5 to 10^7 #cm^{-3} (Fig 4.47). Global studies

suggest that the PNC concentration in the outdoor environment in a polluted urban region ranges from 10^2 to 10^6 #cm^{-3} (Rajagopal et al., 2023) but the indoor concentration during certain episodes increases another one magnitude up to 10^7 #cm^{-3}. The lowest size fractions (N_{nuc} and N_{atk}) concentration varies vastly from 10^2 to 10^5 #cm^{-3} within a day due to the fluctuation of sources (Fig. 4.46 a,b). The concentration of the fine (Fig. 4.47) and coarse particles concentration were found to have less number concentration (< 10^4 #cm^{-3}) compared to the other size fractions. The reduction in concentration was due to the increasing mass based on the size which increases the mass concentration and reduces the number concentration. The particles with smaller sizes act vice versa. The bigger size range particles, such as fine and coarse concentration, do not vary significantly during different hours of the day. This is the result of the background concentrations in the Indoor environment, which is present irrespective of the sources. This reveals that the influence of outdoor sources on indoor air quality is another major concern irrespective of the indoor sources, especially in polluted urban regions. The diurnal pattern in the indoor environment was totally different from the outdoor. In outdoor environment, the majority of the diurnal pattern in the urban regions shows a peak concentration during peak hours of the day (Rajagopal et al., 2024b). Whereas in urban indoor environments, the diurnal concentrations vary during different activities such as cooking hours, non-cooking hours, dusting periods, and firework emissions.

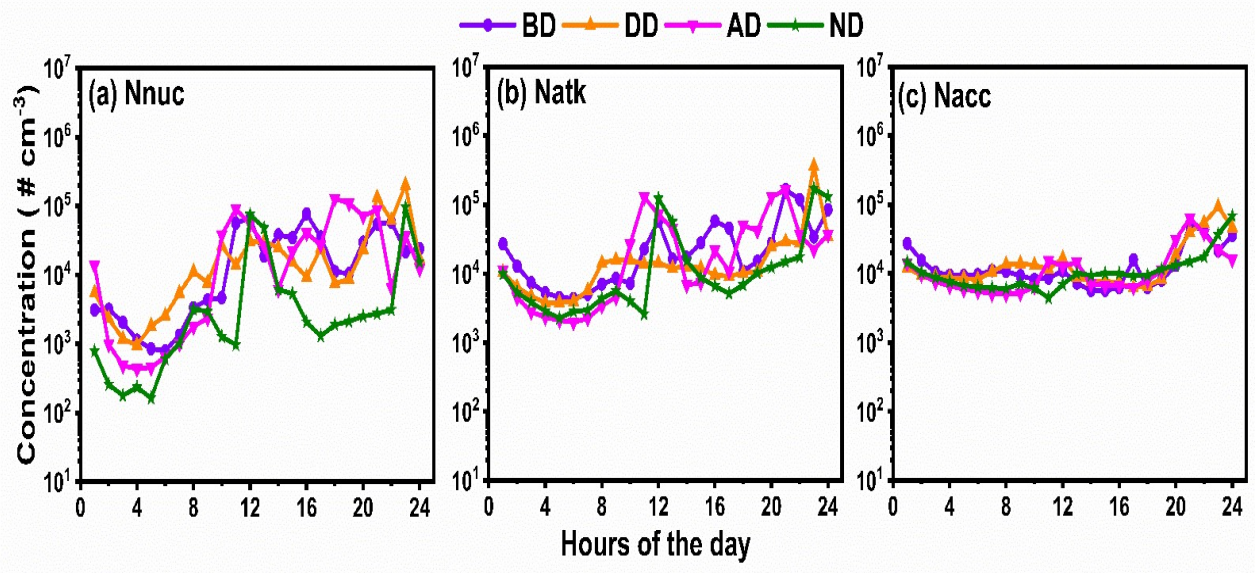

Figure 4.46 Diurnal variation of (a) N_{nuc} (10 to 30nm), (b) N_{atk} (30 to 100nm), and (c) N_{acc} (100 to 1000nm) during different phases (BD, DD, AD, and ND) of the study period.

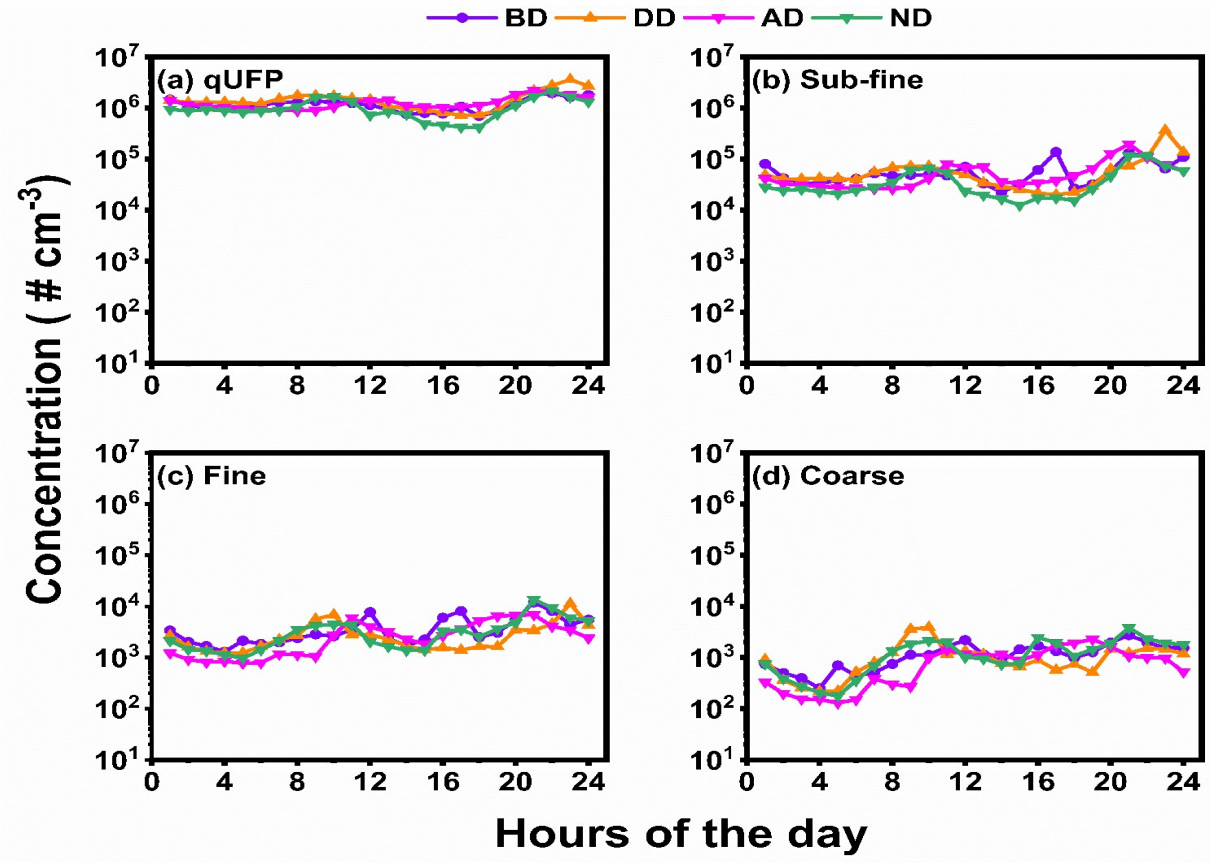

Figure 4.47 Diurnal variation of (a) qUFP (250 to 500nm), (b) Sub-fine (500 to 1000nm), (c) Fine (>1 µm to < 2.5 µm), and (d) Coarse (>2.5 µm to < 10 µm) during different phases of the study period.

4.22 Particle number size distribution

The size distribution of the particles was analyzed for sizes ranging from 10 to 1000 nm during the different phases of the monitoring period. The size distribution of the particles helps to identify the different size fractions emissions from different sources. Every individual source has a different emissions pattern, and the size distribution of the particles varies based on that. During the DD phase, the smaller size particle emissions (N_{nuc}) were found higher with a concentration of 8×10^4 #cm^{-3} which is clearly visible from the size distribution of particles (Fig. 4.48). Similarly, During the BD and AD phases, when there were some excess indoor activities, such as dusting and cooking, the size distribution concentration were maximum concentration of ~7.8×10^4 cm^{-3} but the peak was found between 50 to 100 nm due to the mixture of the sources. The ND size

distribution was similar to the BD and AD phases with a lower concentration. During the BD and AD phases, the activities indoors remained the same, but their intensity resulted in higher concentrations compared to ND phase. This reveals that in indoor environment, the different activities lead to different size distribution, which does not coincide with the urban or background-size distribution patterns in indoor environments. The size distributions of particle numbers are sources oriented and its changes frequently based on the types of emission occurring in the indoor environment. The size distribution of emissions from different activities was analyzed to estimate the particle emission sizes. The fireworks hours (8:00 pm to 00:00 am) on DD phase and cooking hours (8:00 pm to 00:00 am) on ND phase at night were analyzed separately to understand the emission profiles during fireworks and cooking activities (Fig. 4.49). The fireworks alone contribute to a concentration of about ~3.4 × 10^5 #cm^{-3} for N_{nuc} particles whereas the cooking contributes for ~2 × 10^5 # cm^{-3} with a peak at ~100nm. The cooking activities in indoor emit higher-size particles in the size range of N_{atk} and N_{acc}, which increase gradually from the lower size and attain a peak around 100 nm and decrease gradually, whereas during the fireworks period, smaller sizes particles > 30 nm were found to have very high concentrations indoors. During fireworks hours, the influence of particles from the cooking caused a second peak in concentration in the N_{atk} ranges, which is visible from the size distribution. The particle size distribution ~ > 200 nm on cooking hours and firework hours shows similar trends (Fig. 4.49).

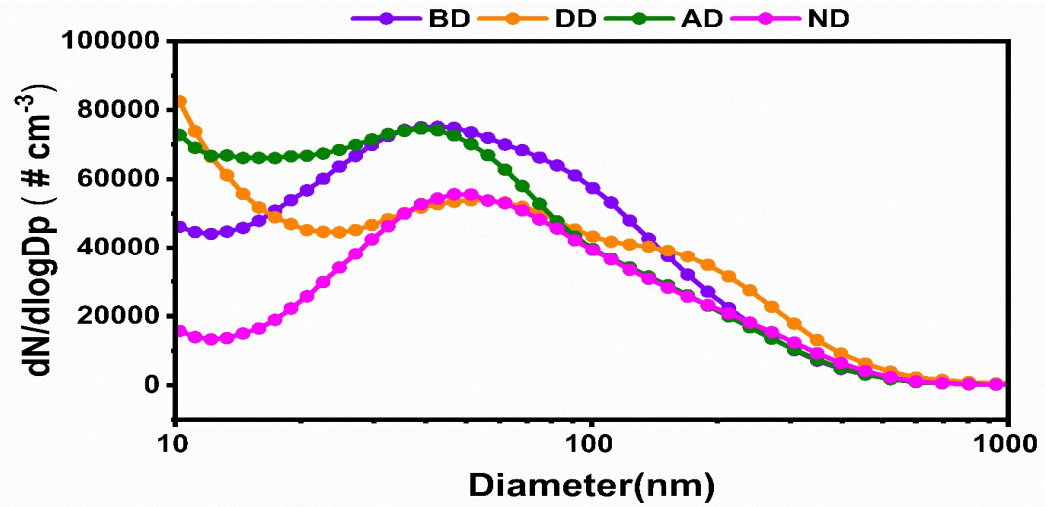

Figure 4.48 Particle Number Size Distribution (PNSD) of particles from 10 to 1000 nm during different phases of the festival.

