Ventilation, Thermal Comfort and Air Quality in Building Indoor Micro-environments: A Measurement and Simulation Based Study

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“ALL THE PRAISES AND THANKS ARE DUE TO ALLAH WHO HAS GUIDED US TO THIS, AND NEVER COULD WE FIND GUIDANCE HAD IT NOT THAT ALLAH GUIDED US (AL QURAN)”

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Ayesha Asif

Table of Contents

List of Tables

List of Figures

List of Abbreviations

IAQ	Indoor Air Quality
T	Temperature
RH	Relative Humidity
VRs	Ventilation Rates
SD	System dynamics
AERs	Air Exchange Rates
IEQ	Indoor Environmental Quality
T_c	Comfort Temperature
PMV-PPD	Predicted Mean Vote-Predicted Percent of Dissatisfied
KNN	K-nearest neighbor
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
WHO	World Health Organization
HVAC	Heating Ventilation and Air Conditioning
PM	Particulate Matter
PNC	Particle Number Concentration
PMC	Particle Mass Concentration
KNN	K nearest neighbor
CIBSE	Chartered Institute of Building Services Engineers
SAGE	Scientific Advisory Group for Emergencies
SARS	Severe Acute Respiratory Syndrome
CFD	Computational Fluid Dynamics
met	Metabolic Rate
clo	Clothing insulation
T_a	Air Temperature
T_g	Globe Temperature
Rh_i	Indoor Relative Humidity

V	Air Velocity
T_o	Outdoor Temperature
Rh_o	Outdoor Relative Humidity
N_{ACon}	Natural ventilation system with split unit air-conditioners during cooling season
N_{ACoff}	Natural ventilation system without air-conditioners during cooling season
CS_C	Central HVAC system during cooling season
N_H	Natural ventilation system during heating season
CS_H	Central HVAC system during heating season
TSV	Thermal Sensation Votes
T_{op}	Indoor Operative Temperature
T_{mrt}	Mean radiant temperature
T_{rm}	Running mean daily outdoor temperature
ε	Emissivity
D	Globe diameter
G	Griffths Constant
T_{opC}	Indoor operative comfort temperature
NCLS	NUST Creative Learning School
AC	Air-conditioners
V	Volume of Room
dC/dt	Change of indoor concentration in time t
q	air flow into/ out of the room
C_o	Outdoor contaminant concentration
C_i	Indoor contaminant concentration
S	Indoor sources
k	First-order degradation constant
P	Indoor pressure (taken as constant i.e. 1 atm)
R	Ideal gas constant= 0.08205 (L.atm/mol.K)
T_i	Indoor temperature (K)

G	CO_2 generation rate per person
N	Number of occupants
P	Probability of infection
I	Number of infectors
q	Quantum generation rate produced by infector
p	Pulmonary ventilation rate
t	Exposure time
Q	Ventilation rate
DR	Dilution ratio
E_o	Quantum concentration in infector’s exhaled breath
E	Quantum concentration in susceptible person’s inhaled breath
$CO_{2\ \text{supplied}}$	Amount of CO_2 coming from outdoor
$CO_{2\ \text{generated}}$	Amount of CO_2 generated from occupants breathing inside a room
$CO_{2\ \text{ventilated}}$	Amount of CO_2 going out of the room through ventilation process
$CO_{2\ \text{buildup indoor}}$	Amount of CO_2 accumulated inside the room.
RMSE	Root mean square error
HSV	Humidity sensation votes
ASV	Air speed sensation votes
TPV	Thermal preference votes
HPV	Humidity preference votes
APV	Air speed preference votes

Abstract

In the Phase 1 of dissertation, a field survey was conducted to assess indoor thermal comfort in dormitory and offices buildings followed by calculation of comfort temperature (T_c). Afterwards, a comparative analysis of three T_c prediction adaptive models (linear, cubic and logistic) was conducted. In the last part of Phase 1, multiple variables were input in logistic and a machine-learning algorithm for prediction of thermal sensation. Furthermore, gender and seasonal differences were considered during dormitories data analysis. However, different ventilation modes were considered for analysis of offices data. Although thermal sensation votes of both genders in dormitories were statistically different, no statistical difference in indoor T_c between two genders were observed. Following Griffth's method T_c in dormitories were calculated as 26.8±1.5ºC and 27.6±1.7ºC during summer and 22.7±2.3ºC and 22.3±2.0ºC during winter for female and male occupants respectively. Furthermore, in offices comparison of natural and central HVAC system showed significance ($p>0.05$) in sensation and preference votes. Mean T_c for offices under all five modes were 27.66, 27.18, 26.89, 19.15 and 19.73ºC. Percentage accuracies of three adaptive prediction methods under study showed better performance of logistic regression. Besides, percentage accuracies of models were improved when all variables were input in the model.

In the Phase 2 of dissertation, indoor air quality (IAQ) and ventilation conditions were assessed. Two-season (summer and winter) monitoring of indoor CO_2 was conducted in classrooms of a primary school and offices. However, monitoring in university classrooms was performed under different ventilation scenarios. Besides, different types of dormitories (cubical, bi-seater and tri-seater) were considered for monitoring and assessment of IAQ in dormitories. Minute-by-minute ventilation (VRs) and air exchange rates (AERs) were also calculated for occupancy hours. Results showed significant variation ($p<0.05$) of indoor CO_2 between occupancy and non-occupancy hours (in primary school classrooms, university classrooms, offices), among all ventilation modes (in offices), between buildings (offices and dormitories) and seasons (primary school classrooms and offices). Moreover, it was found that opening of windows and ventilators have significant positive impact on VRs and AERs. Besides, airborne transmission risk of COVID-19 was also calculated for all ventilation scenarios in university classrooms. Results indicate that airborne transmission could be significantly minimized by increasing VRs through opening of windows and ventilators.

Phase 3 of dissertation includes development of a system dynamics (SD) based model which was used to estimate indoor CO_2 concentrations utilizing calculated VRs (minute-by-minute and averaged) using VENSIM software. Besides, VRs were calculated adopting three methods i.e., transient mass balance, steady-state and decay method, and were then input in SD model for finding best method for calculation of VRs. Lastly, simulations were used to calculate optimum VRs to keep indoor CO_2 levels below recommended limits. Developed SD model results showed high correlation (>0.98 for all classrooms, using minute-by-minute VRs) with monitored CO_2 concentration and low root mean square error. Similarly, minute-by-minute VRs input to models showed more accurate simulation as compared to VRs averaged for a session (Correlation coefficient <70). Furthermore, transient mass balance method was found to be more accurate approach for VRs estimation. Moreover, it was found that to limit indoor CO_2 levels below 1100, 800 and 700 ppm, minimum VRs should be maintained as 10, 16 and 20 l/sec/person respectively.

In the last phase of dissertation, simultaneous monitoring of indoor CO_2 and particulate matter (PM) was performed. Besides, fit curve method was employed for the conversion of dylos particle number count (PNC) to particle mass (PMC). Results showed weak correlation of indoor CO_2 with PM. However, indoor PM levels were strongly correlated with outdoor PM levels. Furthermore, indoor CO_2 levels were strongly correlated with occupancy and indoor activities.

Chapter 1

Introduction

2.1. Background

Well-designed and maintained buildings, providing thermally comfortable conditions and adequate supply of fresh air from outside, are imperative for efficient working and performance of occupants (Ma et al., 2021). Human spend most of their daytime in indoor spaces, thus, a direct influence of indoor air quality (IAQ) and thermal comfort on performance of occupants can't be denied (Dong et al., 2022). In an indoor space, occupants are exposed to various indoor air pollutants, the source of which can be co-existing outdoor as well as indoor (Mannan & Al-Ghamdi, 2021; Asif et al., 2018)). Furthermore, concentration of pollutants in indoor spaces is found greater than that outdoor in most of the cases (Carrazana et al., 2023). Therefore, awareness about indoor pollutant sources, their health consequences and different strategies for their removal is imperative (Karaiskos et al., 2023).

Ventilation system of a building affects (either positively or negatively) the concentrations of indoor pollutants as well as indoor temperatures (T) and relative humidity (RH) levels which determine the indoor thermal comfort (Che et al., 2019; Fernández-Agüera et al., 2019). Adequate ventilation, providing fresh air in indoor spaces from outdoor, dilutes indoor pollutant levels, resulting in improved IAQ, consequently boosting productivity of occupants (Heracleous & Michael, 2019a). On the other hand, inadequate ventilation and poor air quality badly affect the performance (Bako-Biro et al., 2012), learning ability , productivity (Shriram et al., 2019) and perception of occupants. In extreme cases, when pollutant concentrations exceed beyond certain limits, it can even lead to nose and throat ailments resulting in absenteeism(Shriram et al., 2019) from workplaces. Apart from IAQ and ventilation, indoor thermal comfort parameters (T and RH) also affect the academic performance and productivity of students and are considered as a vital design parameter for buildings (Che et al., 2019; de Abreu-Harbich et al., 2018a; Heracleous & Michael, 2019a). In buildings with insufficient ventilation, airtightness and continuous exchange of heat and water vapors across building envelopes significantly affect the RH and T (Fernández-Agüera et al., 2019).

Indoor CO_2, generated mainly by occupants breathing process, is not an indoor pollutant but due to its relatively inexpensive monitoring equipment, is frequently taken as a surrogate of IAQ and measurement of ventilation adequacy, as reported by previous studies (Jinfu Zheng, Xin Guo, Songtao Hu, Fengling Wu, Chunfeng Lao, Haonan Ma, Rujin Liu, 2022)(Asif et al., 2018; Shriram et al., 2019;). Various factors that affect indoor levels of CO_2 include total number of occupants in the confined space, length of occupation period, outdoor air flow rates, size of room and outdoor CO_2 levels. Indoor CO_2 levels beyond reference standards indicate insufficient ventilation (Lee et al., 2023). Increasing ventilation rates (VRs) reduce indoor CO_2 levels as well as indoor concentration of pollutants thus resulted in decreasing health issues (Kwan et al., 2020). Similarly, VRs below 10 l/s/person has been reported as an indicator of poor IAQ, thus resulting in adverse health effects (), while up to 20 l/s/person can significantly lessen these effects with improving quality of air (Turanjanin et al., 2014). VRs can be increased either naturally/passively (by window/ door/ ventilator opening or closing) or mechanically (by exhaust fans or centralized ducts) or by combination of both (Krawczyk et al., 2016; Simanic et al., 2019). Although, mechanical ventilation dilutes indoor air pollutants rapidly and ensures good thermal comfort conditions but it involves higher energy cost (Molina et al., 2021). With the increasing demand of energy worldwide, researchers are more focused towards energy efficient technologies for improving IAQ and VRs (Krawczyk et al., 2016). Natural ventilation based on manual opening/closing of windows and doors is the most applicable type of ventilation especially in naturally ventilated indoor spaces (Duarte et al., 2018). Although it is a very simple phenomenon, due to its free-running nature, keeping records of objective indoor conditions and decision-making about ventilation design specifications is challenging resulting in inappropriate VRs (Duarte et al., 2018). In addition, it may also be a major cause of increase in indoor pollutant levels from outdoor sources (Liu et al., 2021) and poor thermal comfort conditions. Thus, keeping a balance between good IAQ, VRs and thermal comfort with the least energy demand that would not compromise performance of occupants is a challenging situation (Bako-Biro et al., 2012). Maintenance of good indoor thermal comfort requires active strategies (e.g. air conditioners, fans etc.) in some climates which result in increase in energy consumption, particularly when VRs are not optimized (de Abreu-Harbich et al., 2018a).

Optimizing VRs in existing naturally ventilated buildings (as well as the buildings in design phase) that would ensure good IAQ at the same time by consuming lesser energy, is imperative. Various approaches have been practiced previously for this purpose. Krawczyk et al., (Krawczyk et al., 2016) developed a model based on mass-balance equation for estimation of CO_2 levels in areas with maximum occupancy and minimal AER. Quang et al., (Quang et al., 2014) also developed a mass-balance model to ensure good IAQ and minimal energy consumption in mechanically ventilated office buildings. System dynamics (SD), a well-established approach, allows investigating dynamic behaviors of complex systems. Multiple SD software are available with user friendly graphical user interface e.g. VENSIM (VENTANA Systems, Inc.). In recent years, VENSIM has been utilized in many environment related research studies dealing with solid waste management (Ding et al., 2016), water resource management (Abdolabadi et al., 2019) and ambient air quality (Behrens et al., 2018). Up-to the authors' knowledge, no study has been conducted in the field of IAQ that used SD approach for simulation of IAQ previously.

Furthermore, in thermal comfort assessment, determination of comfort temperature (an indoor temperature in which a healthy occupant has a sensation of thermal neutrality) (S. Kumar et al., 2019a), is in practice to curtail high energy demand without compromising thermal comfort of majority occupants. Many past researchers have investigated the indoor thermal comfort of different types of indoor spaces. C. Xu et al., (2018) (Xu et al., 2018), with an aim of improving thermal comfort database for energy saving transformation of traditional dwellings, conducted a field study of thermal comfort and adaptive behaviors of residents during summer and winter seasons in a traditional settlement in Nanjing, China. They calculated comfort temperatures (T_c) for both seasons under study to find the tolerance of traditional dwellers to harsh environment. A. García et al., (2019) (García et al., 2019) aimed to approach thermal comfort in cold, humid tropical zones and analyzed eight naturally ventilated offices of Bogotá, Colombia for approximately three months (19th February- 11th May 2018). They found 96.6% thermal acceptance and T_c as 23.47°C using Griffiths method. M.K. Singh et al., (2016) (Singh et al., 2016) assessed thermal comfort in fully functional pre-1945 residential buildings in Liege (Belgium) through long term monitoring (i.e. from November 2011- May 2012) as well as subjective evaluation of indoor environment and found overall range of comfortable temperature as 17-24ºC. In addition, exceptionally lower indoor T_c has been reported in some previous studies conducted in cold and severe climatic zones (Z. Wang, 2006)(Z. Wang et al., 2010). Thus, determination of a range of optimum indoor T_c is pivotal for the areas with extreme weather conditions (Takasu et al., 2017).

2.2. Aim and Research Question

Pakistan is facing severe energy crisis since long, resulting in frequent power-cuts and consequent disturbance in everyday life (Mahar & Attia, 2018a). Due to its limited energy resources, efficient and effective use of energy along with introduction of new energy saving techniques/technologies is imperatively necessitous. Besides, Pakistan is facing extreme outdoor thermal conditions with daily mean temperatures during coolest and hottest months as 10.1 and 31.2 ºC respectively. Considering the above-mentioned fact and deteriorated outdoor air quality of Pakistan with repetitive event of smog during winter season, building HVAC systems should be designed efficiently so that IAQ won’t compromise due to extreme outdoor air conditions. Thermal comfort and IAQ assessment have already been conducted in numerous previous studies with a special focus on keeping a balance between energy consumption, IAQ and thermal comfort. However, in the context of Pakistan, a wide range of knowledge and research gap in this area can be seen with only few published research studies (Mahar & Attia, 2018b) (R. M. A. Humphreys, 1994) (F. Nicol & Roaf, 1996) (Mahar et al., 2019) (J. F. Nicol et al., 1999) most of which are very old. However, up-to author knowledge no pervious study considers IAQ in context of Pakistan building characteristics. Furthermore, there is limited existent knowledge of change in indoor comfort temperature over seasons and no Pakistani study can be found previously comparing comfort temperatures between different heating and ventilation modes.

Acknowledging this research gap and significance of thermal comfort and IAQ in human life, the dissertation addressed following research question

"How to optimize air exchange rates while ensuring thermal comfort and healthy IAQ during building design and operation phases for minimizing construction resources and energy consumption considering high energy costs and its climate impact?"

2.3. Objectives

To address the above-mentioned research question, the dissertation covered following objectives.

- Thermal comfort assessment based on PMV-PPD and adaptive approach for academic buildings
- Assessment of AERs in building indoor microenvironments
- System dynamics-based modeling for AERs and validation with actual monitoring data
- Relationship between CO_2 levels and indoor air pollutants in building microenvironments

2.4. Thesis Organization

Overall the dissertation has been divided into five chapters, brief explanation of each is given below.

Chapter 1 included background of the study followed by research question and objectives.

Chapter 2 presents a comprehensive literature review of the work done previously on IAQ and thermal comfort.

Chapter 3 discloses the methodology executed to achieve the above-mentioned objectives. Overall the chapter has been divided into 4 phases where each phase presented methods of an objective of dissertation. A brief layout of the methodology is presented in Fig. 1.1

Chapter 4 introduces the results and discussion of each phase along with the in-depth analysis of results.

Finally, Chapter 5 concludes the research work with further recommendations for future work.

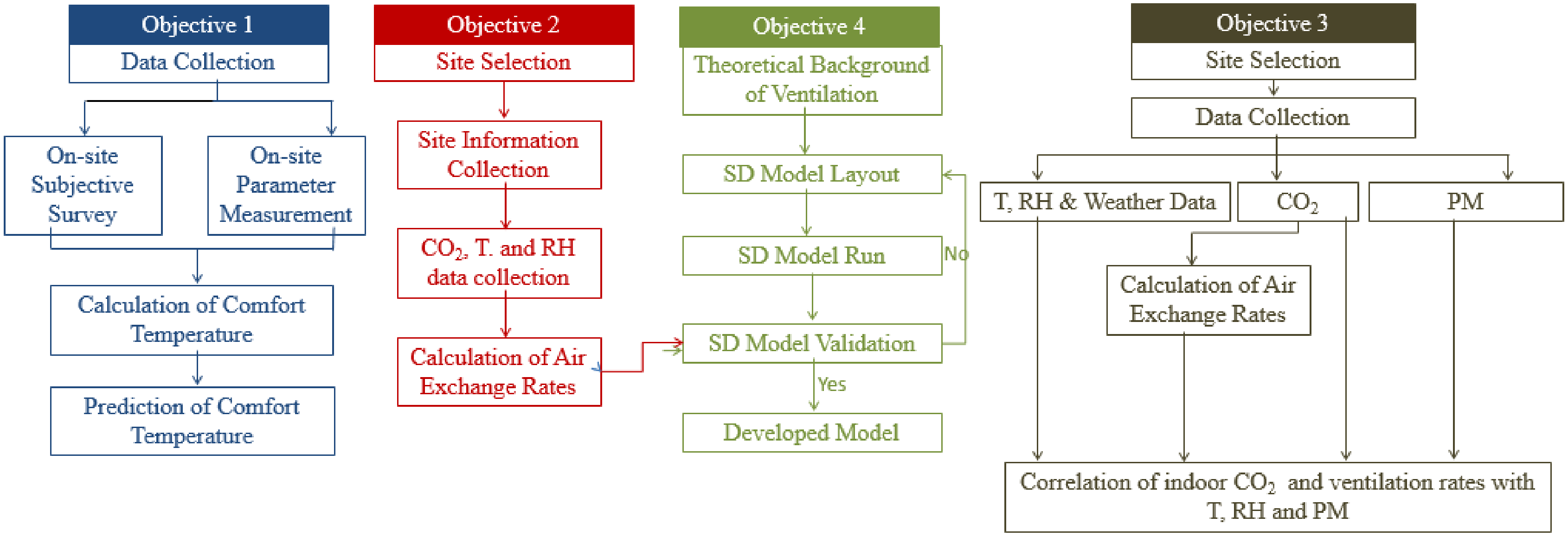

Figure 1.1: Methodology Layout

2.5. Publications

1. **Asif, A.,** & Zeeshan, M. (2020). Indoor temperature, relative humidity and CO2 monitoring and air exchange rates simulation utilizing system dynamics tools for naturally ventilated classrooms. Building and Environment, 180, 106980. (IF: 7.1)
2. **Asif, A**., Zeeshan, M., Khan, S. R., & Sohail, N. F. (2022). Investigating the gender differences in indoor thermal comfort perception for summer and winter seasons and comparison of comfort temperature prediction methods. Journal of Thermal Biology, 110, 103357. (IF: 2.9)
3. **Asif, A.,** & Zeeshan, M. (2023). Comparative analysis of indoor air quality in offices with different ventilation mechanisms and simulation of ventilation process utilizing system dynamics tool. Journal of Building Engineering, 72, 106687. (IF: 6.7)

Chapter 2

Review of Literature

Indoor environmental quality (IEQ) has been an area of growing interest in recent times due to its direct influence on comfort and health of occupants (Shum et al., 2022). IEQ is generally categorized into four components i.e., thermal comfort, indoor air quality (IAQ), visual comfort and acoustic comfort. Among them the dissertation is focused on thermal comfort and IAQ only, detailed discussion on which is presented in hereafter sections.

2.1. Indoor Thermal Comfort

Thermal comfort is an intricate building design and operations problem involving various parameters such as air temperature, relative humidity (RH), outdoor temperature and globe temperature etc. (Takasu et al., 2017). A general insight into occupants' expectations and demands regarding thermal comfort is imperative for efficient design and operation of buildings and also for the provision of suitable indoor environment while ensuring optimum use of energy (Aghniaey et al., 2019). In addition, indoor thermal comfort and building characteristics such as outdoor shading, number, size and orientation of windows, thermal properties of construction materials etc. are interrelated (de Abreu-Harbich et al., 2018b). Due to psychological and physiological factors, occupant's thermal sensation and T_c vary with climatic zones (B. Li et al., 2018) and between genders (Aqilah et al., 2023). Objective indicators as well as subjective ratings, through questionnaire survey, are used for determination of general thermal comfort level . Objective parameters for analysis include air temperature and velocity, globe temperature, relative humidity, occupant's clothing insulation and metabolic activity while subjective parameters include votes for sensations and preferences of the subjects. Substandard indoor thermal comfort could lead to high energy consumption in buildings and trigger long terms and short terms adverse impacts on occupants health (He & Isa, 2024). According to American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) standard 55-2010 (ASHRAE Standard 55-2010), indoor environment is considered comfortable and acceptable if 80% of its occupants are satisfied with indoor environmental conditions (Sarbu & Pacurar, 2015).

Among the factors affecting indoor thermal comfort, the most debated factors of research interest are gender and seasonal differences. Considering these factors prediction of a thermal environment which is accepted by majority of occupants is also a key research question of many past studies. All these factors have been discussed briefly in hereafter subsections.

2.1.1. Gender Differences

The gender difference is relatively more important factor influencing thermal perception of occupants among others, which has captivated significant research interest in recent years. Generally, females are considered more sensitive to ambient air temperatures compared to males and therefore, more dissatisfied with the indoor thermal conditions(Zhang and Zhu, 2022). For instance, Indraganti et al.(2015) worked on behavioral adaptation considering gender and age factors in offices of Chennai and Hyderabad, India and found higher comfort temperature (T_c) and thermal acceptability of females than males. Jin et al., (2020) investigated the gender differences in thermal comfort of pedestrians in severe cold region of China and found higher T_c but low thermal acceptability of females during transition seasons. Similarly, Lan et al., (2018) investigated gender differences in Chinese people through two laboratory experiments and found higher comfortable operative temperature of females than males. In contrast, Fabozzi and Dama, (2020) while working on thermal comfort in naturally ventilated and air-conditioned classrooms found no significant effects of gender on thermal sensation votes. Besides, Aqilah et al., (2023) reported higher mean comfort temperature of males than females while working on thermal comfort in residential buildings. The conflicting results in above-mentioned studies necessitate further research in this area to explore the environmental conditions that result in gender differences in indoor thermal comfort.

2.1.2. Seasonal Changes

In addition to gender difference, seasonal changes are also considered as a significant factor affecting the thermal perception of occupants in an indoor environment. This topic has been investigated by many researchers. Zheng et al., (2022) conducted a field study on adaptive thermal comfort in elderly nursing homes and found T_c for winter and summer seasons as 19.4 and 24.1ºC respectively. Likewise, Wang et al., (2021) studied thermal comfort in naturally ventilated classrooms and calculated T_c for summer and winter seasons as 26.2 and 22.4ºC respectively.

2.1.3. Indoor Comfort Temperature

The determination of indoor temperature set-point, also known as comfort temperature, has been a key research question in various past studies (Aqilah et al., 2023). While investigating thermal comfort, field studies follow either the static approach (Deng and Tan, 2020; Chaiyapinunt and Khamporn, 2021) or adaptive approach (Aparicio-Ruiz et al., 2021; Y. Wu et al., 2019) for the prediction of T_c. Static approach, also known as predicted mean vote-predicted percent of dissatisfied (PMV-PPD) model, was proposed by Fanger in 1972, which is based on heat balance approach. Likewise, an adaptive model is based on correlating results with outdoor environmental conditions which are obtained through field surveys (López-Pérez et al., 2019). However, Fanger's PMV-PPD model is more appropriate for only controlled thermal environments with constant environmental variables such as air-conditioned indoor spaces with a smaller number of subjects (Zhao et al., 2021) and is not applicable to naturally ventilated studies with larger number of subjects and variable environmental conditions (Lei et al., 2017). In naturally ventilated spaces, strong influence of outdoor environmental conditions on indoor T_c is observed and therefore, adaptive model has been found more reliable under such conditions (Vergés et al., 2023). Occupants, being active actors in such an approach, interact with their environment, adapt and modify it according to their comfort needs and preferences (López-Pérez et al., 2019). Most of the previously reported studies followed linear regression method for the prediction of T_c (Khalid et al., 2019) using adaptive method. However, in recent times many other techniques such as logistic regression, k nearest neighbor (KNN), decision tree etc. are being used in adaptive thermal comfort field studies for the prediction purpose which provide more robust results in comparison to the traditional method. The aim of all such studies is to curtail building energy requirements by predicting indoor temperature set-points accepted by majority of the occupants without compromising IAQ.

Due to seasonal, regional, and cultural differences, the adaptive models reported in previous studies couldn’t be used universally, rather their applicability is limited to the respective geographic vicinity. Similarly, the models developed for one building type would not be representative of thermal comfort demands of all building types. Additionally, thermal comfort is function of human physiology, besides other factors, and perceptional differences of thermal comfort between the genders is important area to be investigated. In developed countries, thermal comfort has been investigated and reported, but in developing countries, like Pakistan, the knowledge gap exists. Moreover, there are very limited studies in the past quantifying the accuracies of various techniques used for T_c prediction.

2.2. Indoor Air Quality

IAQ has been debated at length in many recent studies focusing on schools (Zhu et al., 2021), offices (Justo Alonso et al., 2022), residential areas (Al-Rawi et al., 2021) etc. The principal reason behind the aforesaid factor is greater human exposure to pollutants in an indoor environment than outdoor (Sun et al., 2019. Usually, buildup of pollutants in an indoor environment is attributed to the insufficiently low VRs to save energy costs. Having strong indoor emission sources further downgrades the air quality (Sun et al., 2019). Other significant factors affecting IAQ include occupant density and outdoor air quality (Parhizkar et al., 2019) which vary according to building type, activities conducted within the building and demographic properties (Kang et al., 2017). Exceedance of indoor pollutants beyond threshold limits significantly affects comfort, work performance and productivity of occupants and can cause health problems of chronic nature (Lou and Ou, 2019; Parhizkar et al., 2019).

The process of deliberate exchange of ambient air with indoor exhausted air, is ventilation (Bhagat et al., 2020). Amelioration of quality of air in a deteriorated indoor environment and rarefication of indoor generated pollutants levels can be achieved through adequate ventilation (Heracleous & Michael, 2019b). Furthermore, symptoms of sick building syndrome (fatigue, headache, eyes, nose and throat irritation, dry skin etc.) are more prevalent in buildings with low VRs (Sun et al., 2019).

2.2.1. Tracer Gas Technique for VRs Estimation

Use of tracer gas technique for the estimation of VRs and AERs has been an area of interest of many past research studies (Jankovic et al., 2022). In most of those studies, indoor CO_2 levels have been taken as a tracer gas which is a globally accepted surrogate of IAQ and ventilation quality in indoor spaces (Weerasinghe et al., 2023). Furthermore, the methods generally used for the estimation of VRs in buildings, taking indoor CO_2 levels as a surrogate for IAQ, are decay method, steady state method and transient mass balance method (Batterman et al., 2017; Asif and Zeeshan, 2020). Table 2.1 summarizes few of the previously reported studies in which these methods were employed for the measurement of VRs from different indoor microenvironments (detailed description of the methods is provided in Section 2.3). However, up-to author’s knowledge, comparison of accuracy among two or more methods for the prediction of indoor CO_2 levels has not been investigated in previous studies

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Table 4.1: Summary of the literature review on building ventilation methods

Sr. No.	Title	Authors	Reference	Method
1	Mean Age of Air in a Naturally Ventilated Office: Experimental Data and Simulations	Buratti et al.,	(Buratti et al., 2011)	Decay
2	Impact of adaptive thermal comfort on climatic suitability of natural ventilation in office buildings	Emmerich et al.,	(Emmerich et al., 2011)	Steady State
3	Ventilation characteristics of an air-conditioned office building in Singapore	Sekhar et al.,	(Sekhar et al., 2002)	Decay
4	High energy efficiency ventilation to limit COVID-19 contagion in school environments	Schibuola, Chiara Tambani	(Schibuola and Tambani, 2021)	Steady State
5	Measurement of air exchange rates in different indoor environments using continuous CO_2 sensors	You et al.,	(You et al., 2012)	Steady state and decay
6	Review and Extension of CO_2-Based Methods to Determine Ventilation Rates with Application to School Classrooms	Stuart Batterman	(Batterman, 2017)	Steady state, Decay, Transient mass balance

2.2.2. Guidelines and Standards for VRs and Indoor CO_2 Levels

Several guidelines have been published and accepted for determination of the permissible levels of indoor CO_2. According to World Health Organization (WHO), the maximum allowable indoor CO_2 concentration in a closed space is 1000 ppm (WHO, 2000). This limit of indoor CO_2 has been used extensively in many research studies since decades due to its correlation with human bioeffluents and acceptable levels of odor (Persily, 2022). Likewise, as per ASHRAE, the indoor CO_2 levels must not exceed 700 ppm above the outdoor levels (ASHRAE, 2016) which again seconds WHO guidelines. Furthermore, ASHARE proposed minimum VR requirements as 8 l/sec/person (ASHRAE, 1999b). Depending upon space and occupancy, indoor CO_2 levels are proven good surrogate of AERs, however, more recent research on IAQ reported less correlation of many indoor generated pollutants with indoor CO_2 levels (ASHRAE, 2022). Additionally, in recent times, after the outbreak of COVID-19 and airborne transmission being identified as the most dominant route of virus transmission (Curtius et al., 2021), maintenance of good ventilation conditions is imperative. After the pandemic the researchers discussed indoor CO_2 levels as a surrogate of airborne transmission risk of virus too (Dai & Zhao, 2020). Although ASHRAE doesn't established limiting values of indoor CO_2 to minimize the risk of virus spread, many countries and organizations defined the minimum levels (ASHRAE, 2022). WHO in their recent guidelines stated minimum VRs to be 10 l/sec/person for workplaces and ordinary spaces. However, for high risk areas the minimum requirement of VRs was recommended to be 15 l/sec/person (WHO, 2021). The minimum VRs requirements in the recent guidelines of Chartered Institute of Building Services Engineers (CIBSE) were also 10 l/sec/person (CIBSE, 2020b) In addition, UK Scientific Advisory Group for Emergencies (SAGE) recommended limiting value as 1000 and 800 ppm for ordinary and high risk areas respectively (SAGE-EMG, 2020). Consequently, enforcement of regulations to restrict indoor CO_2 levels well below 800 ppm have been practiced in countries like France and Ireland (REHVA, 2020). Moreover, national recommendations of Spain during COVID-19 pandemic suggested that indoor CO_2 levels should be lower than 700 ppm in well mixed spaces to reduce the chances of virus transmission in larger population areas (Marr, L., Miller, S., Prather, K., Haas, C., Bahnfleth, W., Corsi, R., Tang, J., Herrmann, H., Pollitt, K., Ballester, J., Jim´enez, 2020).

2.3. IAQ and COVID-19

2.3.1. History of COVID-19

Coronavirus disease, commonly referred as COVID-19, emerged as a global outbreak and gained worldwide attention (J. Li et al. 2022; Ahmadzadeh and Shams 2022) by severely affecting all facets of life (Verma et al., 2020). The disease resulted in causing immense human and economic loss worldwide (Catching et al., 2021). By March 2023, about 689.2 million confirmed COVID-19 cases and 6.8 million associated deaths were reported around the world ("Worldometer (coronavirus)"). To curtail the impact of disease, countries have adopted several preventive and control measures such as closure of offices, schools, factories, recreational areas etc., social distancing (Catching et al. 2021; Chang et al. 2021), reduction of staff attendance to half, wearing of face masks etc. Although these measures have proven fruitful in decreasing the rate of transmission of disease and number of new cases, but the threat still persists, and these measures will have multifarious socio-economic repercussions in the long term. Due to this reason, restrictions imposed earlier for its curtailment have now been lifted in many countries, thus resulting in increased number of daily cases and mortalities (Catching et al., 2021).

2.3.2. Possible Transmission Routes of Virus

The severity of COVID-19 illuminates many research questions among which possible transmission route(s) of virus is the most crucial one and has been a key research question in many recent studies. For instance, Wang et al., (2020) (Y. Wang et al., 2020) analyzed aerosol and surface distribution of COVID-19 and indicated shoe soles of medical staff in hospitals also served as a carriers of virus, resulting in the proliferation of the disease. To et al., (2020)(To et al., 2020), detected live viruses in the viral cultures of saliva of 91.7% patients. Li et al., (2020)(Y. Li et al., 2020) also second this observation. Lo et al., (2020)(Lo et al.,

2020) concluded in their work on SARS-CoV-2 RNA shedding in clinical specimens that COVID-19 could be transmitted through fecal-oral route and endorsed assessment of fecal and respiratory samples to strengthen diagnostic sensitivity. Likewise, Dhama el al., (2021)(Dhama et al., 2021) investigated existence of virus in sewage and wastewater and declared fecal-oral route as one of the potential route of transmission. Amoah et al., (2021)(Amoah et al., 2021) detected 54-69% contact surfaces in shared sanitary facilities contaminated with COVID-19 virus. They concluded that shedding of urine and feces in shared toilets could increase the risk of virus transmission. In few recent studies, COVID-19 virus was also found in tears specimens of patients (Xia et al. 2020; X. Zhang et al. 2020).

Recently, researchers found that like many other viral diseases e.g., influenza, tuberculosis, severe acute respiratory syndrome (SARS) etc., COVID-19 could possibly be transmitted through air (or aerosols) exclusively in inadequately ventilated indoor spaces (J. Li et al., 2022). Depending upon the efficiency of masks, face masks could possibly reduce the short-length airborne transmission of diseases (J. Ye et al., 2021). Moreover, in many recent studies, ventilation of indoor spaces is considered a decisive factor to minimize the risk of COVID-19 transmission (Zheng et al. 2021; Ren et al. 2022; Cai et al. 2022; Bhattacharya et al. 2021). Additionally safety management of occupants in this pandemic era in closed spaces, more specifically educational buildings, where students, teachers and office workers spend more than 5 hours of their day, has been extensively discussed over the previous year (Di Gilio et al., 2021). In classrooms inadequate ventilation and poor IAQ is commonly found as reported by many relevant studies (Asif et al. 2018; Baloch et al. 2020; A. Di Gilio et al. 2017; Asif and Zeeshan 2020). In most educational institutes, the mechanical HVAC system is absent, and the only mode of ventilation is opening of windows and doors. However, during extreme winter or summer seasons, in order to maintain acceptable thermal comfort conditions in the absence of air conditioning system in place, it is not feasible sometimes to keep the windows open, thus making ventilation a crucial subject in this pandemic era (Di Gilio et al., 2021). WHO recently published guidelines in this regard according to which adequate ventilation should be ensured by the intermittent opening of windows and doors (WHO, 2020).

2.3.3. Wells-Riley Model for Airborne Infection Risk of COVID-19

Scientists worldwide are working to find a reliable and practical method for predicting COVID-19 infection risk to minimize virus transmission (C. Li & Tang, 2021) in closed spaces. In the past multiple models were developed, among which Wells-Riley model (Riley, C.E., Murphy, G. and Riley, 1978) is most extensively used in epidemic modelling to illustrate the transmission of airborne diseases (Noakes et al. 2006; Nicas et al. 2005). In this model direct linkage of ventilation, ratio of infected people and exposure duration is considered. The model has been an area of interest of researchers working on infection risk assessment in airline cabins (Yan et al., 2017), hospitals (Qian et al., 2009), schools and public halls (Hella et al., 2017) etc. Many past investigations used this model to test the interconnection of VRs with infection risks and concluded that providing adequate ventilation in indoor spaces is an efficient and effective way for reducing the risk of airborne diseases (Gao et al. 2012; Mushayabasa 2013a). Moreover, in recent times, this model, owing to its flexibility and universal applicability, has been practiced for COVID-19 risk assessment in indoor spaces (Alessia Di Gilio et al. 2021; C. Li and Tang 2021). Some researchers also developed theoretical models using this model as basis and declared good ventilation quality a crucial element for reducing the transmission of virus in indoor spaces (Michael Riediker 2020; De Oliveira et al. 2021). Li and Tang, (2021)(C. Li & Tang, 2021) modified Wells-Riley model by adding risk assessment of COVID transmission by close contact and touching contaminated surfaces besides airborne transmission. Shao and Li, (2020)(Shao & Li, 2020) and Zhang and Lin (2021)(S. Zhang & Lin, 2021) introduced the factor of dilution ratio in conventional Wells-Riley model. Additionally, some studies integrated the model with computational fluid dynamics (CFD) based risk assessment techniques (Su et al. 2022; Z. Wang et al. 2022).

As mentioned earlier, indoor CO_2 levels, generated mainly by occupants breathing, depict ventilation quality and have been used as a surrogate to assess IAQ in many previously reported studies (Lyu et al., 2023) . In contemporary times, indoor CO_2 levels are considered as a surrogate of transmission risk of many airborne infectious diseases (Di Gilio et al., 2021) including COVID-19. Many modern researchers used indoor CO_2 levels as a tracer gas in Wells-Riley model to predict transmission risk of COVID-19 in indoor spaces, mostly focusing hospital environments (Zemouri et al. 2020; C. Li and Tang 2021) and classrooms (Di Gilio et al., 2021).

2.4. Indoor CO_2 Concentration Modeling

Heating, ventilation and air-conditioning (HVAC) system of a building is responsible for maintaining low indoor CO_2 levels and good IAQ together with keeping the indoor environment thermally comfortable, regardless of how harsh the weather is outside. However, on one side, HVAC system facilitates in improving indoor environmental conditions in the building, on the flipside, it contributes to building energy consumption significantly. Furthermore, modern urban architecture, in an effort to reduce building energy consumption, makes the buildings more air tight, which, inadvertently leads to compromised IAQ (Asif et al., 2018).Thus keeping a balance between good IAQ, energy efficiency and thermal comfort is a huge design and operational challenge especially in public buildings (schools, offices, hospitals etc.) (Sciences, 2018). Thus a reasonable strategy of ventilation providing good IAQ and thermal comfort conditions with less energy consumption is imperative (Cheng et al., 2018; Ye et al., 2019).

One of the solutions in this regard is optimization of VRs in buildings such that good IAQ at optimized energy consumption is ensured. This issue has been well discussed in previously published literature following numerous approaches. One of the most well-established approaches in this regard is CFD, adopted by many previous research studies for the design of ventilation system (T. B. Chang et al., 2018). However, CFD simulations obligate experimental verification and deep knowledge of fluid mechanics and numerical techniques. Likewise, machine learning approaches have also been employed by previously published research studies (Wei et al., 2019). Although those approaches have high predictive power but they require massive training datasets to get good results and are difficult to understand (Kallio et al., 2021). System dynamics (SD), being a well-established approach, has been utilized efficiently in the fields of transportation (J. F. Wang et al., 2008), water management (Stave, 2003), land use planning and development (Shen et al., 2009) etc. previously. Simulation of any phenomenon utilizing this tool is a function of time and it can be referred as “time-step” simulation (Stave, 2003). Multiple SD software are available with user friendly graphical user interface e.g., VENSIM (VENTANA Systems, Inc.). Up-to the authors’ knowledge, no study has been conducted in the field of IAQ that used SD approach for simulation of IAQ under different VRs or for different types of HVAC systems previously.

2.5. Particulate Matter in an Indoor Environment

Indoor air may contain a wide variety of pollutants, among which airborne particles also known as particulate matter (PM) are considered relatively important. The possible route of these pollutants in indoor spaces can be human activities (cleaning, cooking, combustion etc.), buildings and plants. Besides, depending upon outdoor conditions, they may enter indoor spaces through exchange of fresh air from outside (ventilation) or from infiltration (Zhou et al., 2023). Exposure to these indoor pollutants beyond permissible limit could result in health issues e.g., respiratory diseases, lung disorder or even mortality in extreme cases (Scapellato et al., 2019), thus making monitoring of PM crucially important.

Technological advancement in recent years revealed the efficient usage of low-cost sensors for PM monitoring. One such sensor is Dylos DC1700 which has been employed in many recent studies focusing on indoor PM. The instrument expresses PM as two size bins i.e., >0.5 μm and >2.5 μm of particle number concentration (PNC) instead of particle mass concentration (PMC). However, all the guidelines and standards for acceptable PM concentrations are available in PMC. Keeping in view, the dissertation adopted fitted curve method for the conversion of Dylos $PM_{2.5}$ PNC to PMC following previously published research studies.

Chapter 3

Methodology

Based on objectives of study, the section is divided into four main sections, each of which have subsections. General timeline of data collection for each objective has been provided in Fig. 3.1 and detailed description is presented below.

Figure 3.1. Timeline for data collection

3.1. Phase 1: Materials and Methods

The section incorporated collection of subjective responses from subjects along with the records of environmental variables. The collected data was then subjected to procedures for analysis and ultimately calculation of T_c following ASHRAE guidelines and relevant literature. Results were then compared between different ventilation systems (in offices), between genders (in dormitories), with relevant standards and previously reported Pakistani studies. In the end, PMV-PPD models for mechanically ventilated and adaptive models for naturally ventilated offices and dormitories were proposed. Detailed description is presented in the following subsections.

3.1.1. Location and Building Characteristics

Thermal comfort assessment is not a novel area of research, however, it was not investigated sufficiently in Pakistan’s context previously. Thus the assessment of indoor thermal comfort was made in two types of buildings i.e., dormitories and offices belonging to National University of Science and Technology (NUST), Islamabad, Pakistan (33.73^{o}N, 73.09^{o}E). The climate of Islamabad is humid subtropical with four seasons namely spring, summer, autumn and winter. January is the coldest and June is the hottest month of year with daily mean temperatures of 10.1 ºC and 31.2 ºC respectively. The monthly variations in outdoor air temperature and relative humidity during monitoring period are shown in Fig. 3.2.

All the selected rooms were chosen randomly depending upon the convenience and availability of occupants. Furthermore, it is important to mention here that in Pakistan there are separate dormitories for male and female and the ventilation mode in majority is natural. Thus, thermal comfort was assessed across two seasons (summer and winter) and also between genders (male and female). However, variation in ventilation modes can be seen in the offices of NUST, Islamabad. Therefore, assessment of different ventilation modes across two seasons (summer and winter) was made there. All the respondents filled the survey forms only once.

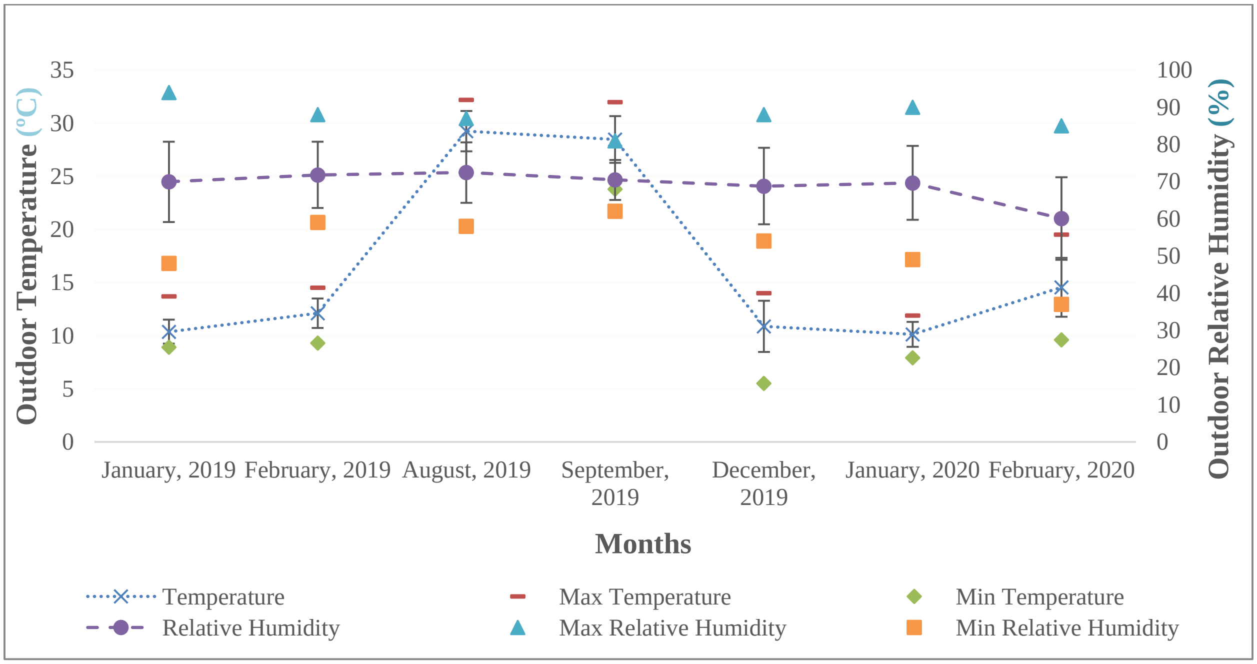


*Fig. 6.2: Variations in outdoor temperature and relative humidity during monitoring period*Survey included five dormitory buildings, out of which four (two female and two male) had single seater rooms while one had bi-seater rooms (male). Sample size of each dormitory building is presented in Table 3.1. All dorms were ventilated naturally through

windows, while some were facilitated with exhaust fans in the attached bathrooms. The bathroom doors were observed to be closed, for almost all rooms during data collection. Each room was equipped with ceiling fan which is usually kept switched ON during summer season. On the flipside, each room was equipped with a radiator, connected to the central water heating system, for heating purposes during the winter season. Windows of majority of dorms were observed open during summer and closed during winter season. All respondents were post graduate students having age group between 20-30 years. The data in all selected dormitories were collected during the daytime before sunset.