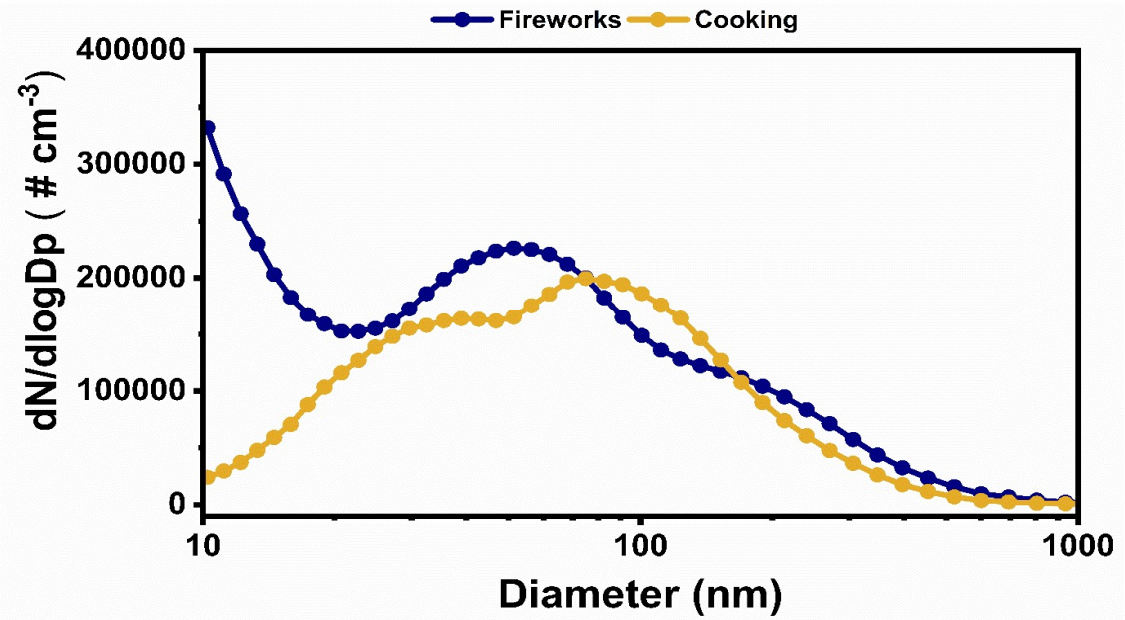

Figure 4.49 Particle Number Size Distribution (PNSD) of particles from 10 to 1000 nm during fireworks hours (8:00 pm to 00:00 am) on DD and cooking hours (8:00 pm to 00:00 am) on ND.

4.23 Contribution of different size fractions to total PNC

The N_{total} (10 to 1000 nm) concentration of the PNC involves the contribution of three different smaller-size fractions (N_{total} = N_{nuc} (10 to 30nm) + N_{atk} (30 to 100nm) + N_{acc} (100 to 1000nm). During ND phase, the N_{acc} mode particles contribute to around 50% which is the highest contribution (Fig. 4.50). This reveals that during ND when regular house hold activities were occurring N_{acc} concentrations were found to have more influence in N_{total}. N_{nuc} was found to have less contribution on ND (13%) but during DD it contributed to ~31 % due to increase in firework emissions.

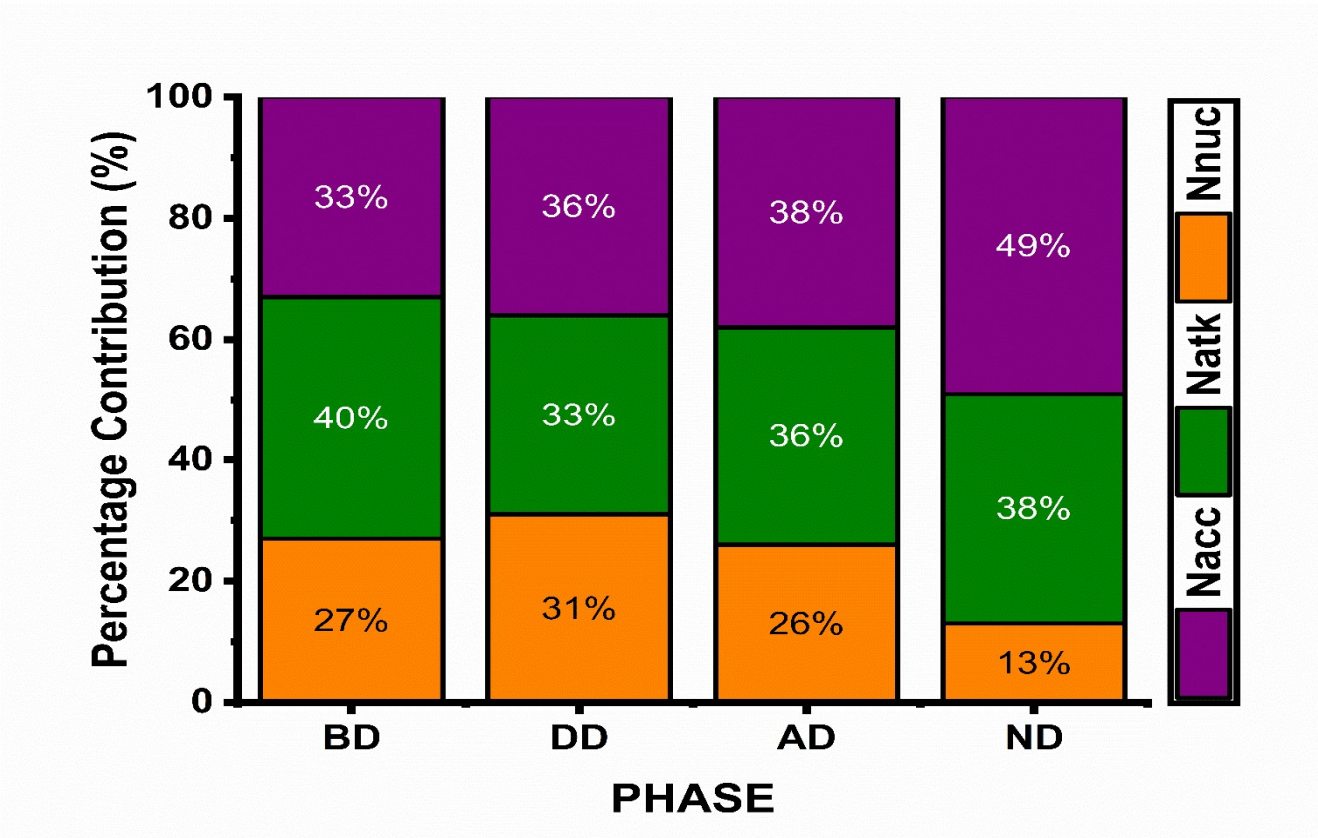

Figure 4.50 Percentage contribution of different size particles (Nnuc, Natk, Nacc) for the N_{total} concentration of the PNC.

The N_{nuc} concentration on DD increased twice the concentration of ND. The N_{atk} concentration remained in the range of 30 to 40% during the different phases of the monitoring period irrespective of the emission sources (Fig. 4.50). This shows that the N_{atk} mode particles were less influenced by the different types of emission sources in indoor environment. The smaller (N_{nuc}) and larger size particles (N_{acc}) were highly influenced by the emissions sources. During Festivals like DD the different sizes (N_{nuc}, N_{atk}, and N_{acc}) contributes (~36%, 33% and 31%) equally for the N_{total} concentration due to the multiple emissions sources occurring at the same time.

4.24 Chemical composition of Indoor pollutants

The chemical composition of the wide range particles were analysed during the DD phase and BD phases to know the contribution of the fireworks composition in the indoor pollutants. The results reveal that fireworks have a direct influence on the concentration

and chemical composition of indoor pollutants. The analysed chemical substances were classified based on their carcinogenic properties as prescribed by the WHO. The chemical analysis shows that during the DD, the concentration both carcinogenic and non-carcinogenic chemical compositions increase compared to the ND. The K (Potassium) and Fe (Iron) elements which were exclusively released during the firework emissions were not presented on ND but reached to a concentration of 30 to 40 ppb (Fig. 4.51, Table.4.20). This shows that the fireworks emission influenced the indoor air quality and the increase in pollution concentration on DD was mainly due to the fireworks. The P (phosphorus) which is common indoor substance found in households due to the usage of different detergents and found to have higher concentration (~30 ppb) whereas all other carcinogenic and non-carcinogenic compounds were found (< 15 ppb) during the normal days (Fig. 4.51, Table.4.20).

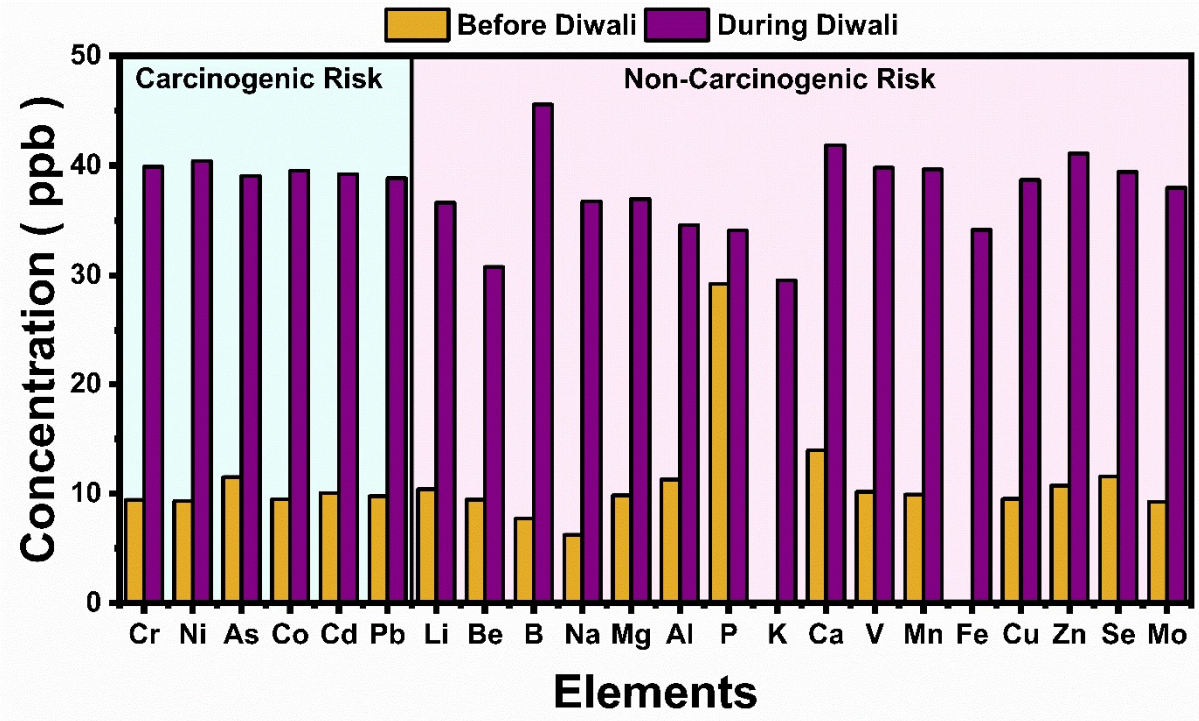

Figure 4.51 Chemical composition of the indoor air pollutants measured during the BD and DD phases.

During DD, the concentration of the compounds increased dramatically and they were found > 30 ppb. The substances like (B, Ca, Mn, Se, Mo) increased during DD, which are the different agents used in the manufacturing of crackers and also the secondary

inorganic compounds formed once the Diwali emissions enter the atmosphere. The Diwali crackers use different chemical substances for sparks, smoke effect, colour and sound which resulted in the increased chemical composition of the indoor air quality.

Table 4.20 Chemical composition of the different chemical analysed using ICP-MS.

Elements	**Before Diwali Conc. [ppb]**	**During Diwali Conc. [ppb]**
Li	21.6	47.8
Be	19.7	41.0
B	13.9	51.7
Na	6.2	36.7
Mg	15.8	42.9
Al	11.2	34.5
P	29.2	34.0
K	<0.000 (BDL)	29.5
Ca	19.9	47.8
V	19.6	49.3
Cr	16.2	46.7
Mn	19.9	49.6
Fe	<0.000 (BDL)	34.1
Co	19.3	49.4
Ni	18.8	49.9
Cu	36.5	65.7
Zn	18.1	48.5
As	20.0	47.5
Se	19.4	47.3
Mo	18.9	47.7
Cd	19.5	48.7
Pb	19.3	48.4

4.25 Deposition of $PM_{2.5}$ in the human respiratory tract

Particulate matter such as PM_1 and $PM_{2.5}$, known for their toxicity, cause severe human health impacts, were found to be high in the kitchens of UP and LIG households, where the building infrastructure was poor, with no mechanical ventilation system and a separate space for kitchen and living. The $PM_{2.5}$ concentration was used in the MPPD model to analyze the concentration of deposition in different age groups of individuals (Children = 3 years, Teenagers = 14 years, and Adults = 21 years) in both bedroom and kitchen (Fig. 4.52).

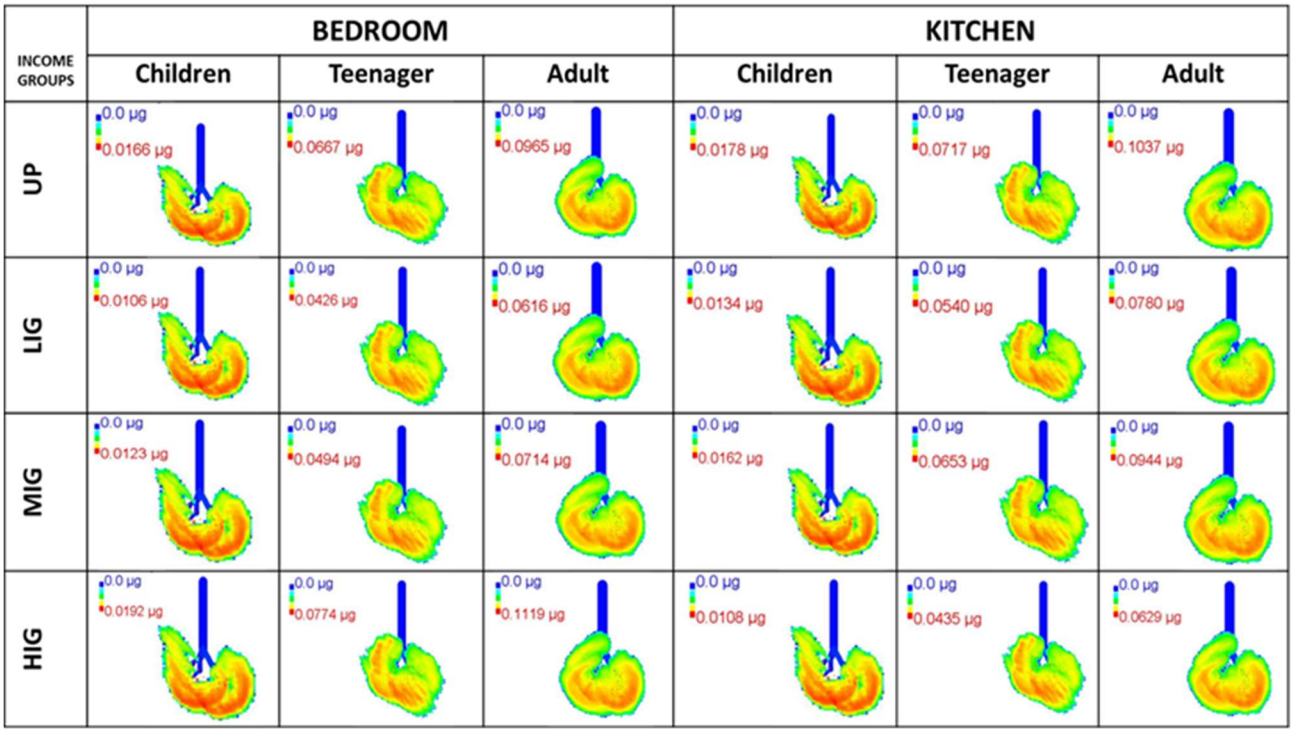

Figure 4.52 $PM_{2.5}$ deposition in different age groups in bedroom and kitchen of the selected household.

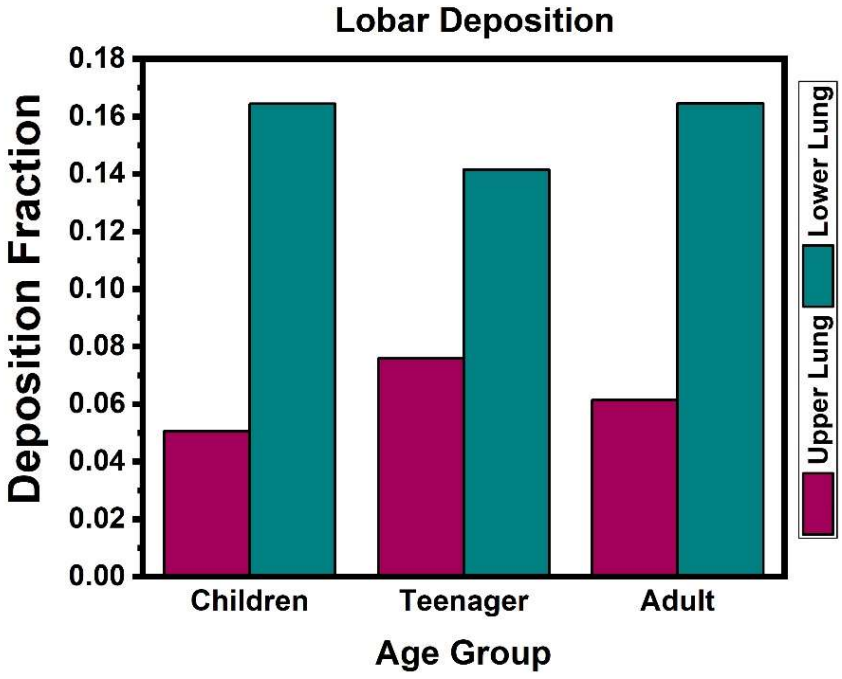

Figure 4.53 Deposition Fraction (DF) of different age groups in the upper and lower regions of the lungs.

The UP kitchen with a higher concentration of $PM_{2.5}$ was found to have more deposition (0.10 µg) compared to other households. The HIG household kitchen environment was found to have less exposure to residents of all different age groups. The HIG with more worship activities in their bedroom was found to be more vulnerable compared to other household kitchens with a deposition of 0.11 µg. This suggests that in indoor air pollution, the exposure is strongly dependent on sources and exposure time. The deposition of the particles in the human respiratory tract is based on the size of the particles. The $PM_{2.5}$ showed more deposition in the lower region of the lungs (Fig.4.53). For all age groups, the deposition fraction is found to be < 0.08, and for the lower lung, it was > 0.14 for all the age groups, suggesting that the $PM_{2.5}$ particles have more deposition in the lower respiratory tract compared to the head or upper regions of the respiratory system.

4.25 Summary

The results and discussion chapter provides a detailed discussion through a year-long observation during different seasonal and temporal analyses on indoor and outdoor PNC and particulate matter, along with the influence of meteorology parameters in different households (UP, LIG, MIG, and HIG) during different seasons, and PNC and PM emission from different indoor activities and methods of cooking. It also examined episodic events during the festival celebration and their impact on indoor particle number, size distribution, and health effects.

Chapter – 5

CONCLUSIONS

5.1 Introduction

This study measured concentrations of different-size particles (PM_{10}, $PM_{2.5}$, PM_1, qUFP: 250 to 500 nm, sub-fine: 500 nm to 1 µm, fine: 1 to 2.5 µm and coarse particles: 2.5 to 10 µm in different microenvironments (i.e., kitchen, bedroom, and outdoor) during three different seasons in the megacity Delhi. The households with differing infrastructures were selected based on their socio-economic strata in the same geographical domain. Concentrations measured in three major seasons (monsoon, winter, and summer) and three microenvironments (bedroom, kitchen, and outdoor) were considered for the analysis**.** The major conclusions of the study are as presented in the following sections.

5.2 Summary of indoor particulate matter in different households

The results showed that the kitchens were more polluted than the bedrooms, irrespective of the income group/household. The highest mean concentration of PM_{10} observed in bedroom (200 µg/m^3) and kitchen (250 µg/m^3) during winter. The order of PM_{10} concentration in different income groups in three seasons was as follows: monsoon (MIG> HIG> LIG> UP), winter (MIG>UP>LIG>HIG), and summer (UP>HIG>LIG>MIG), respectively. In kitchen, during winter and monsoon, the concentration of pollutants in MIG was higher compared to other income groups. During summer, UP households experienced higher concentrations of indoor pollutants in both bedroom and kitchen. During night time, the pollutant concentration was higher in UP and LIG households than in other income groups due to poor household infrastructure. The different-size fractionated particulate matter analysis shows that in indoor environments, PM_1 contributed more to PM_{10}, and the contribution varied depending on sources. In indoor environments, the PM_1 contribution ranged between 70% and 80% in both kitchen and bedroom, whereas in outdoors, particles > $PM_{2.5}$ contributed more to PM_{10} concentration. The diurnal analysis in kitchen showed that the difference in concentration coincided with cooking habits, with concentrations increasing by a factor of two during cooking hours. Indoor-outdoor (I/O) ratio analysis revealed that the

influence of outdoor concentration was less during cooking hours, and it reached a maximum of about 60 during intense indoor activity. The mean I/O ratio analysis established that the influence of outdoor sources on indoor was higher during winter.