Table 3.1: Description of each monitored site

Location		**Ventilation Type**	**Sample Size**	
			Summer	**Winter**
Dormitories	**Female Dormitory-1**	Natural	100	155
	Female Dormitory-2	Natural	150	121
	Male Dormitory-1	Natural	70	77
	Male Dormitory-2	Natural	46	73
	Male Dormitory-3	Natural	99	80
Offices	**Building-1**	Natural	93	65
	Building-2	Natural	80	36
	Building-3	Natural	48	121
	Building-4	Natural	84	57
	Building-5	Natural	54	41
	Building-6	Central	50	80
	Building-7	Central	52	31
	Building-8	Central	24	30
	Building-9	Central	27	43

Besides, survey was also conducted in nine office buildings, out of which four had an operational central HVAC system while the rest were ventilated naturally (Table 3.1). Moreover, it was found that naturally ventilated offices were equipped with split-type air-conditioning units for cooling purposes (during summers) and electric heaters serving the heating purpose (during winters). Occupants in naturally ventilated buildings had full control on heating and cooling systems during both seasons. However, cooling and heating systems couldn't be controlled by occupants in centrally ventilated offices buildings. Out of four centrally ventilated office buildings, two had four floors and other two had three floors. However, three naturally ventilated office buildings had two floors and other two had three floors. The survey in offices was conducted between regular office hours i.e., from 09:00 am to 05:00 pm.

3.1.2. Data Collection

Indoor thermal comfort in selected dormitories and offices was assessed by on-site monitoring of indoor thermal comfort parameters (indoor air temperature, globe temperature, relative humidity and air velocity) and simultaneous subjective evaluation through questionnaires-based survey. Although summer season starts from June and lasts till September in study area, the data collection for summer season was limited to months of August and September 2019 (2 months) due to semester and summer break schedules. However, winter data was collected, for total of five months i.e., during the months of January and February of 2019 and 2020 and December 2019 (Fig. 3.1).

Questionnaire was prepared in english language and following ASHRAE 55-2013 information appendix K. To ensure the survey response accuracy, the survey questionnaires were first explained to subjects in local language. The occupants were instructed to fairly express their routine-wise sensation about thermal comfort in the rooms. The survey questionnaires were constituted of necessary information such as subject’s age, subjective comfort sensations and preferences (temperature, humidity and air speed). The seven-point sensation and five-point preference votes scale was used in the survey which is presented in Table 3.2. Subjects’ clothing and their activity level of past 15 minutes were also noted during the survey. Subject’s metabolic rate (met) was estimated using ASHRAE 55-2013 (ASHRAE Standard 55-2013, 2013). However, it was observed that clothing insulation (clo) values of typical Pakistani dresses are missing in ASHRAE standards. Therefore, the missing clo values were taken from the previous studies ((Tanabe, 1997 ;Nicol et al., 1999). In addition, clo of bed and bedding system (bed sheet, blanket, quilts etc.) is considered in some previously reported studies (Lin & Deng, 2008), thus bedding system of subjects in dormitories, wherever relevant, was also considered. Furthermore, in both studied areas (dormitories and offices) all respondents participated only once.

Table 6.1: Scale used for sensation and preference votes in survey forms

Scale Values	**Thermal Sensation Votes (TSV)**	**Humidity Sensation Votes (HSV)**	**Air Speed Sensation Votes (ASV)**	**Thermal Preference Votes (TPV)**	**Humidity Preference Votes (HPV)**	**Air Speed Preference Votes (APV)**
3	Hot	Very humid	Very breezy			
2	Warm	Humid	Breezy	Much warmer	Much more humid	Much more air movement
1	Slightly warm	Slightly humid	Slightly breezy	A bit warmer	A bit more humid	A bit more air movement
0	Neutral	Neutral	Neutral	Neutral	Neutral	Neutral
-1	Slightly cool	Slightly dry	Slightly stuffy	A bit cooler	A bit drier	A bit less air movement
-2	Cool	Dry	Stuffy	Much cooler	Much drier	Much less air movement
-3	Cold	Too dry	Too stuffy			

Besides, the indoor thermal comfort parameters such as indoor air temperature (T_a), globe temperature (T_{gt}), relative humidity (Rh_i) and air velocity (v_a) were also monitored simultaneously while conducting the surveys. Details of instruments used for monitoring of these parameters and the comparison of their accuracy with ISO standard are given in Table 3.3. Outdoor parameters including outdoor temperature (T_o) and relative humidity (Rh_o) were furnished from nearest weather station (33.61ºN, 73.03ºE). The instruments for measurement of indoor parameters (T_a, T_{gt} and Rh_i) were placed in respective rooms for 15-20 minutes prior to survey. However, v_a was monitored during filling of survey forms at a height of 1.1m and mean v_a observed over 30 seconds is used for analysis purpose. During the winter season, v_a was found to be zero for all subjects as fans were switched off and doors and windows were closed.

Table 6.3: Specifications of instruments used for data collection

Instrument	Parameter used	Accuracy	ISO Standard 7726
HT-2000	Air temperature	±0.5 ºC (at 0 to 50 ºC), ±1.2ºC (at all other temperatures)	Required: ±0.5 ºC
	Relative humidity	±3%	-
DS18B20 Sensor, (globe dia 0.103m)	Globe temperature	±0.25ºC	Required: ±2 (Mean Radiant Temperature)
Testo 405 thermal anemometer	Air velocity	0.01/s	Required: ±0.05 + $0.05v_a$

3.1.3. Data Analysis

Although data collection methods for both indoor environments were similar, however, gender and seasonal differences were considered while performing analysis in dormitories. Furthermore, collected information about building types in offices was first categorized into five modes (here onward called "modes") for analysis, based on the type of HVAC system incorporated in the offices (buildings) and the season of monitoring. The data was then analyzed accordingly. The ventilation modes of offices and data categorization of dormitories are explained in Fig. 3.3.

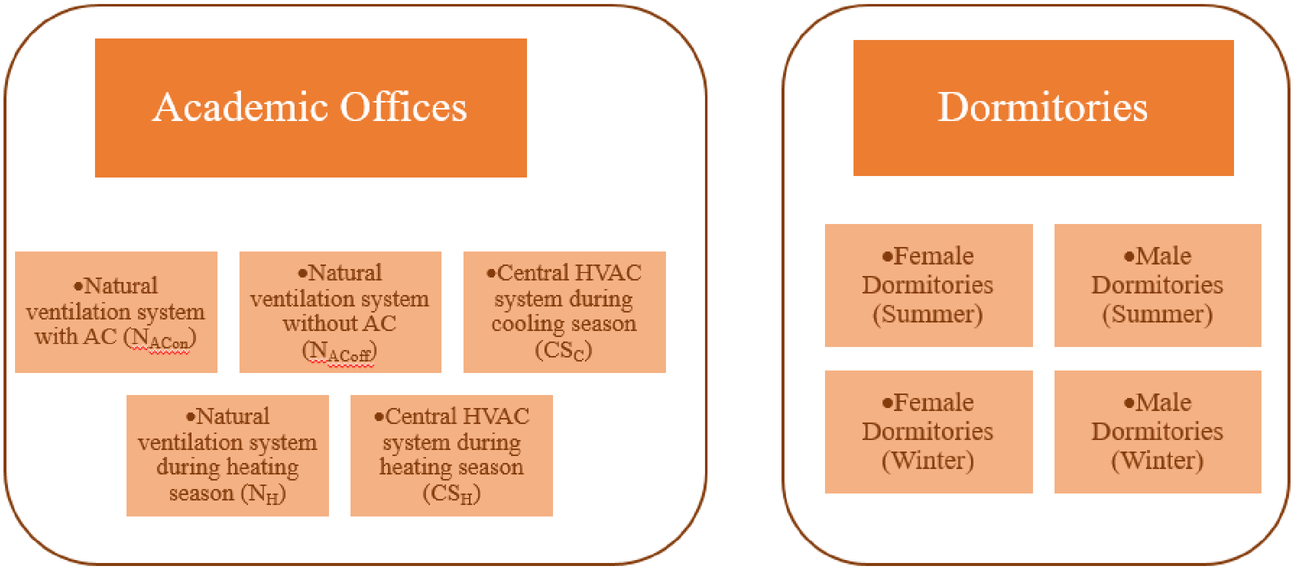


Fig. 3.3. Description of data analysis modes

Thus, the present section has been divided into three subsections; the first one presents methods of thermal environment analysis. Details of methods adopted for the calculation of T_c is given in second subsection. General explanation of thermal comfort models for the prediction of Thermal Sensation Votes (TSV) are discussed in third and fourth subsections.

3.1.3.1. Analysis of Indoor Thermal Environment

Relationship between thermal comfort parameters (clo, T_o, T_a) was estimated using linear regression analysis. As T_c is a function of indoor operative temperature (T_{op}) which is function of mean radiant temperature (T_{mrt}), therefore, T_{mrt} and T_{op} were calculated first and thereafter T_c was estimated. In addition, running mean daily outdoor temperature (T_{rm}) was also calculated and used to assess the adaptive relationships of subjects by regressing it with T_{op}. Details of calculations for T_{mrt}, T_{op}, T_{rm} and T_c are discussed in sub-sections below. In addition, spearman correlation test was performed to find correlation of TSV of both genders with T_a, T_{gt}, T_{op}, T_{mrt} and Rhi. Furthermore, Chi-square, one way ANOVA and t-tests were performed to test statistical difference between seasons and the genders.

Mean Radiant Temperature and Operative Temperature

Mean radiant temperature (T_{mrt}) was calculated using equation 3.1, given below (Shang et al., 2020).

$$Tmrt = \left[(Tg + 273)^4 + \frac{1.1 * 10^8 * V^{0.6}}{\mathcal{E} * D^{0.4}} * (Tg - Ta)\right]^{\frac{1}{4}} - 273 \qquad (3.1)$$

Where, Ɛ is emissivity taken as 0.95 for black surface and D is globe diameter.

Since fans were switched on during summer season, v_a was found greater than 0.2 m/s in all cases. Therefore, T_{op} was calculated following ASHRAE guidelines (ASHRAE Standard 55-2013, 2013), and is given below as equation 3.2.

$$T_{op} = AT_a + (1 - A)T_{mrt} \qquad (3.2)$$

Where, values of A, as a function of V, are given in Table 3.4.

Table 6.2: Values of factor A as a function of air velocity

Air Velocity	<0.2 m/s	0.2-0.6 m/s	0.6-1.0 m/s
A	0.5	0.6	0.7

Although ASHRAE (ASHRAE Standard 55-2013, 2013) provides standard values of A only for airspeed up to 1 m/s, however in this study airspeed was frequently found greater than 1 m/s due to electric fans. Thus, equation 3.3 was used for such cases (S. Kumar et al., 2019a).

$$T_{op} = \frac{[T_{mrt} + (T_a * \sqrt{10} * V)]}{1 + \sqrt{10} * V} \text{ if } V \geq 0.2 \text{ m/s} \qquad (3.3)$$

Running Mean Daily Outdoor Temperature

The weighted T_{rm} was calculated through equation 3.4 as given below(Indraganti et al., 2014; Humphreys et al., 2013)

$$T_{rm\,(tomorrow)} = (\alpha)T_{rm\,(yesterday)} + (1 - \alpha)T_{m\,(today)} \qquad (3.4)$$

Where, T_{rm} is running mean outdoor temperature, α is constant (taken as 0.8) and T_m is mean outdoor daily temperature

The value of T_{rm}, to be used in eq. 3.4, has been computed using eq. 3.5 as reported in previous studies (Khalid et al., 2019).

$$T_{rm} = \frac{T_{-1}+0.8T_{-2}+0.6T_{-3}+0.5T_{-4}+0.4T_{-5}+0.3T_{-6}+0.2T_{-7}}{3.8} \qquad (3.5)$$

Where, T_{-1} is daily mean outdoor temperature of the previous day and T_{-2} is the daily mean outdoor temperature of the two days before and so on.

3.1.3.2. Comfort Temperature

At first, T_c and indoor comfort zone (TSV=±1) were estimated using linear regression method as a function of T_{op} during summer and winter season. Thus, T_{op} was regressed with TSV by using scatter plots. Afterwards, T_c was calculated by putting TSV=0 in regression equations. Comfort bandwidths were also estimated by putting TSV=±1 in regression equations (Ealiwa et al., 2001; Kim et al., 2010). However, some researchers have questioned accuracy of the linear regression method for the calculation of T_c due to technical reasons. For instance, linear regression method is unable to calculate T_c if all votes of two subjects are "neutral" and when there is little variation in T_{gt}. Likewise, it is not recommended when individual adapt (e.g., through clothing, opening/closing windows etc.) with the changing outdoor conditions (Rijal et al., 2010). Furthermore, it couldn't provide reliable estimates when the range of indoor temperature from field data is narrow (S. Kumar et al., 2019a)

To overcome these issues, the use of Griffiths method has been suggested by many researchers for the calculation of T_c. Therefore, T_c was estimated as a function of T_{op}, T_{gt} and T_a using Griffths method following the equation 3.6 given below (Kumar et al., 2019; Takasu et al., 2017).

$$T_C = T + \frac{0-TSV}{G_C} \qquad (3.6)$$

Where; G_C is Griffiths constant/slope taken as 0.25, 0.33 and 0.5 and T is T_{op}, T_{gt} or T_a (Humphreys et al., 2013;.

3.1.3.3. Thermal Comfort Models

Static or PMV-PPD model and adaptive approach have been discussed at length for the prediction of indoor T_c or TSV in many research studies (Weiwei Huo, Yaxian Cheng, Yunxu Jia, 2023). However, PMV-PPD approach was found more reliable in controlled indoor environments. On the flip slide, accuracy of results following adaptive approach was noticed more in naturally ventilated spaces where occupants have full control over heating or cooling system of buildings (Indraganti et al., 2014). Besides, adaptive behavior varies from person to person, season to season and region to region and thus models developed for one climatic conditions couldn't be applied universally. Although the studied methodology is not a novel approach but in Pakistan's context in depth investigation had not been made previously considering differences in gender and seasons. Thus, present study proposed adaptive models for all naturally ventilated office modes (N_{ACon}, N_{ACoff} and N_H) and dormitories. However, PMV-PPD approach was employed for two mechanically ventilated modes (CS_C and CS_H) of offices. Further analysis was performed to check the accuracy of linear adaptive models by comparing them with two well established approaches i.e., cubic and logistic regression. Although logistic regression had been widely used previously in thermal comfort studies (Chaudhuri et al., 2017) (Rehman et al., 2020), up-to author's knowledge, cubic regression analysis had not been investigated much for the prediction of comfort conditions. Moreover, knowledge gap also exists in determining and comparing accuracies of one or more modeling approaches. Thus in the present study in addition to the traditional linear adaptive models, logistic and cubic models were proposed and percentage accuracies were compared. Detailed description of methods applied is provided below.

PMV-PPD Approach

ASHRAE thermal comfort tool (CBE, n.d.) was employed for the calculation of PMV and PPD in two mechanically ventilated modes (CS_C and CS_H) of offices. Input variables in the models included T_{op}, V, Rh_i, met and clo levels for each subject. Like TSV, PMV model also categorized indoor thermal environment into seven-point scale as presented in Table 3.5. Afterwards, PMV was regressed against T_{op} and compared with TSV.

Table 6.3: Sensation scale proposed in PMV model

PMV	(-∞, -2.5)	(-2.5,-1.5)	(-1.5,-0.5)	(-0.5, 0.5)	(0.5, 1.5)	(1.5, 2.5)	(2.5, ∞)
Sensation	Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot

Adaptive Thermal Comfort Approach

Linear regression adaptive models for the prediction of T_c have been an area of interest of many past researchers. (Khalid et al., 2019; Indraganti, 2010). However, in present study two additionally approaches i.e., cubic and logistic regression were used to predict indoor T_c levels. In all three models, T_{rm} was taken as an independent and T_c as a dependent variable. Furthermore, for validation purposes, the data was randomly grouped into training and testing data sets where 70% of the data was used as training and 30% as testing data set in all three models. Generalized equations of models are presented in sub-sections below.

Linear Regression Model:

Generalized equation of linear regression model is given below;

$$y = mx + c \qquad (3.7)$$

herein “y” is indoor operative comfort temperature (T_{opC}) calculated using equation 3.6 and “x” is T_{rm} calculated using equation 3.5. Whereas “m” and “c” correspond to slope and intercept respectively. This analysis was performed using MS Excel (Microsoft Corporation, USA).

Cubic Regression Model:

Generalized equation of cubic regression model is given below;

$$y = ax^3 + bx^2 + cx + d \qquad (3.8)$$

Where a, b, c and d are the regression coefficients. This analysis was also performed using MS Excel (Microsoft Corporation, USA).

Logistic Regression Model:

Logistic model is used to predict the probability distribution of Tc. Analysis was performed using SPSS 14 (IBM Corp., USA) and generalized equation (AGRESTI, 2009) as given below;

logit (P≤j)= α_j+βx (3.9)

Where α and β are regression constants.

3.1.3.4. Thermal Comfort Models with Different Thermal Comfort Variables

In addition to traditional adaptive approach, present study also assessed predictive power of different thermal comfort variables (T_a, T_o, T_{gt}, T_{op}, Rh_i, Rh_o, clo) for the prediction of indoor thermal comfort conditions. Two different machine learning algorithms i.e., K-nearest neighbor (KNN) and logistic regression, were employed for this purpose following previously published research studies (Xiong & Yao, 2021); (Ji & Wang, 2019). In both models, TSV was used as a dependent variable instead of T_c. Moreover, all thermal comfort variables were input separately in models as independent variables. Furthermore, combine effect of all variables on the prediction accuracy of TSV was also investigated. In that case, all the variables were input simultaneously as independent variables. Both models were established using KNN and logistic regression algorithms in MATLAB. To implement both models, data was first normalized using eq. 3.10 and categorized randomly into 70% training and 30% testing datasets.

$$x_{normalization} = \frac{x - min}{max - min} \qquad (3.10)$$

The general equation adopted to develop logistic regression models for single variable was similar as presented in Section 3.2.3.3. However, for multiple variables (to check combine effect), the equation is as below;

$$logit\ (P \leq j) = \alpha_j + \beta_1 x_1 + \beta_2 x_2 \dots\dots\dots\dots\dots\dots . \beta_n x_n \qquad (3.11)$$

However, in KNN algorithm appropriately selected number of nearest neighbor's "K" with maximum accuracy in imperative. Too small or too large value of K can decrease the percentage accuracy of model. Thus, the optimum number of K data points nearest to the test point were obtained by running the model for the range of K values from 1 to 30 for each case separately in MATLAB. Afterwards, the value of K with maximum percentage accuracy was selected as the best number of K.

3.2. Phase 2: Materials and Methods

The section incorporated monitoring of indoor CO_2 levels from selected indoor microenvironments followed by calculation of AERs and VRs. The data was then compared with ASHRAE recommended limits followed by estimation of COVID-19 airborne infection risk assessment in selected microenvironments. The detailed narration is presented in below subsections.

3.2.1. Building Characteristics and Activity Schedule

Four indoor microenvironments were selected for the assessment of IAQ and ventilation condition. Each microenvironment was surveyed prior to data collection and thus analyzed separately depending upon ventilation conditions of the indoor space. A brief overview is given below;

i. Primary school classrooms: All the classrooms were naturally ventilated, thus the analysis included two-season (summer + winter) assessment of ventilation conditions. Data was collected for 1 week during each season including weekdays and weekends.
ii. University classrooms: Like primary school, classrooms selected from university were also naturally ventilated. However, during prior survey it was found that the classrooms had two windows and two ventilators each. Therefore, data was collected for five consecutive days under varying ventilation conditions.
iii. Offices: Out of four selected offices buildings, two had natural ventilation mode while others had mechanical ventilation. Consequently, analysis included assessment of IAQ between natural and mechanical ventilation and also between two seasons (summer + winter). The data was monitored for 1 week from each season including weekdays and weekends.

iv. Dormitories: Prior survey of dormitories indicated that the dormitories in NUST had varying occupancy. Accordingly, data was collected for 1 week during weekdays only and thus analysis was performed between cubical, bi-seater and tri-seater dormitories.

Detailed description of each microenvironment along with occupants' activity schedule is given in below subsections.

3.2.1.1. Primary School Classrooms

Two seasons (summer and winter) IAQ assessment was conducted in 11 classrooms of NUST Creative Learning School (NCLS) located in Islamabad, Pakistan (33.73° N, 73.09° E). Although the building was constructed in 2014, the school started its operation in November 2016. Selected school was a single-storey building having capacity of 400 students from age group 3 to 11 years. A brief survey was conducted prior to data collection for the identification of factors that may have impact on VRs as well as indoor thermal comfort and for thorough information collection of the monitored classrooms. Detailed description of each classroom is given in Table 3.6.

Table 6.4: Description of monitored primary school classrooms

Room	**Windows**	**Windows Area**	**No. of Doors**	**Room Area**	**No. of Occupants**	**Occupation Period**	**Occupation Density**	**Remarks**
		(m^2)		**(m^2)**			**(m^2/person)**	
CR01	1	1.48	1	23.7	28	8:45 am-2:00 pm	0.85	Senior Class
CR02	1	1.48	1	23.7	20	8:45 am-2:00 pm	1.18	Senior Class
CR03	2	1.48+1.48	2	33.9	28	8:45 am-2:00 pm	1.21	Senior Class
CR04	1	1.48	1	20.6	24	8:45 am-2:00 pm	0.86	Senior Class
CR05	1	1.48	1	20.6	22	8:45 am-2:00 pm	0.94	Senior Class

Room	**Windows**	**Windows Area**	**No. of Doors**	**Room Area**	**No. of Occupants**	**Occupation Period**	**Occupation Density**	**Remarks**
		(m^2)		**(m^2)**			**(m^2/person)**	
CR06	2	1.48+1.48	1	26.1	26	8:45 am-1:00 pm	1	Junior Class
CR07	2	1.48+1.48	1	20.5	29	8:45 am-1:00 pm	0.71	Junior Class
CR08	2	1.48+1.48	1	20.3	25	8:45 am-1:00 pm	0.81	Junior Class
CR09	2	1.48+1.48	1	20.3	24	8:45 am-1:00 pm	0.85	Junior Class
CR10	2	1.48+1.48	1	20.3	25	8:45 am-1:00 pm	0.81	Junior Class
CR11	1	1.48	1	20.6	18	8:45 am-2:00 pm	1.14	Senior Class

All selected classrooms were of similar building characteristics and ventilated naturally through doors and windows. During summer monitoring period, split type air-conditioning (AC) units were switched on in the occupancy hours, while during winters, portable fan heaters served the heating purpose. The AC units were generally set to maintain 27°C (as per school policy), however teachers are communicated to change it accordingly in extreme weather conditions. The fan heaters, on the other hand, had no provision of setting up the desired T and were rather switched on or off by teachers to maintain the desired T levels. The opening and closing of the doors/windows were also decided by the teachers. During both seasons class sessions were scheduled at 08:30 am till 01:00 pm for junior classes i.e., Play Group (PG) to Kindergarten (KG), while for classes I to VI, sessions end at 02:00 pm with 25 minutes break from 10:45 to 11:10 am. On Fridays, school closing timing was 12:45 pm with a 25-minute break from 10:20 to 10:45 am for all classes.

3.2.1.2. University Classrooms

Field study was also executed in four naturally ventilated classrooms belonging to Institute of Environmental Sciences and Engineering (IESE), NUST, Islamabad during winter season. The selected building was a double storey academic building constructed in 2005. Moreover, it was noticed that all the monitored classrooms had similar characteristics. The net floor area and volume of each classroom were 76 m^2 and 277.9 m^3 respectively.