5.3 Summary of indoor PNC measurements in different households

In the indoor microenvironment, the mean concentration of qUFP was found to be 1.1×10^{6} #cm^{-3} (UP kitchen), whereas outdoors, it was 8.0×10^{5} #cm^{-3}. The indoor concentration of qUFP was found to be 10^{6}–10^{5} #cm^{-3}, followed by sub-fine (10^{5}–10^{4} #cm^{-3}), fine particles (10^{4}–10^{2} cm^{-3}), and coarse particles (10^{4}–10^{2} #cm^{-3}). The seasonal mean concentration of qUFP was found in the order of winter>summer>monsoon. In the kitchen, qUFP concentration was found in the order of UP>LIG>MIG>HIG, while in the bedroom, it was HIG>UP>LIG>MIG. The qUFP concentration outdoors was observed ~30 % less in UP and HIG households and about 50% lower in LIG and MIG households than indoors. The concentration of coarse particles was found to be greater outdoors than indoors, except during the winter season. The indoor diurnal concentration in UP and LIG households coincided with cooking hours and was also found to influence the bedroom as well due to their inadequate infrastructure. The I/O ratio revealed that the ratio was not uniform and varied seasonally across different households. The presence of strong independent indoor sources diminished the influence of outdoor sources and vice versa. The $C_{Bedroom}/C_{Kitchen}$ ratio clearly indicated that household infrastructure played a major role in the influence of one microenvironment's concentration over another. The bedroom of the HIG household was least influenced by kitchen sources due to well-planned infrastructure. The occupant's cooking pattern determined night time PNC in indoor environments.

5.4 Summary of PNC measurements during different types of cooking

The qUFP concentrations emitted during different activities in indoor environments such as cooking, dusting, and incense stick usage were found in the range of 4 to 6 $\times10^{6}$ #cm^{-3} in almost all seasons, irrespective of the income groups. The particles' decay period was found to be high during winter (180 to 300 minutes) for all the different activities. Particles generated during incense stick burning take a shorter decay period (< 200 minutes) than the dusting activity (120 to 300 minutes). Cooking-generated particles took

more time to decay (up to 330 minutes). PNC of qUFP were found to be high (4 to 5×10^6 #cm^{-3}) during stir frying, roasting, and gravy cooking (veg and non-veg). Roasting and stir-frying generated a large number of subfine and coarse particles as well (7 to 8×10^5 #cm^{-3}). Stir-frying generated a significant number of fine particles (3×10^4 #cm^{-3}), and roasting resulted in a significant number of coarse particles. Compared to all cooking methods, boiling-based cooking was found to generate less number of qUFP and subfine particles, whereas deep fry and boiling both contributed less to fine and coarse particles. The correlation of PNC and $PM_{2.5}$ in the kitchen and bedroom showed that the concentrations were positively correlated in all seasons (r = 0.7 to 0.9). The concentration in both the micrometeorological environments was linearly correlated, and the increase in PNC concentrations increases the PM concentration in the indoor environment and vice versa. The outcomes of the study revealed that the PNC of the indoor environment depends on various factors. Different activities in indoors are responsible for the PNC generation. The concentration in an indoor environment is based on the type of activity, behaviour, household infrastructure, meteorology of the environment, and ventilation status. Indoor environment is more vulnerable than the outdoor environment due to the existing higher concentration and longer exposure time which needs to be monitored and regulated for better standard of living especially in rapidly urbanizing cities.

5.5 Role of festivals in indoor PNC and its chemical composition

During festival seasons, the air quality in indoor is also influenced by different active indoor sources and also due to the influence of external sources. The study was conducted for a period of 8 days which includes 4 different phases which is providing insights about the role of festival activities along with the firework emissions in increasing the pollution concentration in the indoor environment. During the DD phase, the maximum concentration of the daily mean qUFP was found at a concentration of 1.5×10^6 #cm^{-3}. During the DD phase, the concentration observed for all the other size fractions in the order of sub-fine (6.4×10^4 #cm^{-3}), followed by N_{atk} (2.7×10^4 #cm^{-3}), N_{nuc} (2.7×10^4 #cm^{-3}), N_{acc} (1.8×10^4 #cm^{-3}) then fine (2.9×10^3 #cm^{-3}) and coarse particles (1.1×10^3 #cm^{-3}). During the peak firework emission, the concentration reaches up to 3.5×10^6 #cm^{-3}. The N_{acc} and fine mode particles were found higher during the ND phase compared to the DD phase. The order of concentration based on different indoor activities were

fireworks > cooking > dusting > worship (highest to lowest). In indoor environment the concentration of the qUFP ranges from 10^5 to 10^7 #cm^{-3} during different hours of the day. The smaller size particles N_{nuc} and N_{atk} were less during the morning hours (00.00 to 06.00 am) due to the absence of indoor activity. The diurnal pattern in indoor doesn't coincide with the outdoor pattern. The size distribution in indoor also varies based on the intensity of the sources present in indoor. During the DD phase the size distribution of the N_{nuc} particles reaches a maximum of about 8×10^4 #cm^{-3} but during the normal day it was only 2×10^4 #cm^{-3}. The size distribution during the BD and AD phase was more or less similar, but the size distributions during the DD and ND phases were totally different due to the role of different emission sources. The cooking hour and firework hour size distribution shows that the fireworks increase the lower size particles, particularly N_{nuc} particles, whereas cooking activities release particles with a peak around 100 nm. During the DD phase, the N_{nuc}, concentration increased twice (13% to 31%) due to the firework emission whereas the N_{acc} on ND contributed to around 50% of the total PNC in the indoor household. The N_{atk} contributed to around 30 to 40% of the total PNC throughout the monitoring period. The chemical composition of the indoor air pollutants also changes and the chemicals associated with firework emission (K, P, Fe) were found in higher concentration compared to the ND. The carcinogenic chemical substances also increased ~ 2 folded time during the DD phase making indoor air more vulnerable and toxic.

The analysis reveals that indoor air quality in urban regions is a major area of concern. The indoor air pollution depends on various factors, such as sources, meteorology, infrastructure, and outdoor influence. The results suggest that indoor air quality mitigation initiatives are mandatory for reducing exposure of residents. The quantitative outcomes of the study highlight need for mandatory action to improve indoor air quality, especially in urban regions with high population density, which has implications to human health. The results of the present study indicate that indoor pollution is not only directly linked to indoor sources but also influenced by outdoor sources, household infrastructure and ventilation. Indoor PNCs were found to be higher than outdoor PNCs most of the time, underscoring the need for implementing mitigation measures to control indoor pollution. Every individual spends the majority of their lifetime in different indoor environments. The health impacts of indoor air quality are higher than those of ambient

air. The fireworks emission can be reduced by implementing various control measures, but the emissions associated with festivals in indoor environments are still a persisting problem that needs to be taken care of with utmost priority for the betterment of life.

5.6 Importance of the study

The study of aerosols in indoor–outdoor microenvironments for urban households of Delhi holds great importance in understanding human exposure to particulate pollution in an Indian metropolitan context. Global research has consistently demonstrated that fine and ultrafine particulate matter (PM) plays a major role in respiratory, cardiovascular, and neurological health problems. In developing cities like Delhi, where ambient PM concentrations are often several times higher than global air quality standards, indoor exposure contributes significantly to the total inhaled dose since individuals spend nearly 80–90% of their time indoors. Therefore, examining the relationship between indoor and outdoor particulate levels becomes essential for estimating true exposure and associated health risks.

Studies conducted in Europe, East Asia, and North America have shown that ultrafine particles, measured through particle number concentration (PNC), pose distinct health concerns because of their ability to penetrate deep into the lungs and enter the bloodstream. However, limited information is available from Indian households on PNC variations, especially across different income groups and building types. Additionally, previous international investigations have revealed that common indoor activities such as cooking, incense burning, and cleaning generate short-term but intense particle peaks, which may substantially influence daily exposure levels. In Delhi, where such practices are frequent, understanding these peaks and their relation to outdoor air is crucial.

Further, infiltration and ventilation characteristics differ widely across household types, affecting how outdoor pollutants enter and remain indoors. Studying these differences in the local context will help identify factors that either aggravate or reduce exposure. The results of this research will provide a scientific foundation for formulating effective control strategies at both the household and city levels. It will also contribute to ongoing national initiatives for clean air by highlighting the indoor dimension of Delhi's air

quality challenge and supplying valuable data for future epidemiological and exposure modelling studies.

5. Future vistas of research

Despite the city's persistent air quality challenges, indoor air pollution research in Delhi is still at a developing stage. While several studies have assessed outdoor particulate matter, relatively few have examined the dynamic interaction between indoor and outdoor aerosols in urban households. Given the diversity of building types, lifestyles, fuel use, and climatic conditions in Delhi, there remains a broad scope for multidisciplinary studies to better understand the sources, characteristics, and health implications of indoor pollutants. Future work should focus on generating long-term datasets, identifying exposure pathways, and designing practical interventions suitable for Indian urban settings. Integrating global findings with locally relevant data will help in formulating effective public health and policy responses.

Long-term Monitoring: Establish continuous monitoring networks to study seasonal and inter-annual variations in indoor particulate matter and ultrafine particle concentrations across diverse housing categories.

Chemical Composition Studies: Investigate the chemical and elemental composition of indoor aerosols to distinguish contributions from cooking, outdoor infiltration, and indoor materials.

Personal Exposure Assessment: Conduct time–activity-based exposure studies to quantify personal inhaled doses, especially among children, elderly, and women engaged in household work.

Indoor Source Characterization: Evaluate the emission strength of common household activities such as cooking, incense or candle burning, and cleaning to develop activity-specific emission factors.

Ventilation and Building Design Effects: Examine how ventilation type, building age, materials, and air-exchange rates influence indoor pollutant accumulation and dispersion.

Socio-economic Disparities: Explore exposure inequalities across income groups, housing densities, and neighbourhoods to support equitable health interventions.

Low-cost Sensor Validation: Assess the performance of affordable sensors for continuous indoor air quality monitoring and community-level awareness.

Indoor - Outdoor Relationship Modelling: Develop models to predict infiltration and penetration factors using meteorological, structural, and behavioural parameters specific to Delhi's conditions.

Health Impact Correlation: Link indoor air quality data with biomarkers or self-reported health symptoms to strengthen epidemiological evidence.

Policy Evaluation and Intervention Trials: Test the effectiveness of interventions such as air purifiers, improved stoves, and kitchen exhaust systems under real household conditions.

Role of Microclimate and Meteorology: Study how temperature, humidity, and seasonal ventilation patterns affect indoor aerosol dynamics.

Integration with Urban Planning: Incorporate indoor exposure research into broader urban development and housing policy frameworks to promote healthier living environments.

5.8 Recommendations from the study

Indoor air pollution in Delhi represents a major but often underestimated contributor to overall exposure. The presence of fine and ultrafine particles in both indoor and outdoor environments poses a continuous health challenge for city residents. Effective control requires shared responsibility between individuals and policymakers. While households can take simple preventive and behavioural measures to reduce pollutant levels inside homes, broader policy actions are needed to manage emissions, improve urban housing conditions, and strengthen public awareness. The following recommendations are based on research findings from global and Indian studies and have been adapted to the local conditions of Delhi.

i. Recommendations for the Public

Improve Household Ventilation: Keep windows open during low traffic hours and use exhaust fans or chimneys in kitchens to enhance air circulation and reduce indoor smoke accumulation.

Adopt Cleaner Cooking Practices: Shift towards LPG, electricity, or induction-based cooking instead of biomass or kerosene fuels. Avoid frying or burning activities without proper ventilation.

Reduce Indoor Emission Sources: Limit the use of incense sticks, candles, mosquito coils, and smoking indoors. Choose low-VOC paints and eco-friendly household products.

Maintain Indoor Cleanliness and Filtration: Use vacuum cleaners or damp mopping to reduce settled dust. Air purifiers with HEPA filters can be effective during high pollution periods.

Enhance Awareness and Behavioural Change: Stay informed about daily air quality levels and adjust activities such as outdoor exercise or window opening times accordingly, especially during smog episodes.

ii. Recommendations for Policy Makers

Integrate Indoor Air in Urban Clean Air Plans: Extend clean air action programmes to include indoor air monitoring and mitigation strategies alongside outdoor pollution control.

Develop Housing and Ventilation Standards: Introduce building codes that mandate adequate natural ventilation, exhaust systems in kitchens, and low-emission construction materials.

Promote Research and Data Collection: Support long-term indoor–outdoor air quality studies across different income groups and encourage use of standardised monitoring methods.

Implement Public Awareness Campaigns: Conduct citywide campaigns to educate citizens about indoor pollution sources, exposure risks, and simple mitigation practices.

Encourage Green Urban Planning: Increase green cover, control road dust, and promote cleaner transport to reduce ambient PM levels that infiltrate indoors.

5.9 Summary

Addressing indoor air pollution requires a combined effort between households and governing bodies. Small behavioural adjustments at the individual level, supported by scientifically informed policies, can significantly reduce aerosol exposure and improve the health and well-being of Delhi's residents. Collaborative action, continuous research, and sustained public engagement are the keys to achieving cleaner air within urban homes.

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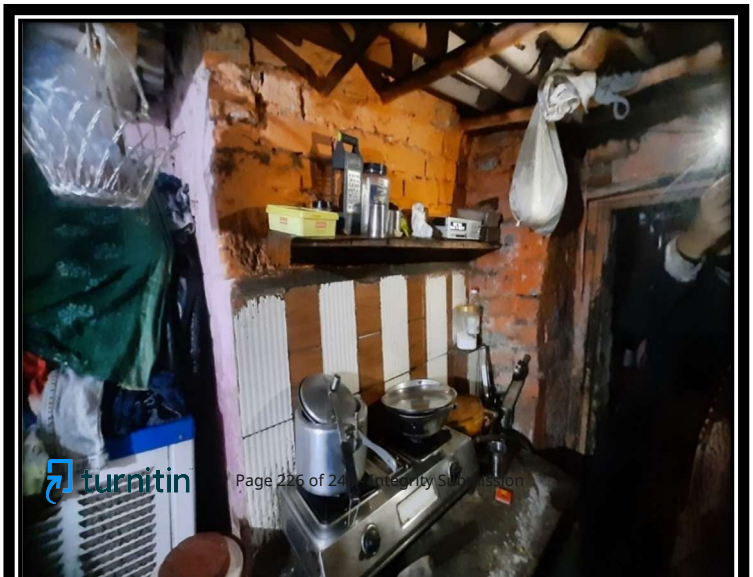
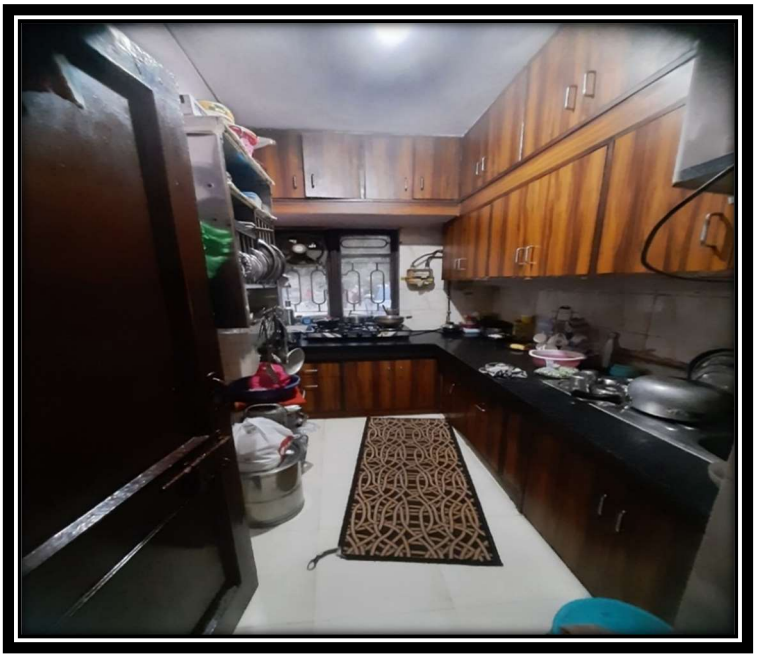
ANNEXURES

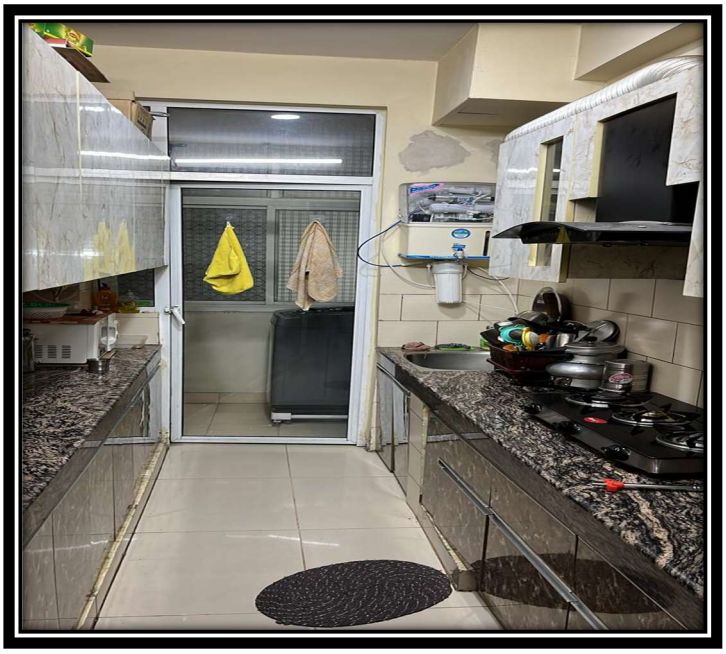
Picture of the selected households (Kitchen)



Urban Poor



Lower Income Group



Middle Income Group

High Income Group

Picture of the selected households (Bedroom)

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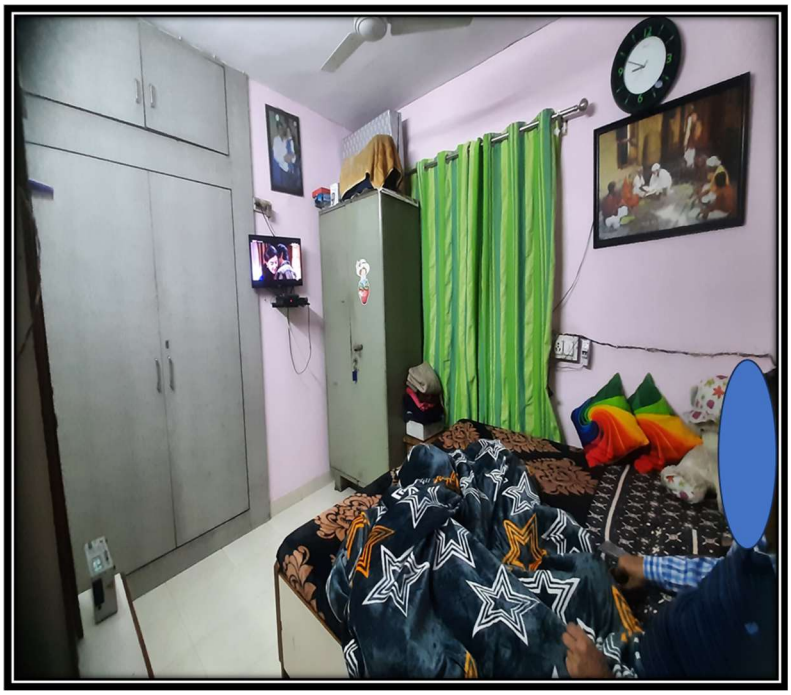
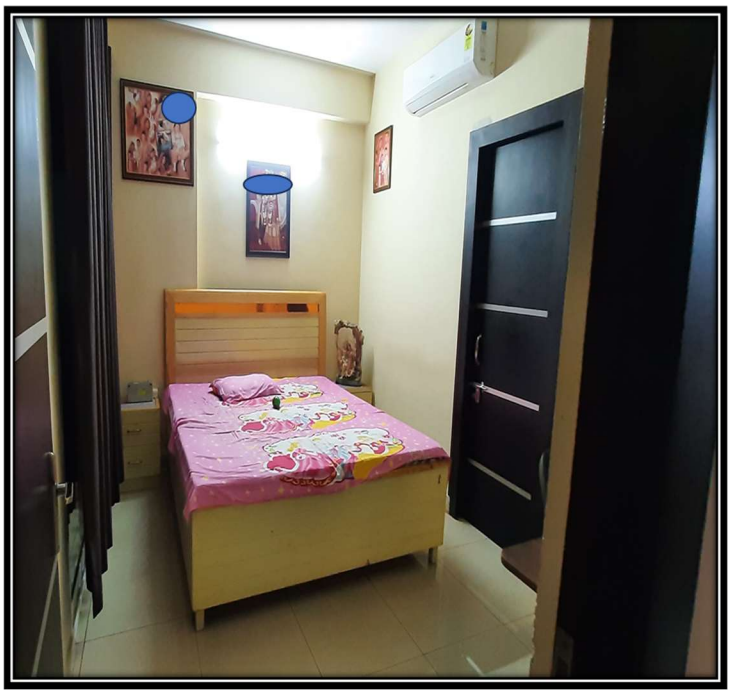
Urban Poor