Besides, each room was equipped with two windows, two doors, two ventilators and portable fan heaters. Two of the monitored classrooms i.e., CR_A and CR_B were located on ground floor while other two, CR_C and CR_D, were on the first floor. Lectures in each classroom were scheduled in two different sessions for undergraduate and postgraduate students, here onward referred to as morning and evening sessions respectively. Morning sessions start at 09:00 am and last till 04:00 pm with an hour-long break from 01:00-02:00 pm. However, evening sessions were scheduled from 05:00 to 08:30 pm with half an hour break from 06:30 to 07:00 pm. Occupancy of each classroom varied during each session and was noted from CCTV camera footages which were installed outside each classroom.

3.2.1.3. Offices

Four office buildings (Buildings A, B, C and D) belonging to National University of Science and Technology (NUST), Islamabad, having different ventilation modes, were selected for monitoring and assessment. Monitored offices were surveyed prior to data collection to identify factors that might have an impact on VRs, detailed description of which is given in Table 3.7. Timing of all selected offices was from 09:00 am to 05:00 pm with an hour-long lunch break from 01:00 pm to 02:00 pm.

Table 6.5: Description of monitored office rooms

Building	**Room**	**Room Area**	**Number of Occupants**	**Occupation Density**	**Remarks**
		(m^2)		**(m^2/person)**	
A	R1A	17.81	3	5.94	Naturally ventilated
	R2A	12.76	2	6.38	
	R3A	37.07	1	37.07	
B	R1B	30.41	3	10.14	Naturally ventilated
	R2B	25.68	4	6.42	
	R3B	20.25	2	10.13	
C	R1C	37.13	2	18.57	Mechanically ventilated
	R2C	37.13	2	18.57	
	R3C	11.74	2	5.87	
D	R1D	84.79	5	21.19	Mechanically ventilated
	R2D	71.37	4	17.84	

Building A and B were naturally ventilated, each having two levels and constructed in 2005 and 2008 respectively. Three offices (R1A, R2A, R3A and R1B, R2B and R3B) from each building were selected for the study purpose. Among them R2A, R1B and R2B were on ground floor while others were on 1st floor. During summer season split type air conditioners were observed to be switched on while during winter season portable electric fan heaters served the heating purpose.

However, building C and D were centrally ventilated having two and four levels, constructed in 2001 and 2017 respectively. Three offices from building C (R1C, R2C and R3C) and two from D (R1D and R2D) were selected for monitoring. Among them R1C, R2C and R2D were on ground floor, R3C on first floor while R1D was on 4th floor. Cooling system during summer and heating system during winter seasons were observed operational during monitoring period.

3.2.1.4. Dormitories

The dormitory rooms were splintered into three categories for monitoring and assessment, i.e., cubical (C208, C210, C215 and C246), bi-seater (B116, B201, B217 and B305) and tri-seater (T311, T407, T412 and T416). The categorization was based on occupancy, room dimensions, no. of windows and doors of the facility. Four dormitories, belonging to NUST, Islamabad, from each category were chosen for monitoring. Cubical dormitories were populated with a single student; however, bi-seater and tri-seater were shared by two and three students respectively. Additionally, students residing in cubical dormitories were provided with the facility of attached washrooms. However, community washroom facilities were set up for bi-seater and tri-seater dormitories which had no direct connection with the rooms. Net floor area of cubical, bi-seater and tri-seater dormitories were found as 7.43, 14.86 and 17.65 m^2 respectively however, volume as 27.18, 54.37 and 64.56 m^3 respectively. Each cubical dormitory had one while all others had two openable windows and one door. Moreover, with an intend of heating, each dormitory had an operational radiator unit hooked up with central water heating system.

3.2.2. Data Collection

Monitoring of indoor CO_2 in NCLS classrooms and NUST offices was conducted in winters (December 2018 - January 2019, November 2019 - January 2020) and summers

(August 2019 - September 2019) using HT-2000 (Asif et al., 2018) with characteristics given in Table 3.8. However, IESE classrooms and NUST dormitories were monitored during December 2019 and February 2019 respectively.

Table 6.6: Specifications of Sensors used

Sensor	**Range**	**Accuracy**
Carbon dioxide	0-9999 ppm	±5% reading
Temperature	-10 - 70ºC	±1.2ºC
Humidity	0.1-99.9%	±3%

One instrument was placed in the center of each room at about six feet height from the ground to make the readings representative of the whole room while keeping the instrument away from the breathing zone of occupants (to avoid errors caused by the direct exposure to exhaled CO_2). Outdoor CO_2 concentration was assumed to be constant i.e., equal to 400 ppm. On the other hand, outdoor T and RH measurements were taken from a nearest weather station (33.61° N, 73.03° E). Indoor readings of indoor CO_2 in NCLS classrooms and NUST offices were recorded at an interval of 1 minute for 1 week during both seasons which include weekdays as well as weekends, both, occupancy and non-occupancy hours. However, continuous record of parameters in NUST dormitories was obtained for weekdays only. Furthermore, experimental framework in IESE classrooms was designed under five different ventilation scenarios which are presented in Table 3.9. During all measurements doors of each classroom were kept closed.

Table 6.7: Ventilation scenarios followed during data collection

Monitoring Day	**Front Window**	**Back Window**	**Front Ventilator**	**Back Ventilator**	**Total Area for Ventilation from Windows and Ventilators (m^2)**			
					CR$_A$	**CR$_B$**	**CR$_C$**	**CR$_D$**
1	Open	Open	Open	Open	1.7+1.7+0.03+0.03[a]	1.7+1.7+0.03+0.03	1.25+1.25+0.03+0.03	1.25+1.25+0.03+0.03
2	Close	Open	Open	Open	1.7+0.03+0.03[b]	1.7+0.03+0.03	1.25+0.03+0.03	1.25+0.03+0.03
3	Close	Close	Open	Open	0.03+0.03[c]	0.03+0.03	0.03+0.03	0.03+0.03
4	Close	Close	Close	Open	0.03[d]	0.03	0.03	0.03
5	Close	Close	Close	Close	0	0	0	0

[a]Front window + back window + front ventilator + back ventilator

[b]Back window + front ventilator + back ventilator

[c]Front ventilator + back ventilator

[d]Back ventilator

3.2.3. Data Analysis

3.2.3.1. Statistical Analysis

All the statistical analysis had been performed using MS Excel (Microsoft Corporation, USA), ORIGIN 2019b (OriginLab Corporation) and SPSS 14 (IBM Corp., USA). Datasets had been first checked for normality using Kolmogrov-Smirnov test. As the data was not normally distributed thus significant difference between two or more datasets had been investigated using non-parametric tests. In NCLS, NUST offices and dormitories difference of indoor CO_2 levels between two or more sampling days (at same location) had been analyzed using non-parametric Kruskal-Wallis Test by taking significance level (α) as 0.05. After that, mean hourly values for each room had been calculated, separately for weekdays and weekends by averaging the multiple-days datasets. The results were then reported as 24-hour mean hourly profiles. However, IESE classrooms data was reported as 24-hour profiles for all ventilation settings instead of 24-hour mean hourly profiles. Non-parametric Wilcoxon Signed Rank and Rank Sum Test were used to test the data for the difference of parameters recorded in same location, along the day (NCLS, IESE classrooms, NUST offices and dormitories), between the seasons (NCLS and NUST offices), among buildings (NUST offices and dormitories), different ventilation settings (IESE classrooms) between sleep hours and non-sleep hours (dormitories).

3.2.3.2. Air Exchange Rates

In naturally ventilated rooms, buildup of indoor CO_2 levels is the result of infiltration of outdoor CO_2 as well as CO_2 generated by occupants by respiration in indoor space. CO_2 levels in an occupied room are found generally higher than the outdoor levels. Concentration of an indoor air contaminant in an occupied naturally ventilated room can be found by using its time derivative (Turanjanin et al., 2014) as given by:

$$\frac{VdC}{dt} = q(C_o - C_i) + S - kC_i \tag{3.12}$$

Where, V= Volume of room

dC/dt= Change of indoor concentration in time t

q= air flow into/ out of the room

C_o= Outdoor contaminant concentration

C_i= Indoor contaminant concentration

S= Indoor sources

k= First-order degradation constant

CO_2 being a conservative contaminant has no degradation, i.e. k=0. Ci and Co were converted from ppm to mg/m^3 for unit consistency in eq.3.12 using eq. 3.13:

$$Conc.in\frac{mg}{m^3} = \frac{Molecular\ Weight * Conc.in\ ppm}{Temp.adjusted\ molar\ gas\ volume} \qquad (3.13)$$

Where, Molecular Weight= 44.01 (g/mol)

Conc. in ppm= Monitored indoor CO_2 levels

Molar gas volume at standard T and pressure (25ºC and 1 atm.) is 24.45 L/mol. Assuming indoor pressure equal to 1 atm, per minute gas volume was calculated utilizing the monitored per minute T records by eq. 3.14.

$$Temp.adjusted\ molar\ gas\ volume = \frac{RT_i}{P} \qquad (3.14)$$

Where, P= Indoor pressure (taken as constant i.e. 1 atm)

R= Ideal gas constant= 0.08205 (L.atm/mol.K)

T_i= Indoor temperature (K)

As occupants are the sole source of indoor CO_2 buildup in a classroom, source (S) was taken as

$$S = NG \qquad (3.15)$$

Where N is the number of occupants and G is the CO_2 generation rate per person which is taken as 0.00411 l/s (or 8.1378 mg/sec) for children and 0.0054 l/s (10.21 mg/s) for adults as presented in (Beisteiner, 2002) . Thus eq. 3.12 was rearranged for the calculation of air flows, i.e. q, into/ out of the building as below:

$$q = \frac{\frac{VdC}{dt} - NG}{C_o - C_i} \qquad (3.16)$$

Here change of indoor CO_2 concentration with time (dC/dt=mg/m^3.sec) was calculated using the difference between two consecutive monitored levels. Thus;

$$Air\ Exchange\ Rate = AER = \frac{q}{V} \tag{3.17}$$

3.2.3.3. Airborne Infection Risk Assessment

Effect of VRs on airborne transmission of COVID-19 in indoor environments can't be denied. According to the recent report of world health organization (WHO) (WHO, 2020), indoor spaces are emphasized to be adequately ventilated to reduce the COVID-19 spread. Wells and Riley (Riley, C.E., Murphy, G. and Riley, 1978) used VRs in their model for the transmission risk assessment of airborne diseases. The model equation is given below as eq. 3.18.

$$PI = \frac{C}{S} = 1 - \exp(-\frac{Iq_{gr}pt}{Q}) \tag{3.18}$$

Where, PI is probability of infection, I is number of infectors, q_{gr} is quantum generation rate produced by infector (quanta/hour), p is pulmonary ventilation rate (m^3/h), t is exposure time (h) and Q is ventilation rate (m^3/h)

It is to be noted that eq. 3.18 is based on an assumption of uniform indoor environment, however, in real world scenario majority of indoor environments are non-uniform. Shao and Li (Shao & Li, 2020) incorporated this non-uniformity factor due to air velocities, temperature and concentration of species in non-uniform indoor environments by introducing the term "dilution ratio" (DR) in conventional Wells-Riley model. DR is defined in eq. 3.19 as given below.

$$DR = \frac{E_o}{E} = \frac{q_{gr}}{pE} \tag{3.19}$$

Where; E_o is Quantum concentration in infector's exhaled breath ($quanta/m^3$), E is Quantum concentration in susceptible person's inhaled breath ($quanta/m^3$)

Using the concept of DR, Shao and Li (Shao & Li, 2020) modified the Wells-Riley equation as given in eq. 3.20 below.

$$P = 1 - \exp\left(\frac{q_{gr}t}{DR}\right) \tag{3.20}$$

The unknown parameters in eq. 3.20 are q_{gr} and DR In the present study, DR was calculated by simulating transport and distribution of indoor CO_2 levels (as a tracer gas) following existing literature (Shao & Li, 2020). However, selection of q for airborne transmission of COVID-19 is critical as different researchers used different values in their studies as presented in Table 3.10. Dai and Zhao (Dai & Zhao, 2020), estimated range of q as 14-48 h^{-1} by using reproductive number-based fitting approach. Thus, in the present study, value of q_{gr} was set to 48 h^{-1} for risk estimation in IESE classrooms under different ventilation scenarios.

Table 6.8: Quantum generation rate (q_{gr}) values for COVID-19

Sr. No	Quantum Generation Rate (quanta/h)	Source
1	45	(C. Li & Tang, 2021)
2	0.32-240	(Buonanno et al., 2020)
3	14-48	(Dai & Zhao, 2020)
4	30 (moderate risk)	(Bazant et al., 2021)
5	11.4 (low risk)	(Zemouri et al., 2020)
	28.94 (intermediate risk)	
	295.5 (high risk)	
6	970	(Miller et al., 2021)
7	100	(Guo et al., 2021)

3.3. Phase 3: Materials and Methods

3.3.1. Modeling of Indoor CO_2 Levels

An SD based model was developed using VENSIM PLE Plus software (Fig. 3.4). The model was based on following general mass balance eq. 3.21.:

$$CO_{2\ \text{supplied}} + CO_{2\ \text{generated}} = CO_{2\ \text{buildup indoor}} + CO_{2\ \text{ventilated}} \qquad (3.21)$$

Where $CO_{2\ \text{supplied}}$ is the amount of CO_2 coming from outdoor, $CO_{2\ \text{generated}}$ is the amount of CO_2 generated from occupants breathing inside a room, $CO_{2\ \text{ventilated}}$ is the amount of

CO_2 going out of the room through ventilation process and $CO_{2\ \text{buildup indoor}}$ is the amount of CO_2 accumulated inside the room.

VRs, in most of the real-world conditions, fluctuate during occupancy hours due to opening or closing of windows, doors, ventilators etc. Additionally, ventilation conditions after occupancy hours are also not exactly as they are during occupancy for some cases. Thus, in indoor spaces where occupancy level is known, accuracy in VR calculation can be achieved by calculating minute-by-minute VRs during occupancy hours using transient mass balance method. Calculations were made using eq.3.16 and the values obtained were then input in the model using VENSIM lookups function through an MS Excel file for the prediction of indoor CO_2 levels (Fig. 3.4(b)). However, in addition to this VRs were also calculated using decay and steady state methods. Decay method could be used in indoor spaces after the end of occupancy session when there is no more active indoor source of CO_2, and thus gradual decrease in indoor CO_2 levels is observed as a result of exchange of air with the outdoor atmosphere. Thus, for this case eq. 3.16 can be written as below.

$$q = \frac{\frac{VdC}{dt}}{C_o - C_i} \qquad (3.22)$$

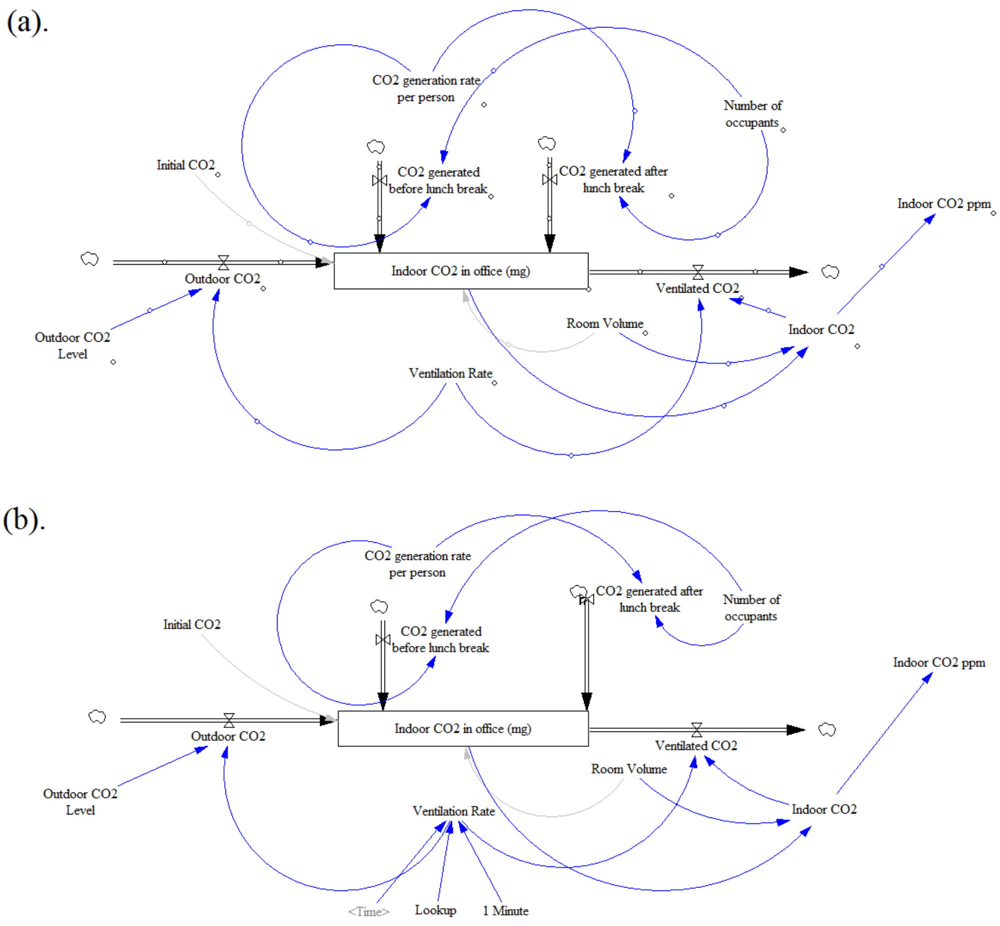


Fig. 6.4: Model structure for simulation of indoor CO_2 concentration utilizing a). average VRs and b). minute-by-minute VRs

3.3.2. Case Study

Validation of the developed model was performed using data collected during Phase 2 of this dissertation. Detailed description of each monitored site is provided in Section 3.2.1. The model was run for the occupancy hours of all the four indoor micro-environments i.e., primary school classrooms, university classrooms, offices and dormitories. Furthermore, following decay method, minute-by-minute VRs were calculated for three consecutive hours after the end of occupancy hours in all monitored sites using eq. 3.22 and average of 3 hours were taken as representative VR for the respective indoor environment (Fig. 3.4(a)).

Besides, steady state method can be applied in an occupied room with an assumption that steady state of indoor CO_2 levels is achieved, and VR is constant for the respective occupancy session. Thus, in the present study using this method, VRs were calculated using eq.3.16 which was then averaged and input as constant to the model (Fig. 3.4(a)).

3.3.3. Statistical Analysis

Accuracy of simulated indoor CO_2 levels was checked by correlating monitored and simulated indoor concentration, practicing spearman's correlation and root mean square error (RMSE) tests. The test results were then used to find the best method for the calculation of VRs among the three methods under study.

3.4. Phase 4: Materials and Methods

3.4.1. Monitoring Mode

An experimental campaign was executed in three naturally and two mechanically ventilated classrooms belonging to NUST, Islamabad, Pakistan during January 2022. Monitored indoor parameters included records of CO_2 and PM at 1 minute frequency for three consecutive days. Besides simultaneous outdoor measurements were also recorded by instruments installed on the rooftop of monitored buildings. The buildings were operational from Monday to Friday with lecture hours from 09:00 am to 05:00 pm for undergraduate students and from 05:00 to 8:30 pm for post-graduate students. However, during the monitoring period, there were two scheduled final exams sessions from 09:30 am to 12:30 pm and from 05:00 to 08:00 pm in naturally ventilated classrooms. Moreover, in mechanically ventilated classrooms, second exam session was from 01:30 to 04:30 pm (Fig. 3.5).

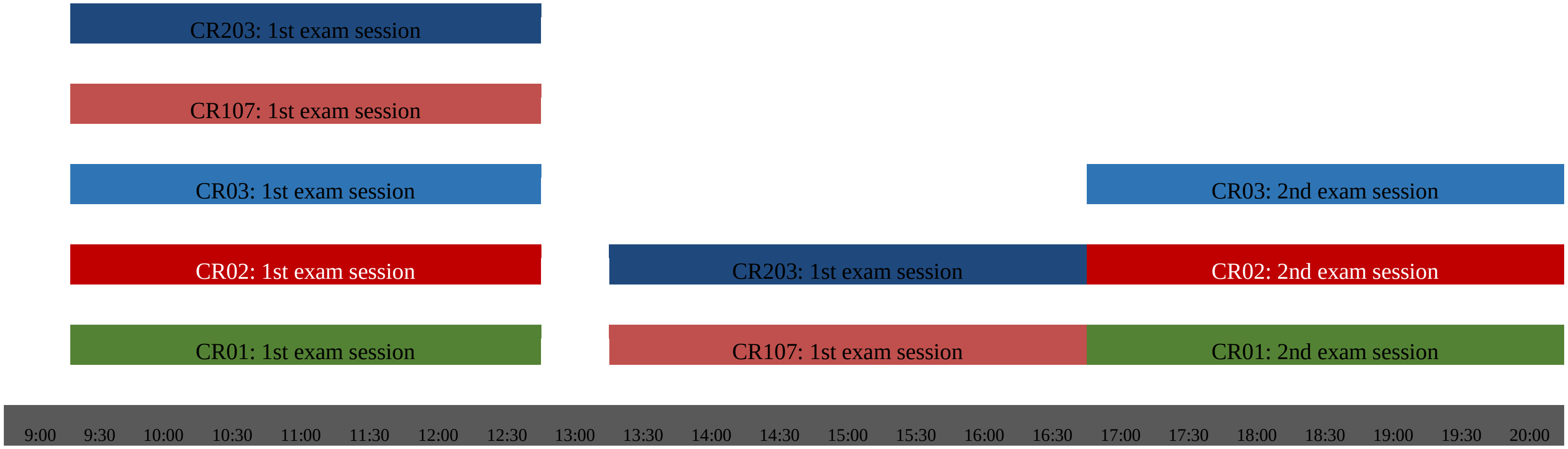


Fig. 3.5: Timeline for data collection

Heating system of mechanically ventilated classroom was found operational from 11:00 am to 05:00 pm. However, there were split type inverter AC units in naturally ventilated classrooms except in CR03. Table 3.11 summarizes building characteristics of each monitored classroom during the monitoring days.

Table 6.9: Building characteristics of the monitored classrooms

Classroom	**Building A**			**Building B**	
	CR01	**CR02**	**CR03**	**CR107**	**CR203**
Ventilation Type	Natural	Natural	Natural	Mechanical	Mechanical
Surface (m^2)	76	76	76	81.3	81.3
Height	3.65	3.65	3.65	3.65	3.65
Volume (m^3)	277.4	277.4	277.4	296.745	296.745
Volume per person (m^3/person)	9.90714	8.94839	9.56552	11.8698	11.41327
Nominal occupancy (person/m^2)	0.36842	0.40789	0.38158	0.3075	0.319803

Instruments used for continuous indoor and outdoor monitoring included HT-2000 for $CO_2$and Dylos 1700 (Dylos Corporation, USA) for PM levels. Accuracies of CO_2 sensors were ±5% reading. However, two size bins of PM PNC were recovered from the real time monitoring of PM i.e., PM≥0.5µm and PM≥2.5µm. PNC for $PM_{2.5}$ was obtained by subtracting large size bins of PM from small size bins.

3.4.2. Data Analysis

3.4.2.1 Statistical Analysis

All the statistical analysis was executed on MS Excel (Microsoft Corporation, USA), SPSS 14 (IBM Corp., USA) and ORIGIN 2019b (Origin Lab Corporation). I/O ratio of CO_2 and $PM_{\geq 0.5\mu m}$ and $PM_{\geq 2.5\mu m}$ was calculated. Moreover, pearson correlation test was used to find the correlation of indoor CO_2 levels with other monitored indoor parameters. Besides, AERs were calculated using eq. 3.17 (Section 3.2.3.2) for all the monitored classrooms.

3.4.2.2. Conversion of Particle Count to Mass Number

Conversion of dylos PNC to mass number (PMC) was an area of research of some previous studies (Franken et al., 2019). In those studies, fit curves were developed by taking simultaneous data records of dylos PNC and PMC of a conventional device. Thus, nephelometer was employed as a conventional instrument in the present study for this purpose. Data was collected in a office by placing nephelometer side-by-side with the Dylos for three consecutive days at 1 minute interval. Afterwards, PNC was plotted against PMC and was then converted into mass number using linear equation.

Chapter 4

Results and Discussion

Like chapter 3, this chapter also comprised of four main sections, each based on one objective followed by subsections. The detailed description is given below.

4.1. Phase 1: Indoor Thermal Comfort in Dormitories and Offices

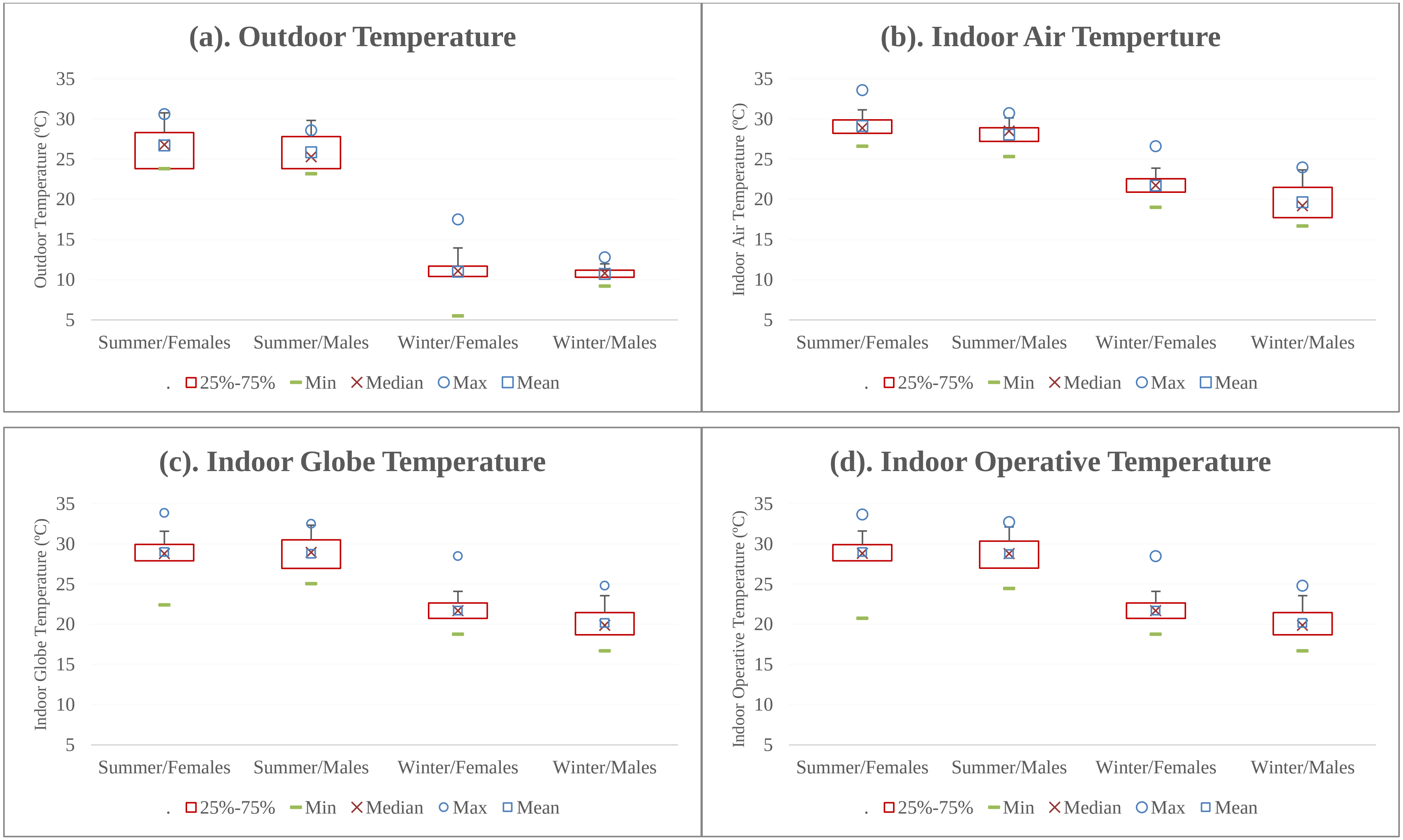
This section has been further divided into four subsections where results of each monitored indoor environment is presented separately. First and second subsection presents results and discussion of indoor thermal environment analysis and estimated indoor T_c levels respectively. Moreover, adaptive thermal comfort models and thermal comfort models with multiple variables are depicted in third and fourth subsections respectively detailed explanation of which are presented below.

4.1.1. Indoor Thermal Environment

4.1.1.1. Sample Size and Environmental Characteristics

A total of 971 and 1016 valid responses were collected from two-season survey of dormitories and offices respectively. Out of collected responses from dormitories, 526 questionnaires were filled by female (250 from summer and 276 from winter season) and 445 by male (215 from summer and 230 from winter season) respondents. Moreover, from five modes of offices under study, 512 responses were from summer season and 504 from winter seasons. Of the valid forms from offices, 702 respondents were male and 314 were female. It is important to mention that all the survey forms were filled out during daytime before sunset for all locations during both seasons and all the respondents participated in survey only once.

In general, environmental and ventilation conditions were identical in all dormitories. Thus, analysis included comparison between the two genders and between seasons. However, offices data was segregated among different modes of ventilation (Section 3.1.3) for analysis. Overall mean T_a, T_{gt} and T_{op} were found higher for female respondents than males during both seasons which could be attributed to higher T_o levels during the survey of female dormitories (Fig. 4.1(a)). Likewise, higher outdoor T_o during the monitoring of offices contributed towards higher indoor T_a, T_{gt} and T_{op} in comparison to dormitories. Detailed descriptive statistical analysis of indoor and outdoor environmental variables that could influence thermal comfort for dormitories and offices are shown in Fig. 4.1 and Fig. 4.2 respectively.


(a). Outdoor Temperature
Outdoor Temperature (ºC)
35
30
25
20
15
10
5
Summer/Females
Summer/Males
Winter/Females
Winter/Males
25%-75%
Min
Median
Max
Mean
(b). Indoor Air Temperture
Indoor Air Temperature (ºC)
35
30
25
20
15
10
5
Summer/Females
Summer/Males
Winter/Females
Winter/Males
25%-75%
Min
Median
Max
Mean
(c). Indoor Globe Temperature
Indoor Globe Temperature (ºC)
35
30
25
20
15
10
5
Summer/Females
Summer/Males
Winter/Females
Winter/Males
25%-75%
Min
Median
Max
Mean
(d). Indoor Operative Temperature
Indoor Operative Temperature (ºC)
35
30
25
20
15
10
5
Summer/Females
Summer/Males
Winter/Females
Winter/Males
25%-75%
Min
Median
Max
Mean

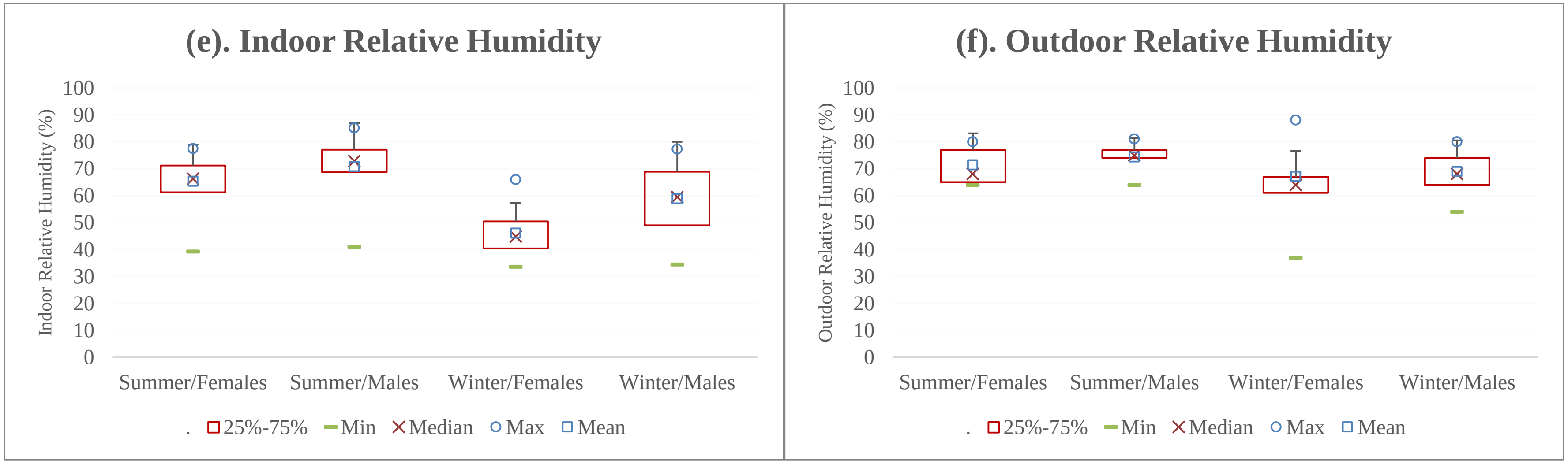
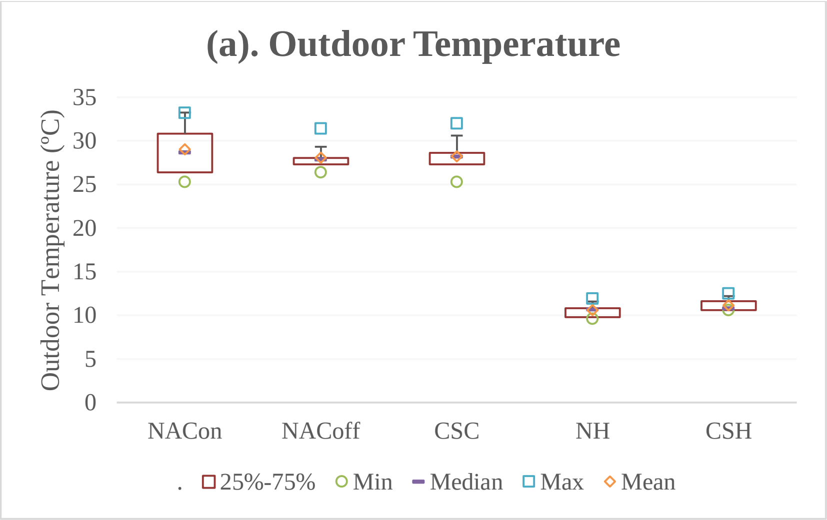
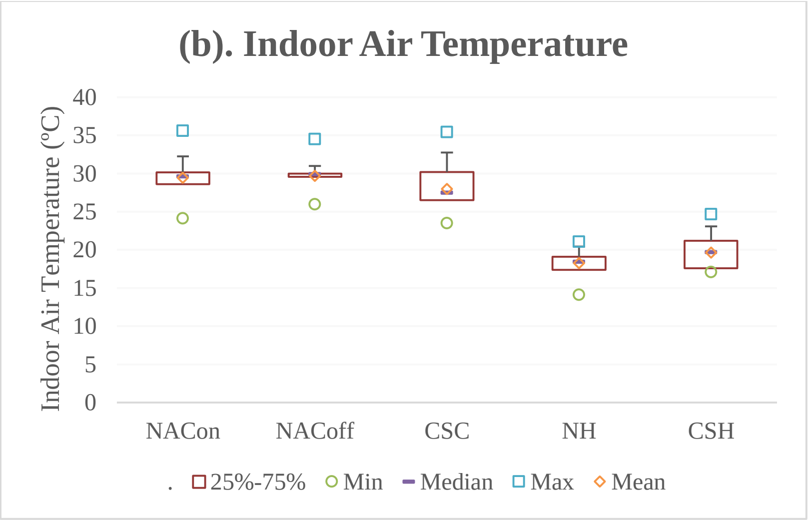
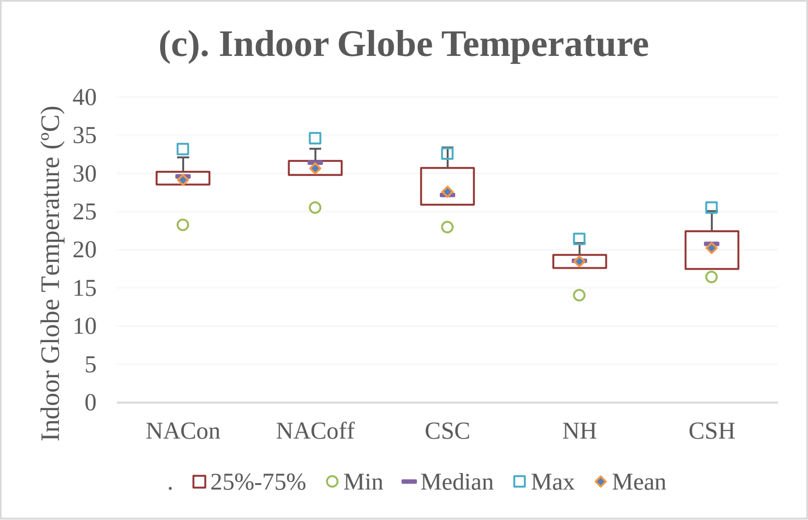
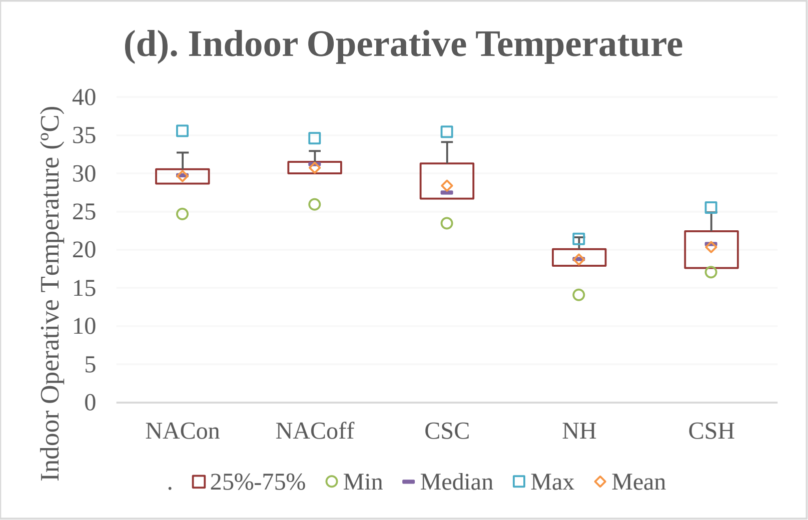


Fig. 8.1: Statistical analysis of outdoor temperature (a), indoor air temperature (b), indoor globe temperature (c), indoor operative temperature (d), indoor relative humidity (e) and outdoor relative humidity (f) of both genders during both seasons in dormitories


(a). Outdoor Temperature


(b). Indoor Air Temperature


(c). Indoor Globe Temperature


(d). Indoor Operative Temperature

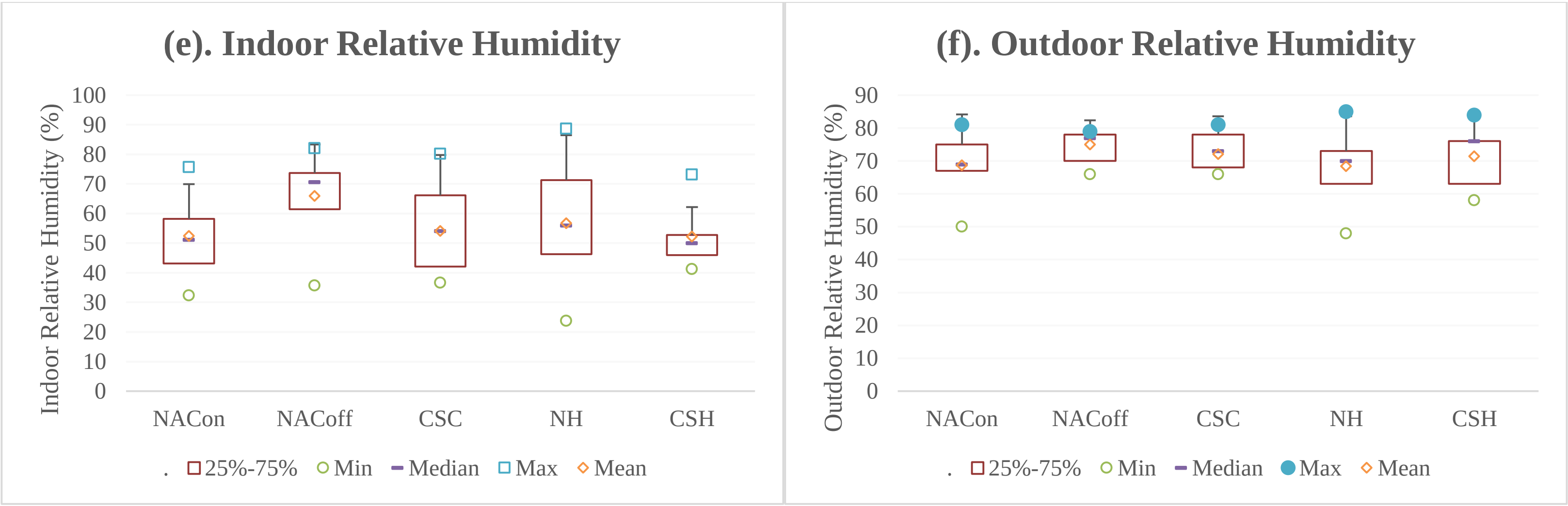


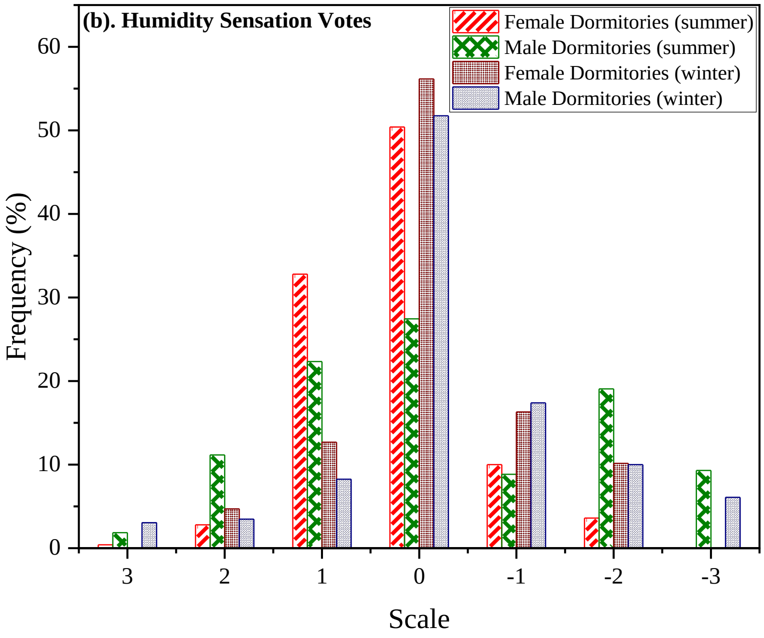
Fig. 8.2: Statistical analysis of outdoor temperature (a), indoor air temperature (b), indoor globe temperature (c), indoor operative temperature (d), indoor relative humidity (e) and outdoor relative humidity (f) in offices

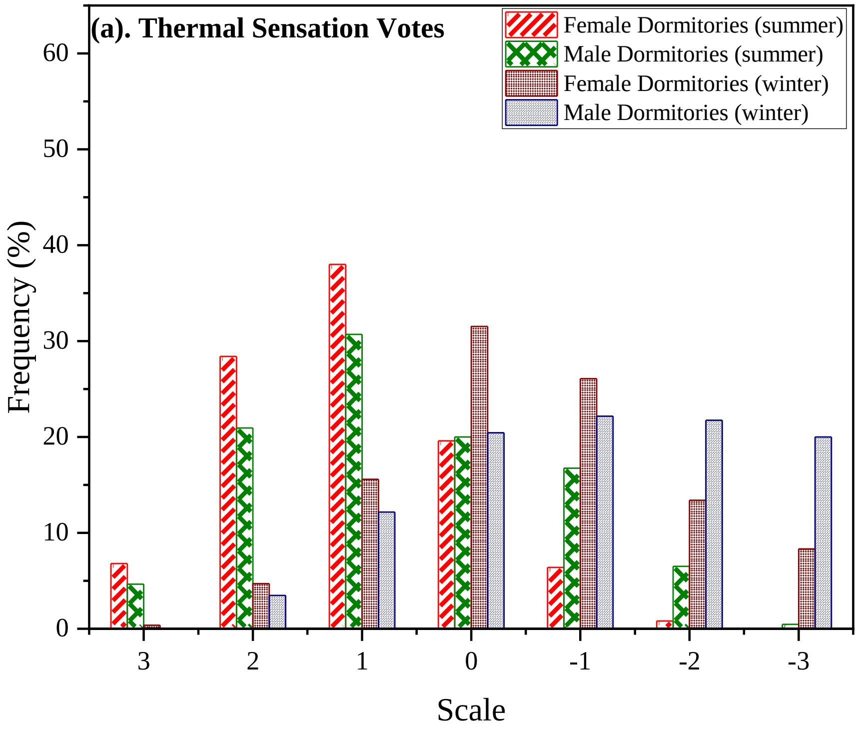
4.1.1.2. Subjective Thermal Evaluation

The respective analysis of sensation and preference votes on ASHRAE seven-point and five-point scale in dormitories and offices are given in following subsections.