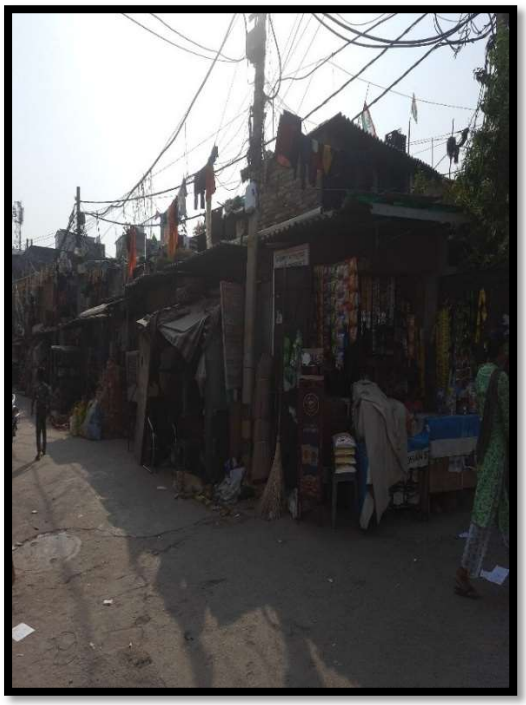


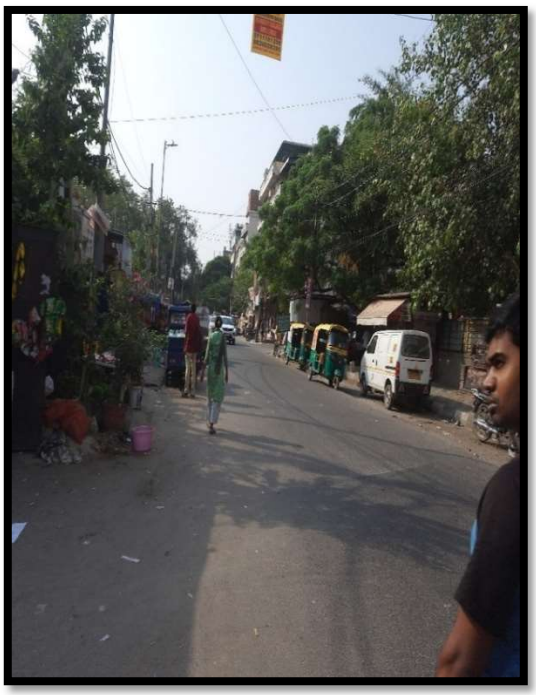
Middle Income Group

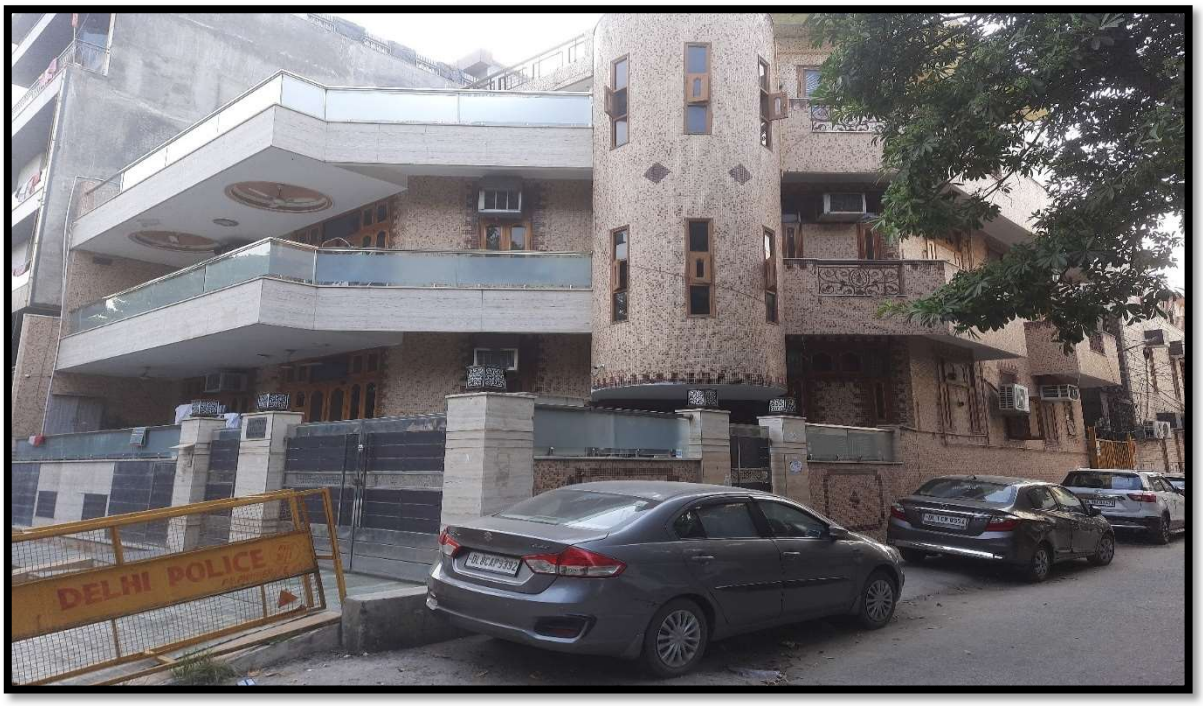


High Income Group

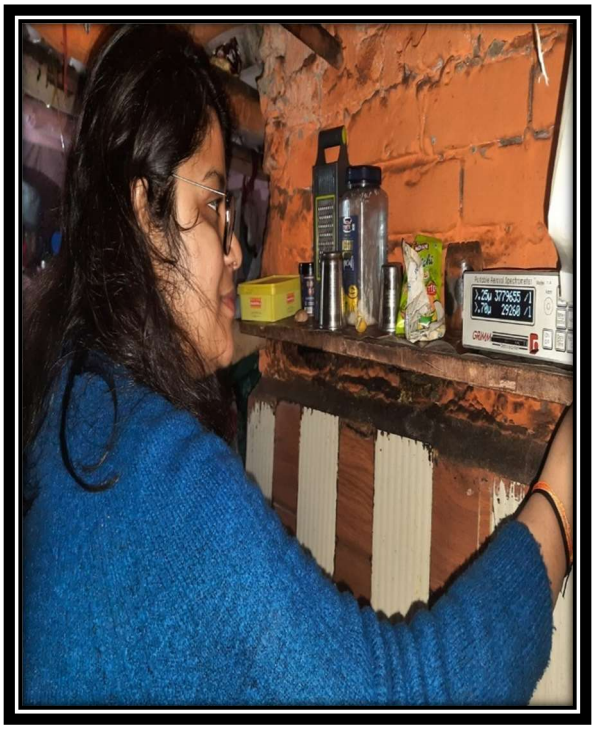
Outdoor activities at GTB Nagar

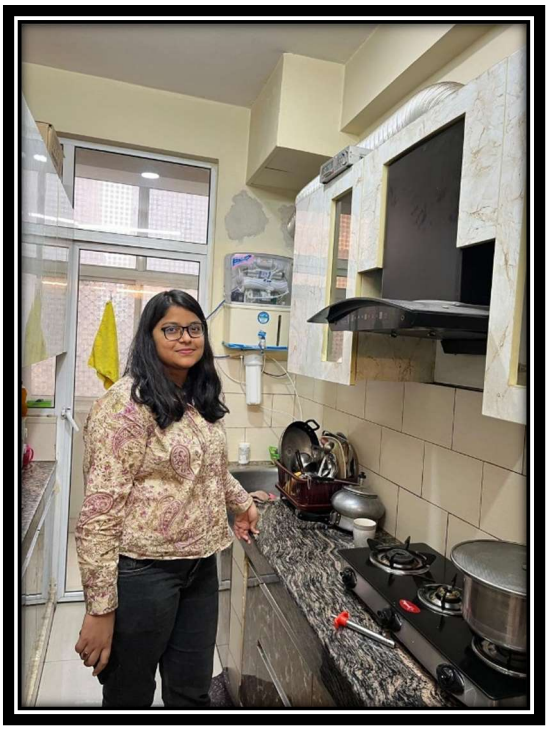


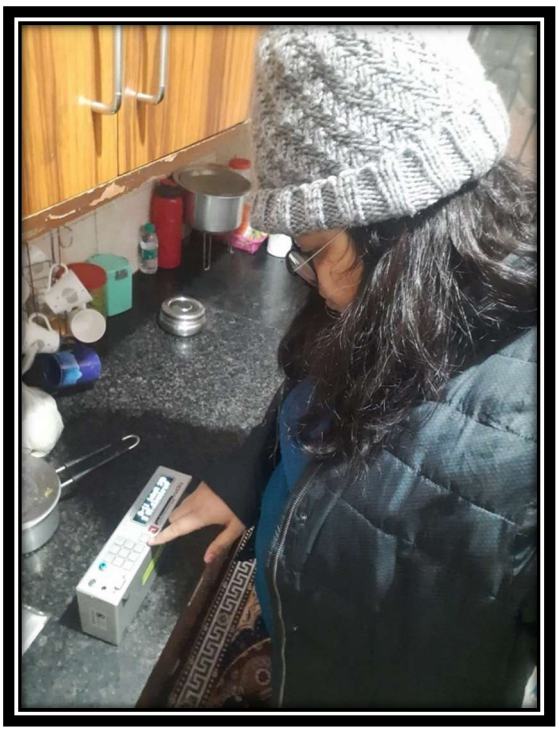



DELHI POLICE

Monitoring in different households







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Indoor particle number concentration measurements across different income group households in urban region

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ARTICLE INFO

Keywords:
Cooking emissions
Household air pollution
Indoor PNC
Socioeconomic strata

ABSTRACT

Indoor air quality in urban regions is a serious concern. This study estimated the seasonal variations of indoor and outdoor particle number concentrations in different socioeconomic household conditions in the urban city Delhi. The portable aerosol spectrometer was employed to measure quasi-ultrafine, sub-fine, fine, and coarse particle concentration in kitchen, bedroom, and outdoor conditions. The findings of the study revealed that quasi-ultrafine (250 to 500 nm) particle concentration was high (2.1×10^6 #cm^{-3}) in urban poor households during the winter season. Indoor quasi-ultrafine particle concentration ranged between $\sim 10^5$–10^6 #cm^{-3} in the kitchen and bedroom. In a properly ventilated kitchen, a significant reduction in indoor particle number concentration (1.2×10^6 #cm^{-3} to 7.1×10^5 #cm^{-3}) was observed. The number concentration of coarse particles was found to be the lowest ($< 1.1 \times 10^3$ #cm^{-3}) among other sizes. However, indoor sources resulted in a higher I/O ratio of 40. Lower-income group kitchens exhibited higher number concentrations of different-size particles, which also influenced bedroom concentration. Households with good infrastructure conditions were found to have less influence on one microenvironment than another. Improving indoor air quality relies not only on sources but also on ventilation status, built infrastructure, occupants' behaviour, and the influence of outdoor air.

1. Introduction

Air pollution is a significant threat because it worsens the ecosystem and causes diseases and premature death. Globally, around 55 % of the population resides in urban regions and contributes to around 85 % of global economic activity (Jbaily et al., 2022; Rentschler and Leonova, 2023). Cities that are rapidly urbanizing in developing countries are severely impacted by air pollution (Rajagopal et al., 2023). Globally, regulations and efforts are made to control major pollutants such as particulate matter (PM_{10} and $PM_{2.5}$) and gaseous pollutants such as nitrogen oxides (NOx), sulphur dioxide (SO_2), and polycyclic aromatic hydrocarbons (Datta et al., 2017). In addition to these, several unregulated pollutants, including quasi-ultrafine (qUFP: 250 to 500 nm) and sub-fine (500 nm to 1 μm) particles, are also present in various microenvironments (Moreno-Rios et al., 2022). Major sources of these pollutants include traffic emissions, thermal power plants, waste burning, mining, fireworks, cooking, printers, and incense sticks (Di Fiore et al., 2023; Mohan et al., 2024; Rajagopal et al., 2024a, Rajagopal et al., 2024b; TERI and ARAI, 2018; Sharma et al., 2024; Yang et al., 2024; Zhang et al., 2023).