(a). Thermal Evaluation in Dormitories

Thermal sensations vary among genders and people living in same environment under same indoor temperature (Z. Wang, 2006). Frequency distribution of male and female sensation votes in dormitories during both seasons on ASHRAE seven-point scale is shown in Fig. 4.3


(b). Humidity Sensation Votes
Female Dormitories (summer)
Male Dormitories (summer)
Female Dormitories (winter)
Male Dormitories (winter)
Frequency (%)
0
10
20
30
40
50
60
3
2
1
0
-1
-2
-3
Scale


(a). Thermal Sensation Votes
Female Dormitories (summer)
Male Dormitories (summer)
Female Dormitories (winter)
Male Dormitories (winter)
Frequency (%)
0
10
20
30
40
50
60
3
2
1
0
-1
-2
-3
Scale

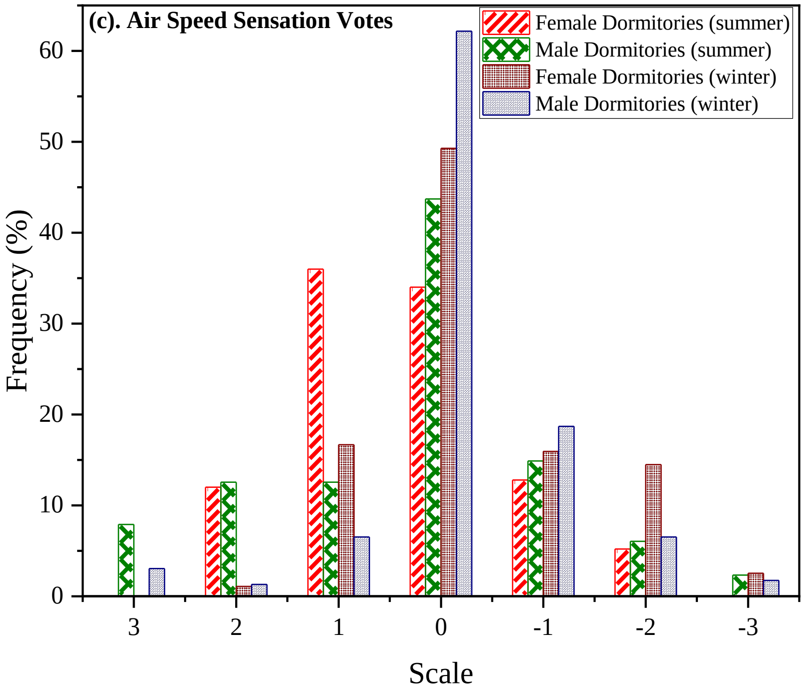


Fig. 8.3: Frequency distribution of (a), thermal (b) humidity and (c) air speed sensation votes in dormitories

Frequency distribution of thermal sensation votes (TSV) has been presented in Fig. 4.3 (a). It was observed that during summer season most subjects (both genders) felt “slightly warm” (TSV=+1). However, during winter season majority of females voted for “neutral” (TSV=0) sensation while males voted for “slightly cool” (TSV= -1) thermal sensation. The proportion of votes for “slightly warm”, “neutral” and “slightly cool” responses (i.e., between comfort range +1 to -1) accounts for 64 and 73.2% for females and 67.4 and 54.8% for males during summer and winter seasons respectively. Table 4.1 shows percentages of subjects voted within comfort range of thermal sensation in dormitories along with their corresponding T_{a}.. The data was analyzed statistically to check significant difference between genders and seasons using chi-square and t-test. Results of both analysis showed statistical difference ($p<0.05$) between two genders with the mean TSV of females slightly higher than males during both seasons i.e. 1.1±1 and -0.5±1.3 during summer and winter seasons respectively. While, for males, mean TSV were 0.5±1.3 and -1.1±1.4 for summer and winter respectively. Additionally, significant difference ($p<0.05$) was also found when TSVs of both genders were compared over two seasons.

Table 8.1: Percentages of subjects who voted within comfort range of thermal sensations and their respective indoor air temperatures in dormitories

	Thermal Sensation Vote (TSV)	**Females**		**Males**	
		Percentage	**Indoor Air Temperature (ºC)**	**Percentage**	**Indoor Air Temperature (ºC)**
Summer	Slightly Warm (TSV=+1)	38	28.9±0.9	30.7	28.7±0.9
	Neutral (TSV=0)	19.6	28.2±0.7	20	27.4±1.0
	Slightly Cool (TSV=-1)	6.4	27.9±0.8	16.7	26.8±0.8
Winter	Slightly Warm (TSV=+1)	16.2	22.2±1.2	12.2	22.0±1.0
	Neutral (TSV=0)	30.5	22.0±1.2	20.4	21.4±1.5
	Slightly Cool (TSV=-1)	26.3	21.9±1.0	22.2	19.2±1.7

Thapa et al., (Thapa, Bansal, Panda, et al., 2018) found majority of subjects (41.9%) voted for "slightly cool" TSV during investigation of adaptive thermal comfort in different buildings of eastern India under comparable ambient conditions in a cold season. However, they found more percentage of votes (88.2 and 82.6% during summer and winter season respectively) within comfort range in comparison to this study. In another comparable study, Wu et al., (Z. Wu et al., 2019) while investigating naturally ventilated dormitories of Changsha, China, found mean TSV of 1.38 during summer season which is slightly higher than mean summer results of this study (female dormitories mean TSV=1.1, male dormitories mean TSV=0.5). They also found that about 56% of subjects voted within comfort range which is lower than findings of this study except male dormitories during winter season.

Results of spearman correlation test (Table 4.2) of TSV of both genders in dormitories with T_a, T_{gt}, T_{op} and T_{mrt} showed strong influence of temperature on TSV and relatively weak influence of Rh_i on TSV.

Table 8.2: Spearman correlation coefficients between thermal sensation votes and recorded temperatures

	Thermal Sensation Votes of Females		**Thermal Sensation Votes of Males**	
	Correlation Coefficient	p-value	Correlation Coefficient	p-value
T_a	0.69	<0.001	0.74	<0.001
T_{gt}	0.73	<0.001	0.75	<0.001
T_{op}	0.73	<0.001	0.77	<0.001
T_{mrt}	0.73	<0.001	0.74	<0.001
Rh_i	0.40	<0.001	0.29	<0.001

Frequency distribution of humidity sensation votes (HSV) have been presented in Fig. 4.3 (b). It was observed that most of subjects during both seasons felt "neutral" (HSV= 0) humidity sensation. Similar findings were reported previously (Khalid et al., 2019), in a Malaysian study where more than 60% subjects voted for neutral HSV. However, in another study of India (S. Kumar et al., 2019a), majority of subjects voted towards humid side which could be due to higher outdoor humidity levels during the study period. Proportion of votes with an acceptable humidity sensation (i.e. HSV= +1, 0 and -1) accounts for 93.2 and 85.1% for females and 58.6 and 77.4% for males during summer and winter seasons respectively. Table 4.3 shows percentages of subjects voted within comfort range of HSV along with their corresponding Rh_i. Significant statistical difference ($p<0.05$) was found between females and males HSV during summer and winter seasons. Likewise, comparison of HSV between seasons (for combined data of females and males) was also significant ($p<0.05$). Mean HSV for females during summer and winter season was higher (0.2±0.8 and -0.1±0.9 respectively) than males (-0.2±1.6 and -0.3±1.2 respectively).

Table 8.3: Percentages of subjects voted within comfort range of humidity sensation and their respective indoor relative humidity in dormitories

	Humidity Sensation Vote (HSV)	**Females**		**Males**	
		Percentage	**Indoor Relative Humidity (%)**	**Percentage**	**Indoor Relative Humidity (%)**
Summer	Slightly Humid (HSV=+1)	32.8	67.3±8.2	22.3	71.0±10.2
	Neutral (HSV=0)	50.4	64.5±7.5	27.4	72.3±9.1
	Slightly Dry (HSV=-1)	10	63.6±8.3	8.8	69.2±11.4
Winter	Slightly Humid (HSV=+1)	13.2	45.8±6.2	8.3	61.2±14.0
	Neutral (HSV=0)	54.9	47.0±7.2	51.7	54.6±10.1
	Slightly Dry (HSV=-1)	16.5	46.6±6.8	17.4	58.3±9.8

Fig. 4.3 (c) shows frequency distribution of air speed sensation votes (ASV) for all subjects under study. It was observed that most of subjects voted for “neutral” (ASV= 0) air speed sensation, similar to HSV, during both seasons. Similar findings were reported in a previous study, (S. Kumar et al., 2019a) of comparable ambience during summer season. Proportion of votes with an acceptable air movement sensation (ASV= +1, 0 and -1) accounts for 82.8 and 81.9% for females and 71.2 and 87.4% for males during summer and winter seasons respectively. During summer season 36.0% females and 12.6% males felt “slightly breezy” (ASV= +1), 34.0% females and 43.7% males felt “neutral” (ASV= 0) and 10.0% females and 14.9% males felt “slightly stuffy” (ASV= -1) air speed sensation. However, during winter season 15.6% females and 6.5% males voted for “slightly breezy” (ASV= +1), 49.3% females and 62.2% males felt “neutral” (ASV= 0) and 15.9% females and 18.7% males felt “slightly stuffy” (ASV= -1) humidity sensation. No significant

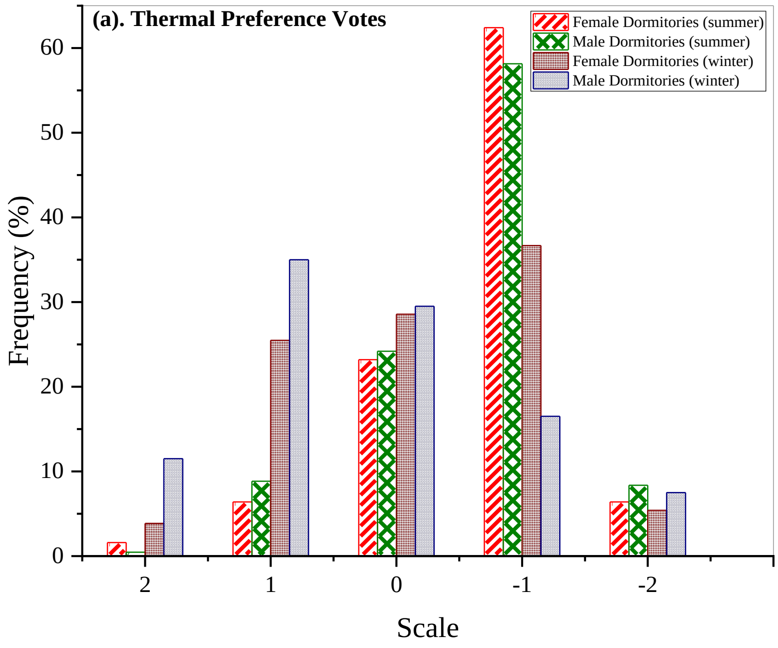
difference ($p>0.05$) in females and males ASV was found. However, comparison of ASV between seasons showed a significant difference ($p<0.05$) for combined data of both genders.

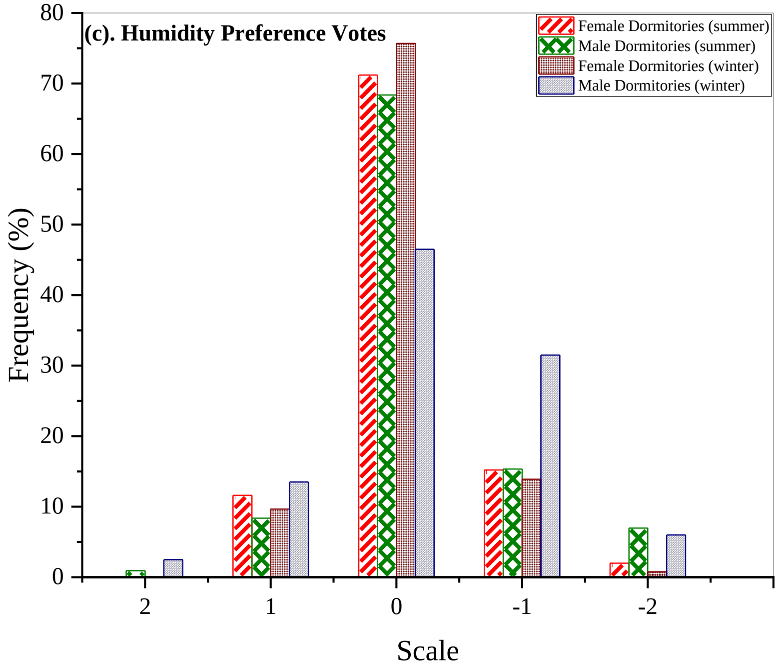
Some previously reported related studies (Karjalainen, 2007; Wang, 2006), found that females are more sensitive to hot and cold outdoor conditions in comparison to males. Cui et al., (Cui et al., 2013) worked on the influence of T_a on human thermal comfort and found significant difference in TSV values with changing temperature. However, Trebilcock et al., (Trebilcock et al., 2017) while working on adaptive thermal comfort in primary schools of Chile found that occupants adapt dramatically to changing outdoor condition with no effect of fluctuating temperature on mean TSV (Mean TSV=0). Xu et al., (Xu et al., 2018) while working on thermal comfort of traditional dwellings of Nanjing, China, showed 84.6% and 76.3% respondents voted within comfort range (i.e., TSV= -1 to +1) during summer and winter seasons respectively. Maykot et al., (Maykot et al., 2018b) found higher TSV for males in comparison to females in buildings with switched off air-conditioners and open windows and lower TSV for males in buildings with switched off air-conditioners and close windows.

In addition to sensation votes, subjects were asked to vote their preferences on ASHRAE five-point scale (Table 3.1). Frequency distribution of thermal preference votes (TPV), as depicted in Fig. 4.4(a) shows “a bit cooler” (TPV= -1) as a preferred thermal environment of majority of subjects except male subjects during winter season, who preferred “a bit warmer” (TPV= 1) thermal environment. Mean TPV during both seasons also corroborate this observation with values of -0.7 ± 0.8 for females and -0.6 ± 0.8 for males, during summer season and -0.1 ± 1.0 for females and 0.3 ± 1.1 for males, during winter season. The previous observation reported (Lu et al., 2016), on thermal comfort comparison between locals and tourists during early summers also vindicate this observation of “a bit cooler” thermal preference of majority of subjects. However, another study (Jin et al., 2020), focusing on thermal comfort of pedestrians in the streets of China during cold and transition seasons reported that females prefer higher temperatures to attain a thermally comfortable environment compared to males. Additionally, sensation votes were compared with the preference votes to further investigate the reasons of subjects’ thermal preferences. The one of the possible reasons of “a bit cooler” thermal preference of majority of subjects during summer season could be their “slightly warm” thermal sensation. Likewise, most of the male respondents during winter season felt “slightly cool” which could be a possible reason of “a bit warmer” thermal environment preference.

Frequency distribution of humidity preference votes (HPV), given in Fig. 4.4(b), shows a “neutral” (HPV= 0) humidity as preference of majority of respondents during both seasons. Mean values of HPV during summer season were -0.08±0.59 and -0.19±0.72 for female and male respondents respectively. However, during winter mean levels were -0.1±0.5 and -0.2±0.9 for females and males respectively. Results presented in Fig. 4.4 (b) imply that most of the subjects are satisfied with their Rh_i.

The results of air speed preference votes (APV), shown in Fig. 4.4 (c) indicate that most of female subjects during both seasons and male subjects during summer season preferred “a bit more air movement” (APV= 1) environment. The mean APV of 0.5±1.0 and 0.9±0.9 for female and male respondents during summer season respectively and of 0.4±1.0 for female respondents during winter season were calculated. However, male subjects during winter season preferred “neutral” (APV= 0) air speed with mean APV 0.02±0.9 as shown in Fig. 4.4 (c). Results given in Fig. 4.3 (c) and 4.4 (c) can be interpreted as male subjects during winter season were satisfied with their existing thermal environment as their ASV and APV were same, i.e., “neutral”. However, all female subjects and male subjects during summer season perceived less air speed than desired due to dissatisfaction with prevailing conditions.


(a). Thermal Preference Votes
Female Dormitories (summer)
Male Dormitories (summer)
Female Dormitories (winter)
Male Dormitories (winter)
Frequency (%)
0
10
20
30
40
50
60
2
1
0
-1
-2
Scale


(c). Humidity Preference Votes
Female Dormitories (summer)
Male Dormitories (summer)
Female Dormitories (winter)
Male Dormitories (winter)
Frequency (%)
0
10
20
30
40
50
60
70
80
2
1
0
-1
-2
Scale

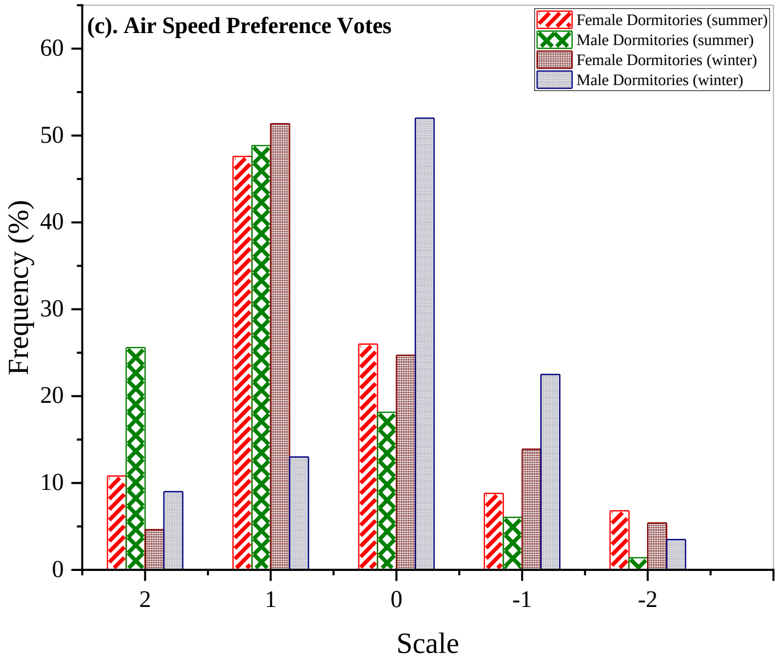


Fig. 8.4: Frequency distribution of thermal (a), humidity (b) and air speed (c) preference votes in dormitories

(b). Thermal Evaluation in Offices

Evaluation of subjective responses from all five modes of offices under study is presented below;

Thermal Sensation and Preference Votes

Frequency distribution of TSV and TPV on ASHRAE seven-point and five-point scales respectively for all ventilation modes in offices under study is given in Fig. 4.5.

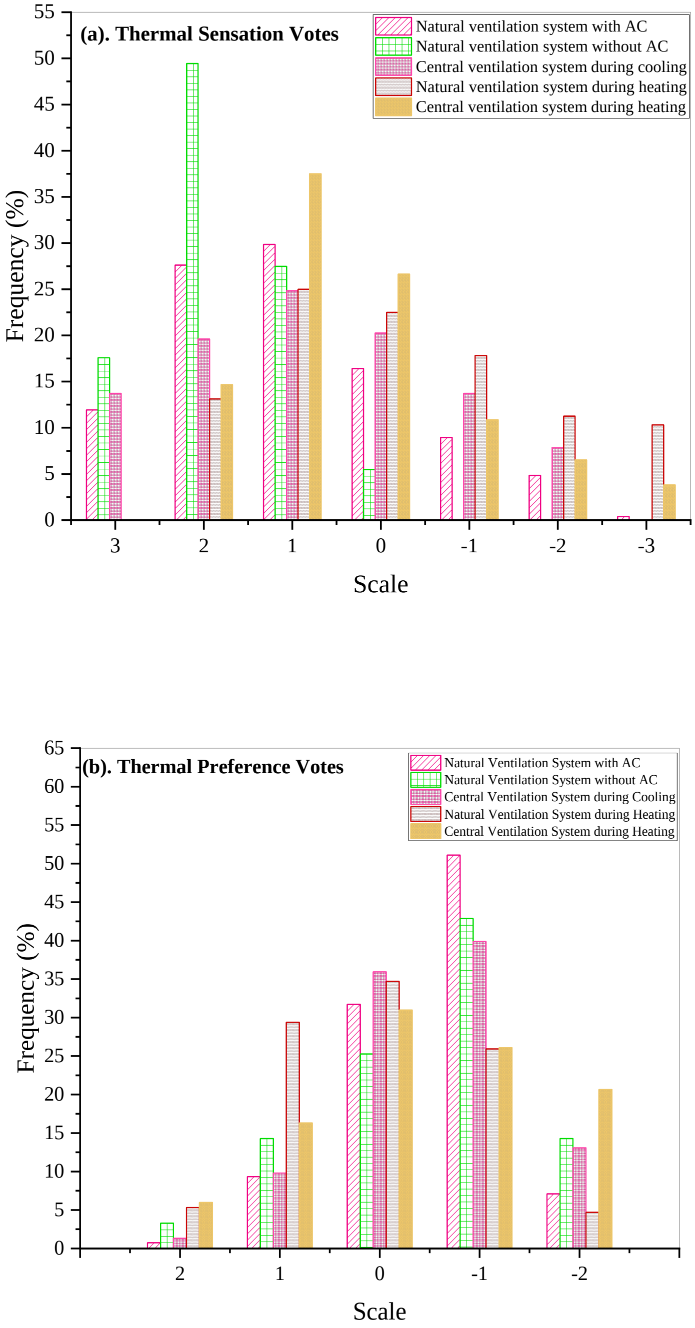


Fig. 8.5: Frequency distribution of (a) thermal sensation, (b) thermal preference votes in offices

Frequency distribution of TSV for all the five ventilation modes is depicted in Fig. 4.5 (a). It was observed that due to extreme outdoor conditions, thermal sensation of majority subjects in summer modes (N_{ACon}, N_{ACoff} and CS_C) was inclined towards the warmer side. Likewise, due to substantially higher clo levels, presence of portable heaters in N_H mode and operational central heating system in CS_H mode, thermal sensation of majority was slightly warm during winter season. Moreover, mean and standard deviation of TSV (Table 4.4) for all modes were positive which again shows more inclination of the occupant's thermal sensation towards the warmer side. Besides, comparison of TSV between natural and central ventilation system was also made. Difference between NACon and CSC, NACoff and CSC and NH and CSH modes was analyzed using chi-square test and ANOVA. Results showed significant difference ($p<0.05$) between the two ventilation systems with less responses of subjects in central ventilation system on warmer side during summer and cooler side during winter seasons. Maykot et al., (Maykot et al., 2018b) reported similar observations during their thermal comfort assessment in three offices buildings operated under different types of ventilation. Thus, it can be concluded as subjects in central ventilation system were more satisfied with their thermal environment than subjects in natural ventilation system. Furthermore, hottest and coolest modes during summer and winter seasons respectively were also naturally ventilated (N_{ACoff} during summer and N_H during winter). Highest mean TSV was also found in N_{ACoff} (TSV_{mean} = 1.79 ± 0.8) and in the order $N_{ACoff} > N_{ACon} > CS_C > CS_H > N_H$.

Table 8.4: Statistics of subjective responses for all the five modes under study

Mode	**N_{ACon}**		**N_{ACoff}**		**CS_C**		**N_H**		**CS_H**	
N	**268**		**91**		**153**		**320**		**184**	
	Mean	**Stdev**	**Mean**	**Stdev**	**Mean**	**Stdev**	**Mean**	**Stdev**	**Mean**	**Stdev**
TSV	1.01	1.33	1.79	0.80	0.76	1.47	0.20	1.52	0.32	1.26
TPV	-0.54	0.79	-0.51	1.02	-0.54	0.89	0.04	0.98	-0.39	1.16
HSV	0.55	0.95	0.38	1.22	0.47	1.00	0.04	1.30	-0.55	1.62
HPV	-0.21	0.70	-0.22	1.01	-0.22	0.80	-0.17	0.76	-0.03	1.02
AMV	0.00	1.23	-0.27	1.00	-0.22	1.11	-0.14	1.23	-0.66	1.35
APV	0.29	0.94	0.57	1.18	0.25	0.94	0.01	0.91	0.20	1.28

Furthermore, percentage of subjects responded within comfort zone i.e., TSV= +1 to -1, in all modes under study along with their respective indoor temperature levels were also assessed and is presented in Table 4.5. Results of proportion of votes, when the three scale points of comfort zone (TSV= -1, 0 and +1) were put together, showed that majority of subjects were comfortable with their indoor temperature (proportion of votes within comfort zone ≥50%) except subjects in N_H mode (proportion of votes within comfort zone = 29.04%). The results are comparable with previously reported studies. Indraganti et al. (Indraganti et al., 2015) found 80% of subjects' votes within comfort range i.e. TSV=±1 while investigating thermal comfort in offices of India for 14 months long survey period. In another study of comparable ambience, Jindal 2018 found 90.6 and 97% subject responses within comfort zone during winter and monsoon seasons respectively. Results exhibit that subjects adapt to the changing outdoor climatic conditions by practicing different adaptive measures.