Indoor air pollution (IAP) is prevalent in both rural and urban regions (Fuller et al., 2022; Salvi and Apte, 2016). It has more adverse

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Indoor air pollution and exposure analysis in different residential dwellings of a South Asian urban city

Monika Sharma, Mukesh Khare & Rajeev Kumar Mishra

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Indoor ultrafine particle concentrations and their size distributions during festival-associated emissions in urban region

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ARTICLE INFO

Keywords:
Chemical composition
Cooking
Fireworks
Indoor pollution
Ultrafine particles

ABSTRACT

Indoor air quality is crucial for the well-being of residents, as people spend 80 % of their time indoors. This study investigated the impact of festival activities on household indoor air quality in megacity Delhi. The study included different phases and activities during the festival and normal conditions and analyzed the impact of different emission sources. During the festival period, the indoor ultrafine particle concentration was found to be 6.7×10^4 #cm^{-3}, which was the highest observed indoor concentration throughout the study. The particle number concentration of the nanoparticles in indoor environment ranged from 10^4 to 10^5 #cm^{-3}. Ultrafine size range particles contributed up to ~85 % to the total particle numbers. Fireworks contributed to higher particle numbers in indoors, followed by cooking, dusting, and worshiping. The size distribution pattern of the particles emitted during cooking activities and fireworks was found to be different. Particle size range 10–30 nm contributed ~31 % to total particle numbers on fireworks day, whereas on a normal day, it contributed only ~13 %. During normal day, 100–1000 nm size particles contributed ~50 % to total particle numbers. The diurnal pattern of the indoor environment was different from the outdoor. The outdoor fireworks activities also influenced indoor pollutants with respect to trace metals, which makes the indoor air quality more toxic, and affects the occupants' health.

1. Introduction

Air quality is a global concern, and achieving better air quality is a challenging task that requires efforts and support from different stakeholders. Continuous exposure to poor air quality leads to various health hazards such as asthma, chronic obstructive pulmonary disease (COPD), lower respiratory infections, lung cancer, Alzheimer's disease, allergies, headache, runny nose, sneezing, and watery eyes (Apte and Salvi, 2022; Metrics, 2020; Singh et al., 2019). Particulate matter (PM) is one of the globally known pollutants which is recognized as one of the significant threats to human health due to its adverse effects. It is generated through various sources (Daga et al., 2019; Karri et al., 2024; Morelli et al., 2016; Rizwan et al., 2013; Singh et al., 2019; Zhang et al., 2015). Recent advancements in air pollution measurements paved the way for examining several other smaller-sized particles found in the atmosphere. The size range of the particles ranges from nanometers to micrometers (Rajagopal et al., 2024a,b). The ultrafine particles (UFP) and quasi-ultrafine (qUFP) particles are well known for higher toxicity than the course PM. The UFP and qUFP particles are measured in number concentrations due to their negligible concentration in terms of mass concentration. The particles emitted through different sources form a complex mixture of pollutants consisting of various organic and inorganic compounds (including heavy metals) (Agarwal et al., 2020; Pekey et al., 2010; Singh et al., 2019). The composition of particles also varies from one region to another depending on the respective sources. In urban regions, transportation, construction, industries, and waste burning are the major sectors of emissions (Patel et al., 2021; Sharma et al., 2024; Yadav et al., 2020). Among the well-known regular sources, there are several other episodic events that deteriorate the air quality within a short period of time. The episodic events include dust storms, forest fires, and some festival events. The use of firecrackers during festivals and other celebrations (New Year, Guy Fawkes night, and Deepawali) is a part of the tradition that is still followed in different countries (Li et al., 2017; Tanda et al., 2019; Wang et al., 2024; Zhang et al., 2010). Deepawali festival is one of the major festivals in India (Izhar et al., 2018a,b; Jamal et al., 2024; Prabhu et al., 2019; Saxena et al., 2022; Sharma et al., 2018; Yadav et al., 2022a,b; Yerramsetti et al., 2013). It generally falls in October or November month based on

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Conference Certificates

CERTIFICATE OF PARTICIPATION

This certificate is proudly presented to

Monika Sharma

in recognition of their participation during Healthy Buildings Asia 2025, an ISIAQ scientific conference held August 18-21, 2025, in Hyderabad, India. This certificate confirms that the below listed abstract was presented during the conference.

Impact of urban settings on indoor particle number concentrations: A case study from Delhi

Kerry Kinney, PhD
ISIAQ President

Ranga Reddy Burri
HonoraryConference President

Vinod Kumar Sekar
Conference President

International Society of Indoor Air Quality and Climate | isiaq.org

IASTA National Aerosol Conference
On
Aerosol Impacts to Air Quality, Human Health & Climate Change
(December 17-20, 2024)
Flagship Conference of
Indian Aerosol Science and Technology Association (IASTA)

CERTIFICATE

This is to certify that Prof./Dr./Mr./Ms. Monika Sharma Participated in IASTA National Aerosol Conference 2024 as Plenary Speaker/Invited Speaker/Session Chair/Poster Paper Presenter/Lightning Talk Presenter/Oral Paper Presenter/Exhibitor/Organizer/Others, jointly organized by Aryabhatta Research Institute of Observational Sciences (ARIES), Nainital and Doon University, Dehradun,

Dr. Manish Joshi
Secretary, IASTA

Dr. Umesh Chandra Dumka
Convener, ARIES

Dr. Vijay Sridhar
Convener, Doon University

Australian National University
UNIVERSITY OF BATH

IICAQM 2023

This is to certify that

Monika Sharma

has presented a technical paper titled

Impact of solid waste dumpyards fire on air quality of national capital, Delhi during

8th INDIAN INTERNATIONAL CONFERENCE ON AIR QUALITY MANAGEMENT (IICAQM 2023)

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Certificate of Participation

This is to certify that Prof./Dr./Mr./Ms. Monika Sharma
From Delhi Technological University, Delhi
has Participated and Contributed in the *"International Conference on "Waste Recycling & Environmental Technology (WRET - 2024)"* held during 8 - 9th, February 2024, organized by the **Department of - Environmental Science, Babasaheb Bhimrao Ambedkar University (A Central University), Lucknow, India.**
He/She has presented a paper (Oral/Poster) entitled Investigating the effects of Delhi's odd-even vehicle restriction policy on particle number concentrations
Prof./Dr./Mr./Ms. Monika Sharma Ranked 1st for Oral/Poster presentation award on the above title.

Dr. Shailendra Kumar Yadav, Co-Organizing Secretary
Dr. Jiwan Singh, Organizing Secretary
Prof. Shikha, Chairperson
Prof. Naveen Kumar Arora, Dean, SEES

CV of the Candidate

MONIKA SHARMA

Mobile: +91-8376948050 monikasharma_2k20phden06@dtu.ac.in Monika Sharma Monika Sharma

EDUCATION

Ph.D. Environmental Engineering**,** *Delhi Technological University* Aug 2020 -Present
Department of Environmental Engineering SGPA- **84.3/10**

M.Sc. Environmental Science **–** *Dr. Bhimrao Ambedkar University***,** Agra, UP 2017-2019
Department of Environmental Studies CGPA- **7.6/10**

B.Sc. (Hons.) Zoology – Daulat Ram College**,** *University of Delhi*, Delhi 2013-2016
Daulat Ram College Percentage – **60.6%**

Certificate Course in the Spanish Language - *University of Delhi*, Delhi 2017
Daulat Ram College

RESEARCH INTERESTS

Indoor-Outdoor air quality, measurement & modeling, urban aerosols, building ventilation, health effects

RESEARCH EXPERIENCE

Doctoral Researcher Aug 2020 -Present
Supervisor: Dr. Rajeev Kumar Mishra (DTU) **DTU, Delhi**
Co-supervisor: Prof. Mukesh Khare (IIT Delhi)
Thesis: Study of aerosols in indoor-outdoor microenvironments for urban households of Delhi

Consulting Intern **Delhi**
Advisor: Dr. Sreekanth Vakacherla, Senior Scientist Advisor April – September 2023
Environment Defense Fund (EDF)

- Analyse air quality data and interpret results, run data visualization. Handle large collocation datasets for performing statistical analysis.

Proxy Relationship of Ultrafine Particles Number Concentration, New Particle Formation and Its Growth Rate in Transport Microenvironment in Delhi. Oct 2019 – Feb 2021
PI: Dr. Rajeev Kumar Mishra, Assistant Professor
Co-PI Prof. B.R. Gurjar, Professor
Department of Environmental Engineering, DTU, and Department of Civil Engineering, IIT Roorkee

- The project involved the study of new particle formation and its growth near road conditions. Covered monitoring and data analysis for 2019 to 2020 (met and pollutant data) and report writing.

Air Pollution Study during Odd-Even Scheme in Delhi Nov 2019
Advisor: Dr. Rajeev Kumar Mishra
Department of Environmental Engineering, DTU

- Four Major transport corridors of Delhi were selected for monitoring and analyze data to evaluate the effectiveness of the Odd-Even policy impact on the air quality of the megacity Delhi.

Master's Research Project Fellow
Measurement of $PM_{2.5}$ aerosols and their effects on human health in Agra, a semi-arid region of India.
Prof. Bhupendra Swarup Sharma (HOD & Dean) 2019
Department of Environmental Studies, Dr. Bhimrao Ambedkar University, Agra, Uttar Pradesh

- Selected 4 monitoring locations based on land-use patterns and covered the health effects of $PM_{2.5}$ on human health.

RESEARCH TRAINING

Training on "Revamping on-road vehicle emission management in cities". May 2025
Centre for Science and Environment

Training on "Air Quality Monitoring for Key Air Pollution Parameters". Dec 2020
Council of Scientific & Industrial Research (CSIR), NEERI, Nagpur, Maharashtra

Industrial Training on "Common Effluent Treatment Plant (CETP), Jhilmil, for Wastewater Management." Jun 2018 - Jul 2018
Advisor: Dr. Narender Sharma, Additional Director (Scientist 'E')
Central Pollution Control Board (CPCB), Delhi

- Qualitative analysis of water parameters from CETP, Jhilmil in Delhi and suggestions were given to save the river water from further degradation.