Table 8.5: Proportion of subjects who voted within comfort range of thermal sensations and their respective indoor air temperatures in offices

Mode	**Subjective Responses**			**TSV**					
	Total	**Male**	**Female**	**Slightly Warm (TSV=+1)**		**Neutral (TSV=0)**		**Slightly Cool (TSV= -1)**	
				%age	**Indoor Air Temperature (ºC)**	**%age**	**Indoor Air Temperature (ºC)**	**%age**	**Indoor Air Temperature (ºC)**
N_{ACon}	268	182	86	26.12	29.6±1.24	14.93	28.0±1.68	8.96	27.03±1.12
N_{ACoff}	91	75	16	25.81	29.34±0.71	3.23	27.98±1.8	0	-
CS_C	153	93	60	24.84	27.62±1.27	20.26	26.88±1.04	13.73	25.66±1.57
N_H	320	247	73	25.00	18.76±1.12	22.5	18.58±1.09	17.81	17.7±1.36
CS_H	184	110	74	37.50	20.05±1.86	26.63	19.48±1.66	10.87	17.96±0.90

Besides, spearman correlation test was also executed to check the influence of change in T_a, T_{gt}, T_{op}, T_{mrt} and Rh_i levels on TSV in all modes under study. Results (Table 4.6) depicted strong correlation of all the temperature values and comparatively less correlation of Rh_i levels. Asif et al., (Asif et al., 2022) reported similar findings while working on naturally ventilated dormitories.

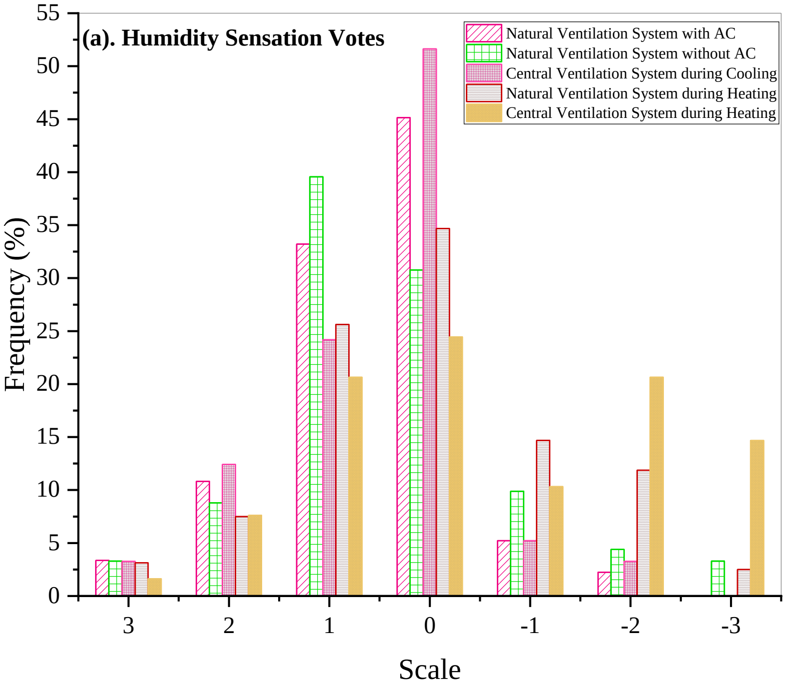
Table 8.6: Spearman correlation coefficients between thermal sensation votes and recorded temperatures and indoor relative humidity levels in offices

	N_{ACon}		**N_{ACoff}**		**CS_C**		**N_H**		**CS_H**	
	Coefficient	p-value	Coefficient	p-value	Coefficient	p-value	Coefficient	p-value	Coefficient	p-value
T_a	0.70	<0.001	0.58	<0.001	0.73	<0.001	0.42	<0.001	0.57	<0.001
T_{gt}	0.70	<0.001	0.61	<0.001	0.78	<0.001	0.39	<0.001	0.57	<0.001
T_{op}	0.71	<0.001	0.55	<0.001	0.79	<0.001	0.44	<0.001	0.57	<0.001
T_{mrt}	0.72	<0.001	0.61	<0.001	0.78	<0.001	0.44	<0.001	0.57	<0.001
Rh_i	0.14	<0.001	0.08	<0.001	0.06	<0.001	0.08	<0.001	0.05	<0.001

Frequency distribution of TPV for all modes under study is exhibited in Fig. 4.5 (b). Graphical representation can be interpreted as majority of subjects preferred slightly cool (TPV= -1) thermal environment during summer season (N_{ACon} : 51%, N_{ACoff} : 43% and CS_C : 40%) and neutral (TPV= 0) thermal environment during winter season (N_H = 35%, CS_H = 31%). Rijal el al., (Rijal et al., 2010) uncovered comparable observations in their study of seasonal differences in thermal comfort of Nepalese houses. The results were reported as subjects prefer "warmer" thermal environment during winter season and vice versa. Results of TPV when data of all modes was assessed together (Fig. 4.5b) showed about 49% of respondents desiring a cooler thermal environment and only 19%, warmer environment for all modes under study. Mean and standard deviation of TPV for all modes as given in Table 4.4 which also seconds this observation. The findings are comparable with previously published studies (S. Kumar et al., 2019a). Mean TPV is found in the order $N_H > CS_H > N_{ACoff} > N_{ACon} = CS_c$.

Humidity Sensation and Preference Votes

Frequency distribution of HSV and HPV are exhibited in Fig. 4.6. In all modes under study HSV (Fig. 4.6(a)) and HPV (Fig. 4.6(b)) of majority was found neutral (HSV= 0) except N_{ACoff} mode where majority felt slight humidity (HSV= +1) in their indoor environment. Thapa et al., (Thapa, Bansal, Panda, et al., 2018) focused on adaptive thermal comfort in different buildings of east India and reported similar findings during winter season..



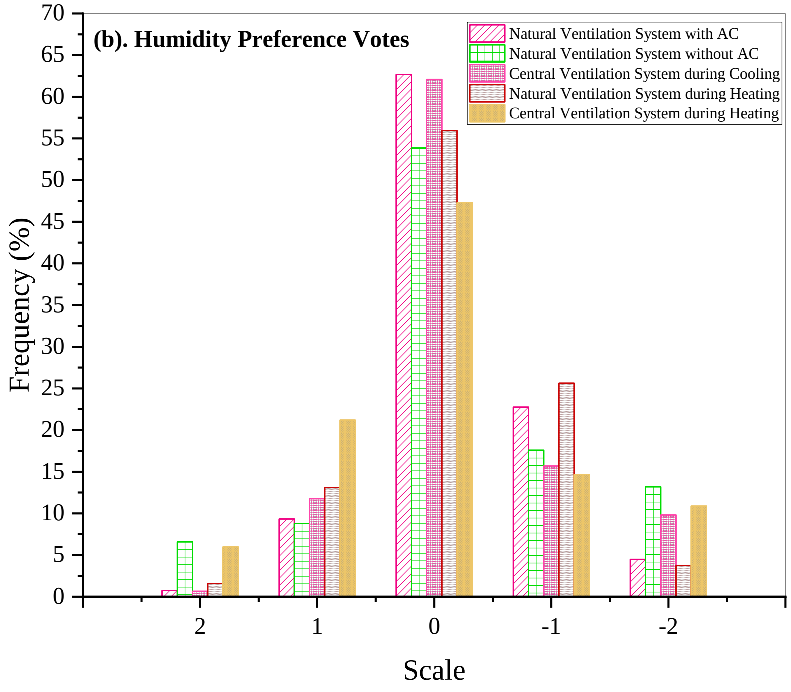


Fig. 8.6: Frequency distribution of (a) humidity sensation and (b) preference votes in offices

Like TSV, proportion of HSV within comfort zone (HSV= -1 to +1) were also accessed and is presented in Table 4.6. It was notes that majority of the subjects' responses in all modes under study were within the comfort range. Thus, from Fig. 4.6 and Table 4.7 it can be concluded as majority of the subjects were satisfied with their indoor humidity levels. Furthermore, comparison of HSV among different modes of ventilation showed less responses of subjects towards humid side in the two mechanical ventilation modes (CS_C and CS_H). Mean and standard deviation of HSV for all modes has been summarized in Table 3.8. Mean HSV when the data of all modes was analyzed together was 0.16 ± 1.3 and was in the order $N_{ACon} > CS_C > N_{ACoff} > N_H > CS_H$. Moreover, mean HPV of all the subjects under study was 0.17 ± 0.83 and was in the order $CS_H > N_H > N_{ACon} > N_{ACoff} = CS_C$.

Table 8.7: Proportion of subjects voted within comfort range of humidity sensation and their respective indoor relative humidity in offices

Mode	Subjective Responses			HSV					
	Total	Male	Female	Slightly Humid (HSV= +1)		Neutral (HSV=0)		Slightly Dry (HSV= -1)	
				%age	Indoor Relative Humidity (%)	%age	Indoor Relative Humidity (%)	%age	Indoor Relative Humidity (%)
N_{ACon}	268	182	86	31.34	52.56±11.43	42.91	52.28±12.32	4.85	54.18±12.65
N_{ACoff}	91	75	16	39.5604	67.53±7.84	30.77	62.09±11.57	9.68	72.92±5.04
CS_C	153	93	60	24.18	53.43±12.97	51.63	55.83±13.62	5.23	46.01±11.24
N_H	320	247	73	25.63	56.00±15.47	34.69	56.66±16.61	14.69	58.38±14.27
CS_H	184	110	74	20.65	48.13±5.40	24.46	52.39±8.76	10.33	55.78±12.73

Air Speed Sensation and Preference Votes

Similar to HSV, AMV of majority subjects in all five modes was neutral and is presented in Fig. 4.7(a). Moreover, it was observed that most of the subjects preferred “neutral” air speed during winter and “a bit more air movement” during summer season (Fig. 4.7(b)).

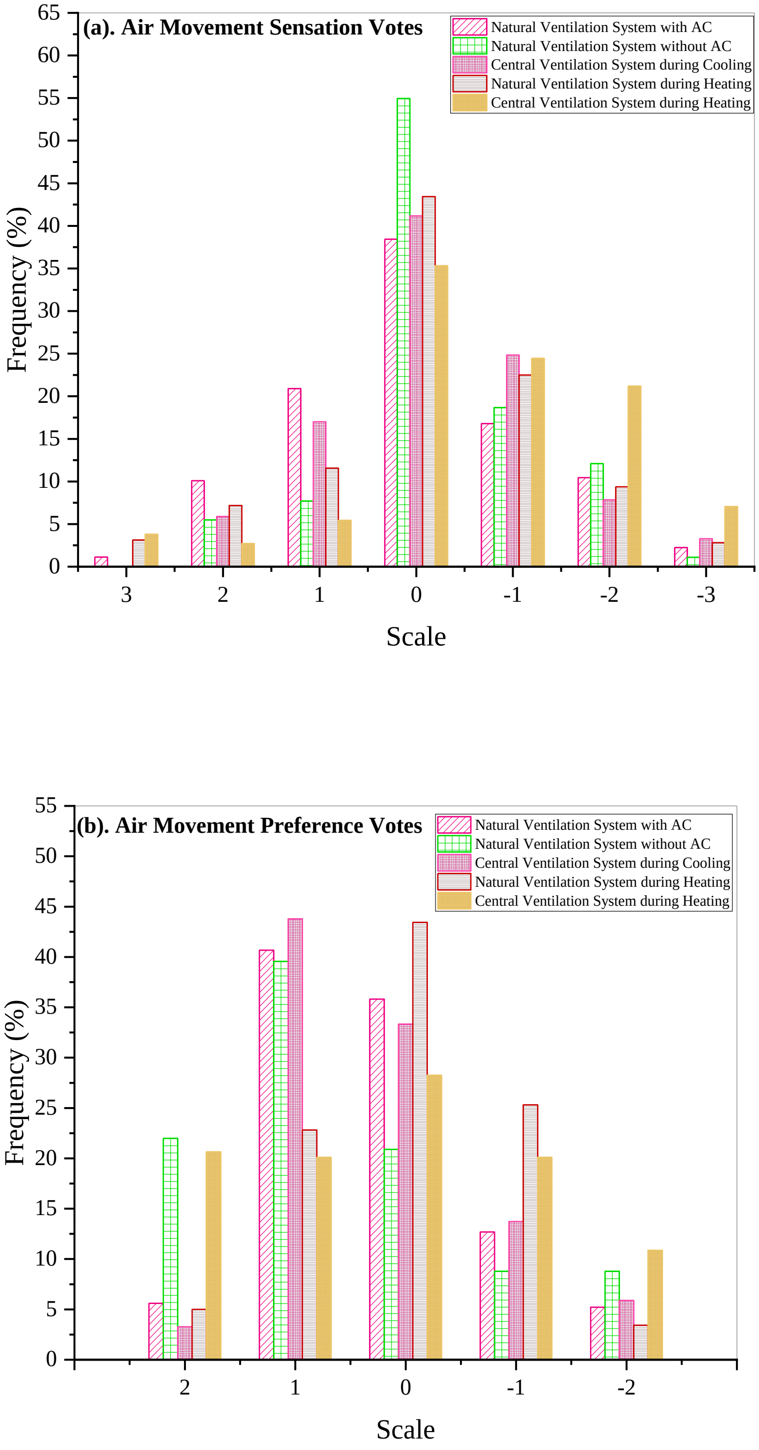


Fig. 8.7: Frequency distribution of (a) air movement sensation and (b) preference votes in offices

On comparing AMV of all modes, it was observed that most subjects (71%) in the offices of N_{ACon} mode felt sensations from neutral to breezy (Fig. 4.7). However, AMV of subjects in all other four modes (N_{ACoff}, CS_C, N_H and CS_H) were inclined from neutral to stuffy side (87, 77, 78 and 88% respectively). Mean and standard deviation of AMV of all modes under study is given in Table 4.4 which again shows inclination towards neutral side of sensation scale. Order of mean AMV of all five modes is $N_{ACon} > N_H > CS_C > N_{ACoff} > CS_H$. Moreover, order of mean APV of all modes under study is $N_{ACoff} > N_{ACon} > CS_C > CS_H > N_H$

4.1.1.3. Clothing Insulation and Metabolic Activity

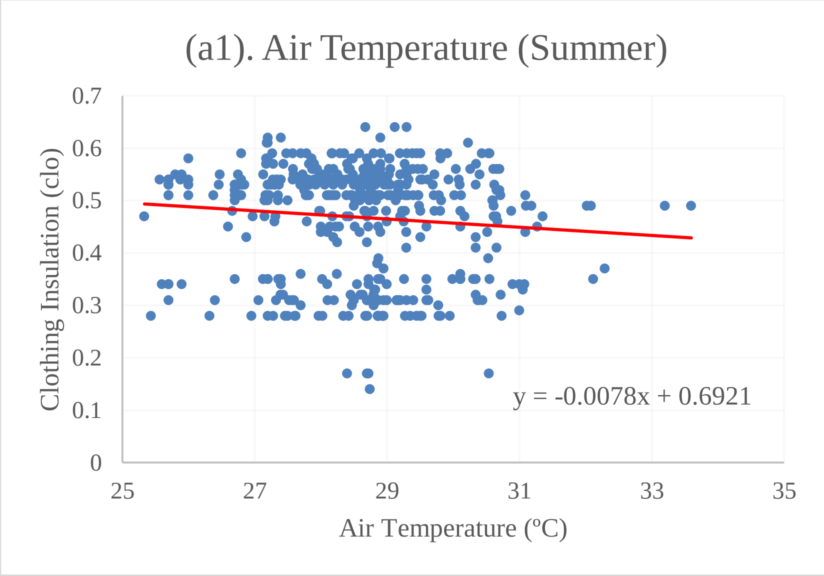
As mentioned earlier (Section 3.1.2), clo levels of traditional Pakistani dresses are not included in ASHRAE 55-2013 (ASHRAE Standard 55-2s010, 1979) which are adopted from previously reported studies (Nicol et al., 1999; Tanabe, 1997). Additionally, in dormitories majority of the subjects were found either sitting or inclining on the bed. During winter season, subjects were also found inclining in their blankets or quilts which also provide thermal insulation. Therefore, these factors were assessed through survey and clo values of bedding i.e. blanket, quilt, bed sheet etc. were calculated accordingly as reported previously (Lin & Deng, 2008). Clothing levels during winter were observed higher in comparison to summers which are in consonance with previous studies (Jiao et al., 2017). Moreover, it was found that the traditional female dress in Pakistan include dopatta (a long piece of cloth for covering head) in addition to shalwar-kameez. Due to this reason females clothing levels were found higher than males. Mean clothing levels during summer season in dormitories were observed as 0.50±0.09 clo for females and 0.45±0.12 clo for males. Moreover, mean clothing levels in offices during summer season were noted as 0.53±0.08, 0.49±0.09 and 0.52±0.07 clo in N_{ACon}, N_{ACoff} and CS_C modes respectively. However, occupants mostly adapt their thermal environment during winter season with increased clothing resulting in higher clo values with mean levels as 2.30±0.5 and 1.70±0.60 for female and males respectively. Similar results were observed in offices with mean clo as 1.2±0.25 and 1.13±0.21 for N_H and CS_H modes respectively. Moreover, results were in agreement with some previously reported Pakistani (Nicol et al., 1999; Mahar and Attia, 2018), and Indian studies (Jindal, 2018)with more or less similar outdoor conditions.

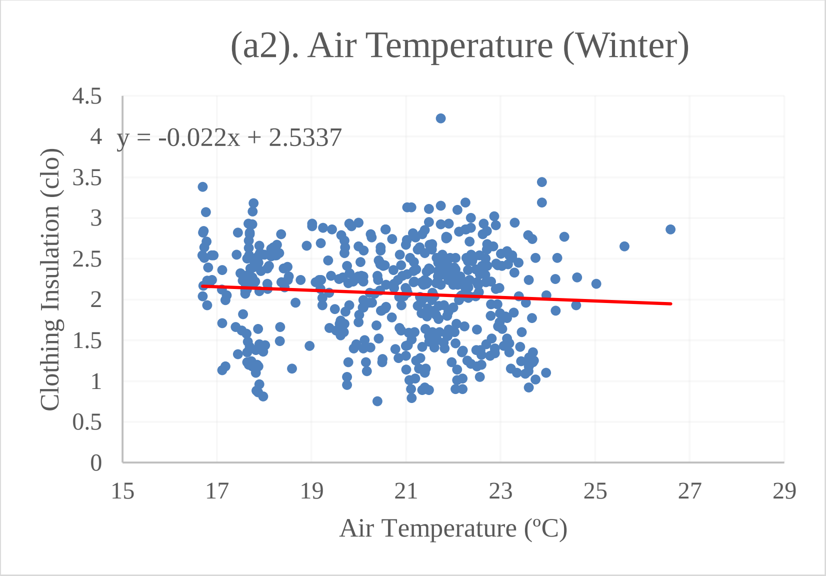
Results of linear regression analysis of clo with T_o, T_{op} and T_a for both seasons in dormitories and offices are depicted in Fig. 4.8 and Fig. 4.9 respectively while combined results are shown in Fig. 4.10. As slope of regression equations for all the cases were negative thus, clo levels were observed decreasing with the increase in T_o, T_a and T_{op}. Similar observations were reported by previously reported studies (Heidari and Sharples, 2002; Kumar et al., 2019). Furthermore, strong correlation of clo with T_a, T_{op} and T_o, was observed with R^2 values >0.5 for all cases on combined data of dormitories and offices. However, it was found that R^2 value between varied 0.57-0.75. The possible reason for this could be differences in min and max levels of temperature as provided in Table 4.8.

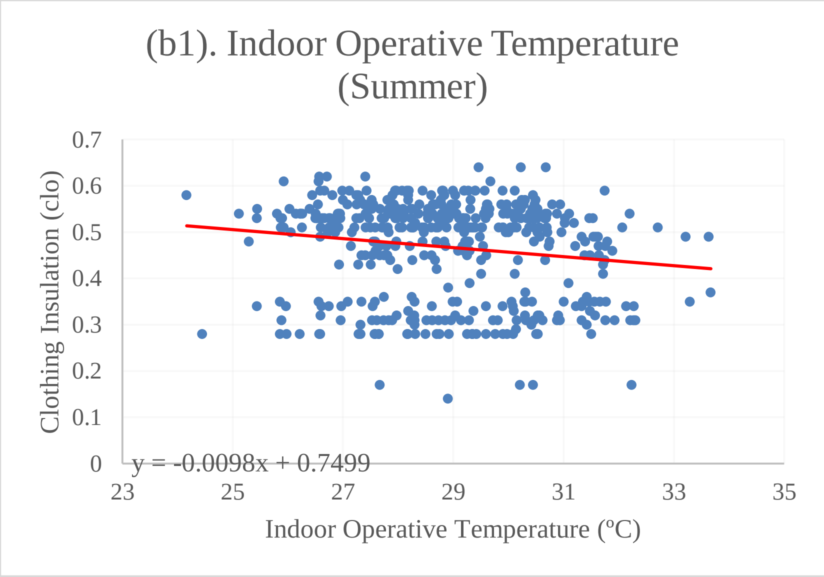
Table 4.8: Variation of R^2 values with temperature changes

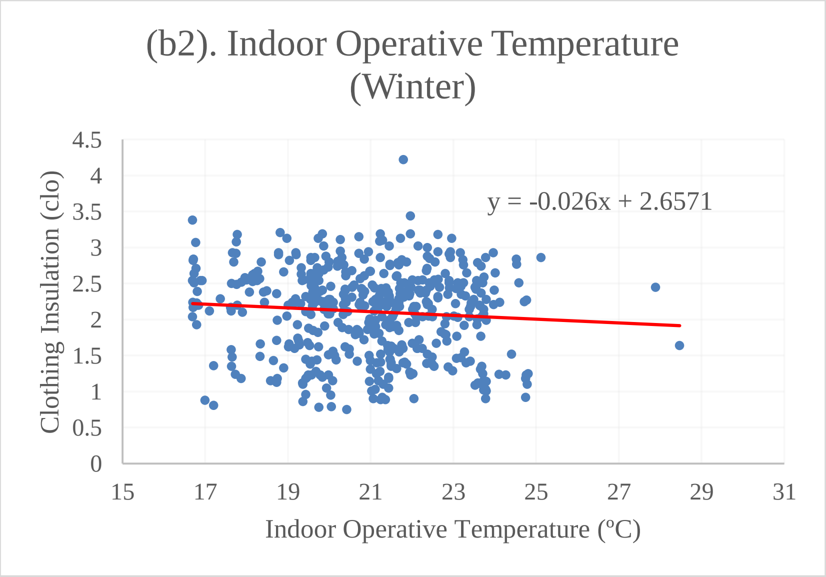
Sr. No.	Location	Variable	Range	R^2 Value
1	Dormitories	T_a	16.7-33.6°C	0.57
2		T_{op}	16.69-33.6°C	0.57
3		T_o	5.5-30.6°C	0.71
4	Offices	T_a	14.1-35.6°C	0.70
5		T_{op}	14.09-34.8°C	0.67
6		T_o	9.6-33.2°C	0.75

Further analysis was performed on season wise segregated data where R^2 values were found low (R^2<0.5) which could also be explained in terms of less temperature difference in seasonal data. Similar observations on seasonal data were reported in relevant studies (Xu et al., 2018; Imagawa and Rijal, 2015). Linear equations for each case are presented on their respective graphs (Fig. 4.8, Fig. 4.9 and Fig. 4.10).