Training on "Role of Remote Sensing, Geographical Information System (GIS) and GPS in natural resources management" Oct 2018
Remote Sensing Application Centre, Lucknow, Uttar Pradesh, India

PUBLICATIONS

1. **Sharma, M.**, M. Khare, and R. K. Mishra. 2024. Air quality changes in Delhi due to open waste burning: An accidental fire in Bhalswa landfill. *International Journal of Environmental Science and Technology* 21 (1):655–64. 10.1007/s13762-023-04921-w **(SCIE, IF: 3.4)**
2. Krithika, N., Jain, R., **Sharma, M.**, & Mishra, R. K. (2023). Organic Farming in India and its Way Forward. *Defence Life Science Journal*, *8*(3), 239–247. https://doi.org/10.14429/dlsj.8.18975 **(Scopus)**
3. **Sharma, M.**, Khare, M., & Mishra, R. K. (2025). Indoor particle number concentration measurements across different income group households in urban region. *Urban Climate*, 59. https://doi.org/10.1016/j.uclim.2025.102329 **(SCIE, IF: 6.9)**
4. **Sharma, M.**, Khare, M., & Mishra, R. K. (2025). Indoor air pollution and exposure analysis in different residential dwellings of a South Asian urban city. *Particulate Science and Technology*, 1–13. https://doi.org/10.1080/02726351.2025.2537769 **(SCIE, IF: 1.5)**

5. **Sharma, M.**, Khare, M., & Mishra, R. K. (2025). Indoor ultrafine particle concentrations and their size distributions during festival-associated emissions in urban region. *Atmospheric Pollution Research*, 102671. https://doi.org/10.1016/j.apr.2025.102671 **(SCIE, IF: 3.5)**
6. Rajagopal, K., Mohan, V., **Sharma, M.**, Yadav, S.K., Sahu, V., Mishra, R.K., Gautam, S., Gurjar, B.R., and Kumar, P. (2025). Impact of the odd–even scheme on particulate matter reduction in Delhi traffic intersections. *Particulate Science and Technology* https://doi.org/10.1080/02726351.2025.2558979 **(SCIE, IF: 1.5)**

Book Chapters

Mishra, R. K., Rana, R., Tomar, S., Sidhant, & **Sharma, M**. (2025). Air Quality Prediction Using Machine Learning Techniques. In Blue Sky, Blue Water (pp. 305–320). Springer Nature Switzerland. DOI: https://doi.org/10.1007/978-3-031-82559-0_15

Sharma, M., Khare, M., & Mishra, R. K. (2025). Impact of Solid Waste Dump Yards Fire on Air Quality of National Capital Delhi. In *Select Proceedings of the 8th Indian International Conference on Air Quality Management (IICAQM 2023)* (Vol. 582, p. 115). Springer Nature. DOI: 10.1007/978-981-96-2359-4_9

CONFERENCES, SEMINARS, SYMPOSIUMS, and WORKSHOPS

- International Health Building Asia 2025, an ISIAQ scientific conference held in Hyderabad, India, from August 18th to 21st, 2025.
- National Aerosol Conference on Aerosol Impacts to Air Quality, Human Health & Climate Change at Doon University, Dehradun, December 17-20, 2024.
- International Conference on Waste Recycling and Environmental Technology- Presenter, Babasaheb Bhimrao Ambedkar Central University, Lucknow, February 2024 **(Awarded: 1st Prize)**
- 8th Indian International Conference on Air Quality Management- Presenter, Indian Institute of Science (IISC), Bangalore, December 2023.
- Selected for *Scicomm for Scientists 2021*, a workshop organized by the Indian Institute of Science Education and Research (IISER) Kolkata, May 2021
- Participated in Workshop on "*Air Pollution Data Analysis using OpenAir on R*" organized by DexLab, Gurugram, June 2020.
- Participated in Poster Making competition at the National Conference on "*Reproductive Health in India: Concerns and Awareness"* organized by Deshbandhu College, University of Delhi, Feb 2016,
- National Symposium on "*Environmental Contamination and Public Health"*- Presenter Zakir Husain, Delhi College, University of Delhi, 2015

AWARDS/EXTRA-CURRICULAR ACTIVITIES / OUTSTANDING ACHIEVEMENTS

- Team (Handball) and individual (Rifle Shooting) games: National Level Player
- Team (Basketball and Kabaddi) and individual (Judo: Silver Medalists) games: State-level player.
- Participated in a Debate competition organized by the GOI and secured the second position at the State level
- Inter College Topper: Gold Medalists

LEADERSHIP, RESPONSIBILITIES, AND ORGANIZING SKILLS

- Selected as Residential Warden of Sister Nivedita Girls Hostel, DTU, Delhi. Mar 22-Present
- Volunteer at National Cadet Corps (NCC) and National Service Scheme (NSS), Amar Singh Inter College, and Daulat Ram College, University of Delhi, from August 2011 to February 2015.
- Team Captain of junior and senior women's Handball, Basketball, and Kabaddi teams 2009-2013.

SKILLS

MEASUREMENTS: GRIMM SMPS+ CPC, GRIMM OPC (Portable Aerosol Spectrometer 1.109 &; 11 A), TSI OPS (Optical Particle Sizer Model 3330), CO Analyzer & SO_2 Analyzer (Horiba), NOx Analyzer & O_3 Analyzer (2B Technologies), Cascade Impactor (SKC), Haz Dust-EPAM-5000(SKC), Fine Particulate Sampler (Envirotech)

ANALYSIS: Atomic Absorption spectrophotometry, UV-visible spectrophotometry, Chromatography

SOFTWARE: ArcGIS / QGIS, ORIGIN, MATLAB, R Statistical Tool, AIRQ+, MPPD model.

PROFESSIONAL MEMBERSHIPS

International Society of Indoor Air Quality and Climate (ISIAQ), Collaborative for Air Pollution and Health Effects Research-India (CAPHER-India), European Geoscience Union (EGU), and Society for Indoor Environment (SIE)

Impact of Research

Danik Jagran (04 March 2025)

राजधानी में रसोई और शयनकक्ष में भी घर बना चुका है प्रदूषण

धनंजय यादव • जागरण

बाहरी दिल्ली: राजधानी में वायु प्रदूषण एक बड़ी समस्या है। इसकी वजह से कभी-कभी सांस लेना मुश्किल हो जाता है। लेकिन आपको जानकर हैरानी होगी कि ये प्रदूषण बाहर के साथ हमारे घरों में भी स्थान बना चुका है। दिल्ली प्रौद्योगिकी विश्वविद्यालय (डीटीयू) ने अपनी एक हालिया शोध में बताया है कि दिल्ली में घरों के भीतर की वायु प्रदूषित और सेहत के लिए जोखिम भरी है। रसोई में खाना पकाते, शयनकक्ष में धूल झाड़ने और पूजा के दौरान अगरबत्ती जलाते समय वायु प्रदूषण अधिक पाया गया। सबसे खराब वायु गुणवत्ता अति गरीब व निम्न आय वर्ग के घरों में पाई गई। इन दोनों श्रेणी के घरों में रसोईघर में वेंटिलेशन बहुत खराब पाया गया।

विना वेंटिलेशन का रसोईघर • सौ. डीटीयू

मध्यम आय वर्ग और उच्च आय वर्ग घर में सीमित स्तर पर प्रदूषण के कण पाए गए। जबकि, इन दोनों श्रेणियों के घरों में वेंटिलेशन की स्थिति सही पाई गई। घर के भीतर वायु प्रदूषण का मुख्य कारण वेंटिलेशन की खराब स्थिति को माना गया है।

डीटीयू के पर्यावरण इंजीनियरिंग विभाग, भारतीय प्रौद्योगिकी संस्थान दिल्ली व एडवांस एयर एंड एकस्टिक्स रिसर्च लेबोरेटरी की ओर से शहरी क्षेत्र में इनडोर वायु प्रदूषण को लेकर शोध किया गया है। शोध में इनडोर वायु प्रदूषण को स्वास्थ्य के लिए जोखिम भरा बताया और कहा कि इस जोखिम को नजरअंदाज किया जा रहा है। डीटीयू के पर्यावरण इंजीनियरिंग विभाग के एसोसिएट प्रोफेसर डा. राजीव कुमार मिश्रा के नेतृत्व में किए गए शोध टीम में आइआइटी दिल्ली के प्रोफेसर मुकेश खरे और डीटीयू एडवांस एयर एंड एकस्टिक्स रिसर्च लेबोरेटरी की शोधार्थी मोनिका शर्मा शामिल रहीं। टीम ने दिल्ली के जोटीवी नगर में चार अलग-अलग आय वर्ग के घरों में एक साल तक शोध किया। इनमें अति गरीब, निम्न आय वर्ग, मध्यम आय वर्ग और उच्च आय वर्ग शामिल हैं। इनमें प्रदूषण मापने की मशीनें भी लगाई गईं।

शोध में बताया गया है कि अति गरीब श्रेणी के घर में हवा में प्रति सेंटीमीटर क्यूब 11 लाख प्रदूषित कण पाए गए। गर्मी और मानसून की तुलना में घरों में सबसे ज्यादा वायु प्रदूषण सर्दी के मौसम में पाया गया। शोध में कहा गया है कि इनडोर वायु गुणवत्ता प्रमुख मुद्दा है। मनुष्य 80-90 प्रतिशत अपना जीवन इनडोर वातावरण में व्यतीत करता है।

रसोईघर में वायु प्रदूषण सबसे ज्यादा: चारों श्रेणियों के घरों की रसोई में प्रदूषित कण पाए गए हैं। सबसे ज्यादा प्रदूषित कण अति गरीब की रसोई में पाए गए। डा. राजीव कुमार मिश्रा ने बताया कि अति गरीब श्रेणी के मकान की रसोई में प्रति सेंटीमीटर क्यूब हवा में 12 लाख क्वासी अल्ट्राफाइन पार्टिकल पाए गए। निम्न आय वर्ग घर की रसोईघर में 9.5 लाख, मध्य आय वर्ग 8.4 लाख और उच्च आय वर्ग परिवार की रसोई में प्रति सेंटीमीटर क्यूब हवा में 7.1 लाख क्वासी अल्ट्राफाइन पार्टिकल पाए गए।

घर में वायु प्रदूषण के कारण व समाधान: शोध टीम के प्रमुख डा. राजीव कुमार मिश्रा का मानना है कि घर के अंदर का वायु प्रदूषण बाहरी प्रदूषण से ज्यादा हानिकारक है। घर के अंदर के प्रदूषण को कम करने के लिए घर को अच्छी तरह हवादार रखना ज्यादा जरूरी है, खास तौर पर खाना बनाते समय, धूल झाड़ते समय और निर्माण सामग्री का इस्तेमाल करते समय। घर के अंदर सिगरेट पीना, खाना पकाने या गर्म करने के लिए ठोस ईंधन का इस्तेमाल जैसी हानिकारक इनडोर गतिविधियों से बचना चाहिए। नगर निगमों, विकास प्राधिकरणों के साथ-साथ मंत्रालय और प्रदूषण नियंत्रण बोर्डों को नए निर्माण के लिए कुछ बुनियादी मानकों और मानदंडों को लागू करना चाहिए, जिसमें न्यूनतम वेंटिलेशन अनिवार्य किया जाए।

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The Times of India (24 October 2025)

TIMES CITY

305 AQI IN DELHI ON THURSDAY (VERY POOR)

292 stray dog feeding points in 80 wards | 3

32.2° MAXIMUM 18.1° MINIMUM

Agency picked to build Tehkhand waste plant | 6

PWD reads the road sign, it says repair | 5

In Or Out, Every Breath You Take Is Poison

Fireworks Cause Particles 25 Times Finer Than PM2.5 To Shoot Up Sharply Indoors

FIREWORKS TURN HOMES INTO TOXIC CHAMBERS

DTU highlights extreme indoor pollution during Diwali

1. Ultrafine particle surge indoors

2. Toxic mix released indoors

3. Spike in toxic & non-carcinogenic metals

4. Carcinogenic metals multiply indoors

5. Indoor air more dangerous than outdoor smog

6. Health & environmental warning

Artificial rain for first time in city on Oct 29, says CM

Air very poor for fourth day

The Times of India (24 October 2025)