(a1). Air Temperature (Summer)


(a2). Air Temperature (Winter)


(b1). Indoor Operative Temperature (Summer)


(b2). Indoor Operative Temperature (Winter)

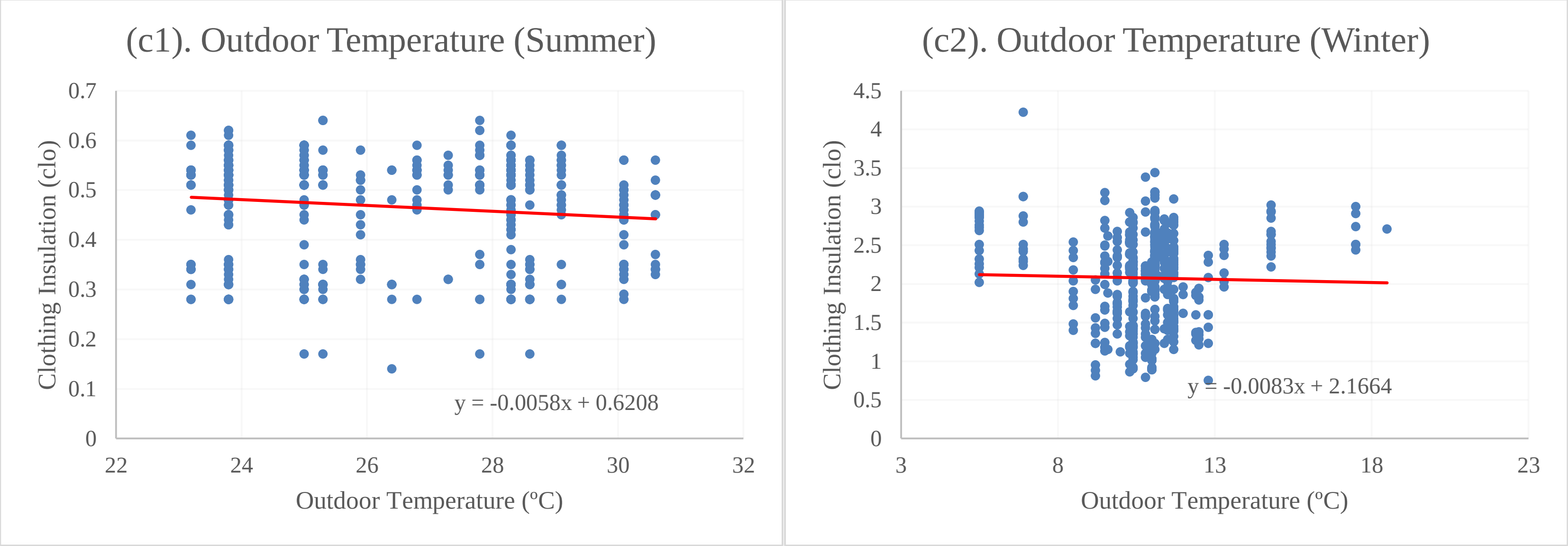
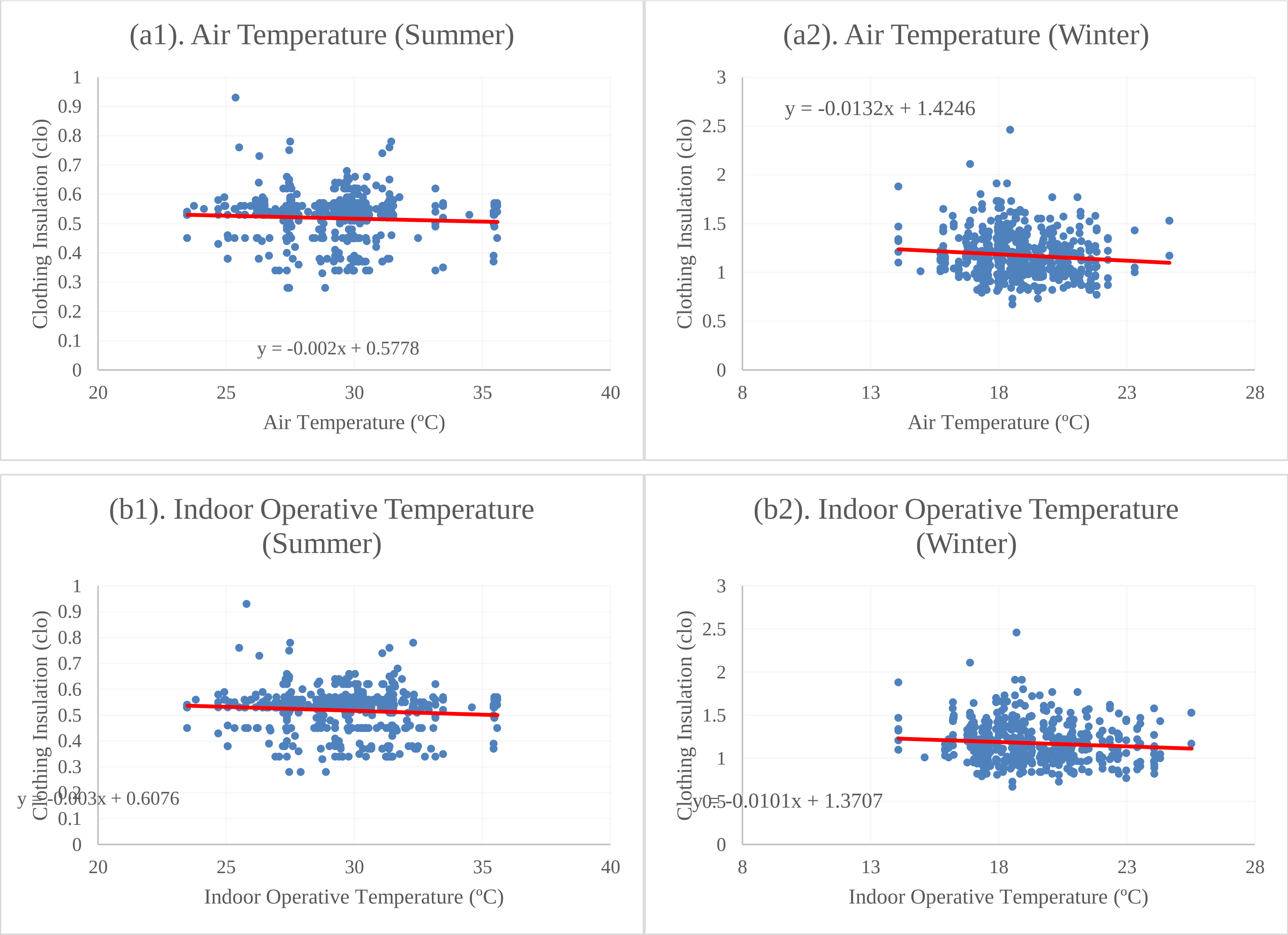


Fig. 8.8: Correlation of clo with (a1). indoor air (summer), (a2). indoor air (winter), (b1). indoor operative (summer), (b2). indoor operative (winter), (c1) outdoor (summer) and (c2) outdoor (winter) temperatures in dormitories


(a1). Air Temperature (Summer)
Clothing Insulation (clo)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
y = -0.002x + 0.5778
20
25
30
35
40
Air Temperature (ºC)
(a2). Air Temperature (Winter)
Clothing Insulation (clo)
3
2.5
2
1.5
1
0.5
0
y = -0.0132x + 1.4246
8
13
18
23
28
Air Temperature (ºC)
(b1). Indoor Operative Temperature (Summer)
Clothing Insulation (clo)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
y = -0.003x + 0.6076
20
25
30
35
40
Indoor Operative Temperature (ºC)
(b2). Indoor Operative Temperature (Winter)
Clothing Insulation (clo)
3
2.5
2
1.5
1
0.5
0
y = -0.0101x + 1.3707
8
13
18
23
28
Indoor Operative Temperature (ºC)

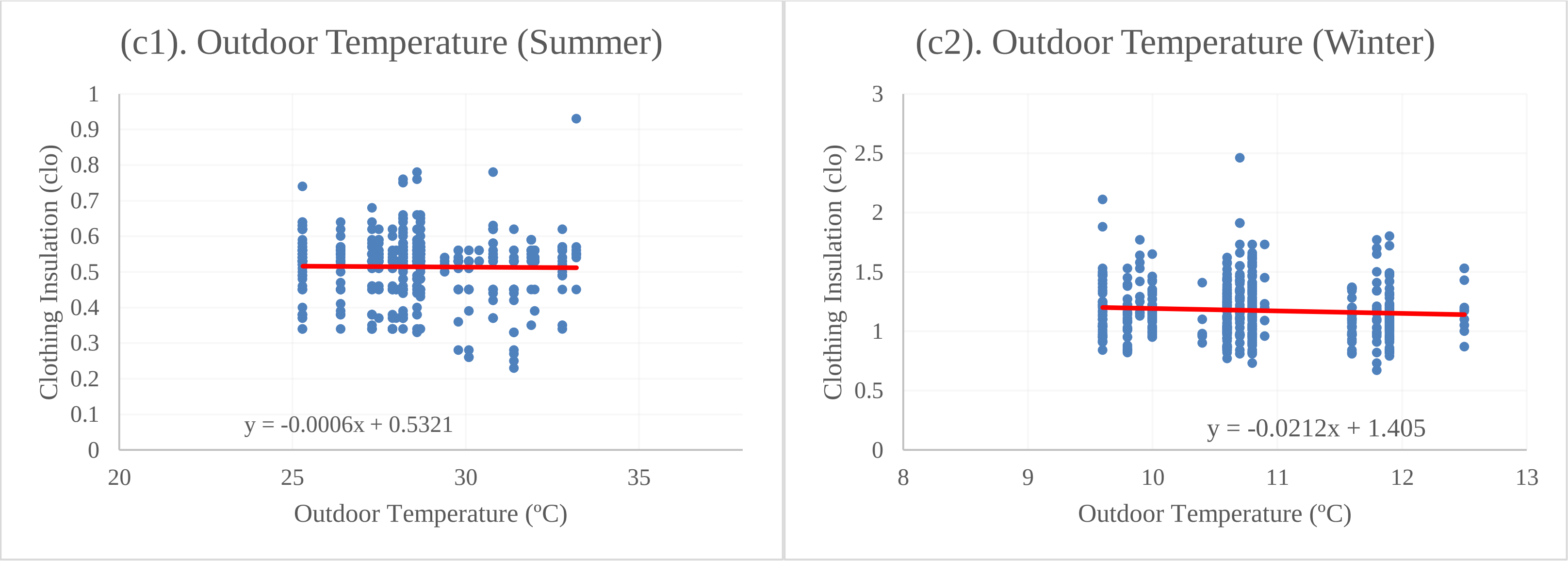
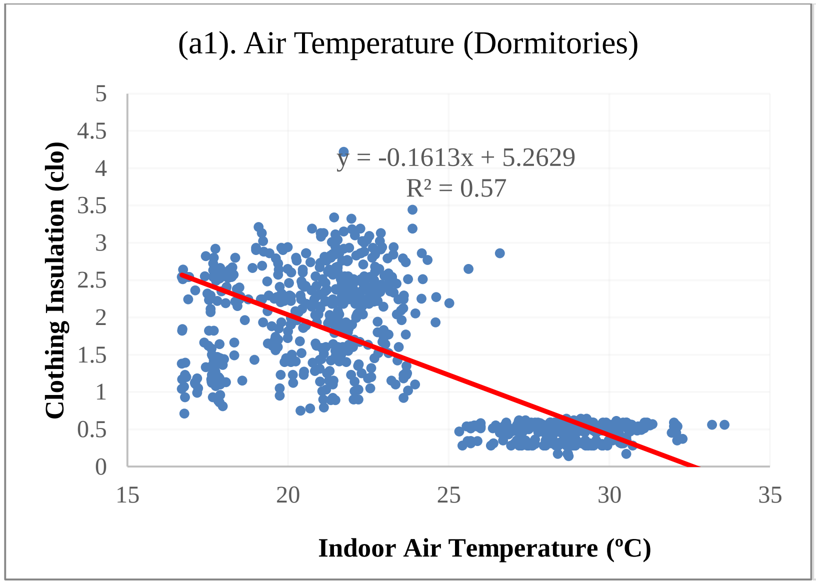
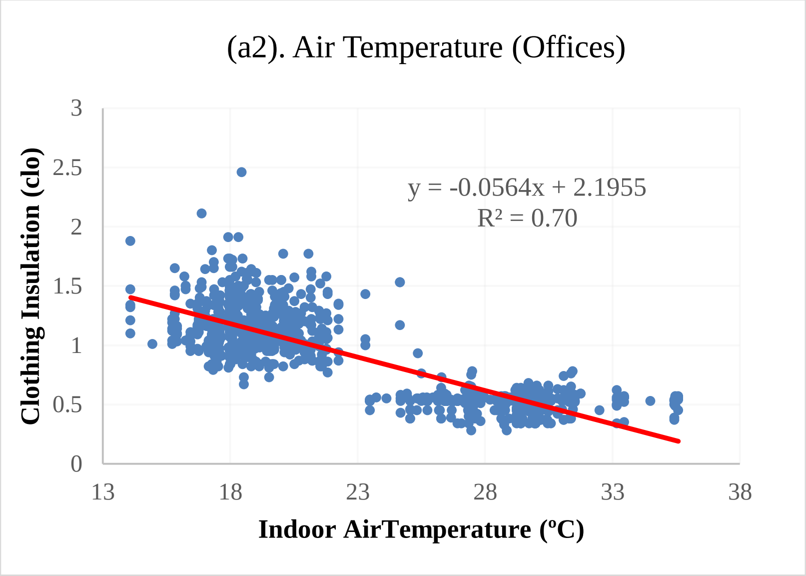
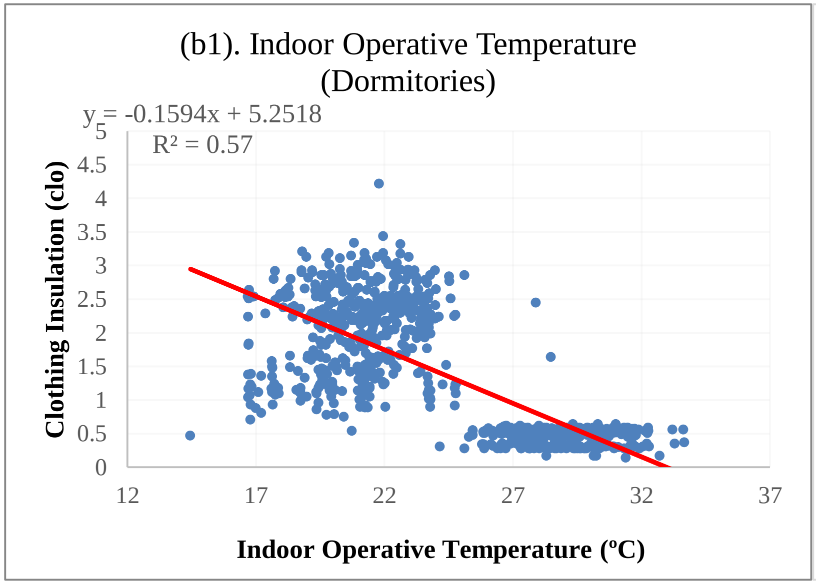
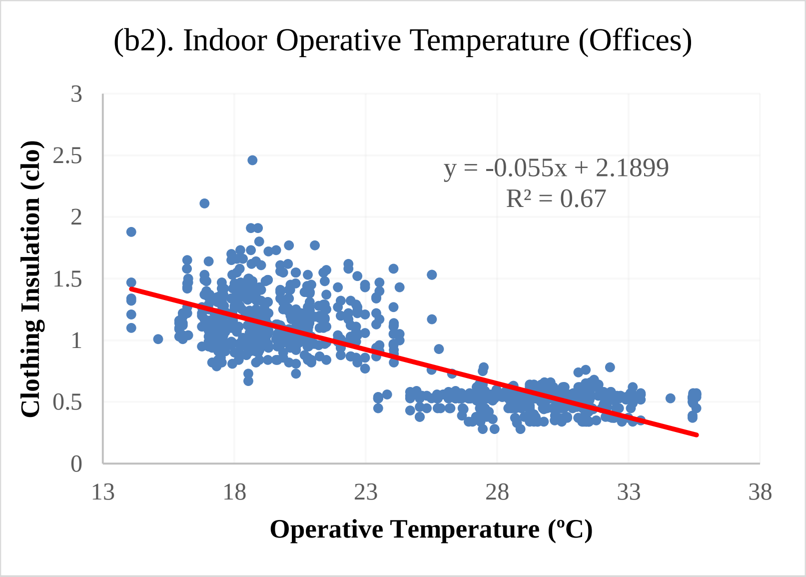


Fig. 8.9: Correlation of clo with (a1). indoor air (summer), (a2). indoor air (winter), (b1). indoor operative (summer), (b2). indoor operative (winter), (c1) outdoor (summer) and (c2) outdoor (winter) temperatures in offices


(a1). Air Temperature (Dormitories)


(a2). Air Temperature (Offices)


(b1). Indoor Operative Temperature (Dormitories)


(b2). Indoor Operative Temperature (Offices)

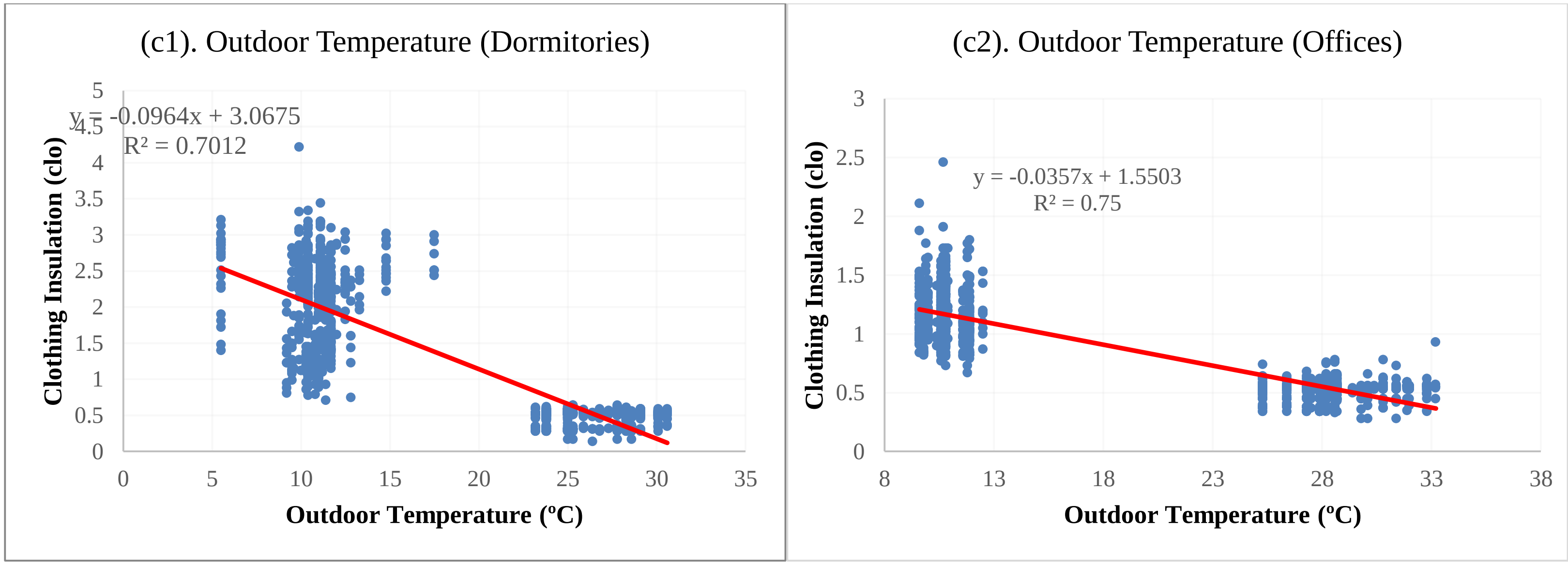


Fig. 8.10: Correlation of clo with indoor air (dormitories) (a1), indoor air (offices) (a2), indoor operative (dormitories) (b1), indoor operative (offices) (b2), outdoor (dormitories) (c1) and outdoor (offices) (c2) temperatures

4.1.2. Comfort Temperature

Comfort temperature is delineated as temperature in which maximum number of occupants enjoy a comfortable thermal indoor environment. In general, two methods are in practice by thermal comfort researchers: linear regression method and Griffths method. Below subsections present detailed description, analysis and results of the above-mentioned methods in dormitories (for both genders) and offices (for all five modes under study).

4.1.2.1. Linear Regression Method

Indoor Tc for both genders in dormitories and for all five modes of ventilation in offices were estimated using linear regression method. The procedure included plotting TSV against Top, and then regressing it linearly. Afterwards Tc was estimated by putting TSV= 0 in respective linear equations. The detailed results are presented below.

(a). Dormitories

Scatter plots of TSV against T_{op} for both genders during summer and winter seasons are presented in Fig. 4.11. It was noticed that the calculated T_c for female dormitories were lower (26.4°C) in comparison to males (27.8ºC) during summer season. The observation have been compared with previously reported studies of comparable ambience. Z. Wu et al., 2019 et l. reported an indoor operative T_c of 26.2 ºC under similar summer conditions using linear regression method which is comparable to the findings of this study. In another study focusing on naturally ventilated hostels in India found T_c of 30.15ºC during their monitoring from August to November which is higher than the observations of current study (Dhaka et al., 2013). Similarly, Indraganti et al (2014) collected the data for 14 months in offices under hot and humid climate of Chennai and Hyderabad (Indraganti et al., 2014) and reported T_c of 27.3 ºC which is also close to current observations Similarly (Indraganti & Boussaa, 2017) investigated T_c and adaptive behaviors in the offices of Qatar during summer season and reported T_c as 24.5ºC which is relatively lower than results of present study. Moreover, during winters, calculated T_c were 22.7

for females and 22.4 ºC for males which are comparable. Lan et al., (Lan et al., 2008) reported similar observation comparable T_c for both genders. A slightly higher T_c for females (21.9ºC) in comparison to males (20.9ºC) was reported by Wang et al (Z. Wang, 2006). Likewise, Al-Rashidi et al., while working on thermal comfort in Kawait classrooms during winter season (Al-Rashidi et al., 2009) calculated T_c for females (22ºC) 1ºC higher than males (21ºC). Liang et al., (Liang et al., 2012) worked on thermal perceptions in naturally ventilated school buildings and observed T_c of 26.5, 23.1 and 22.4ºC for the months of November, December and January respectively. Besides, comfort bandwidth was also estimated for both genders during summer and winter season using TSV=±1 in respective regression equations. Results showed comfort bandwidth of 24.1-28.8ºC and 20.7-24.6ºC for females and 26.0-29.5ºC and 20.3-24.4ºC for males during summer and winter seasons, respectively. Slopes of equations (Fig. 4.11) are 0.42, 0.58, 0.51 and 0.48 for female and male respondents during summer and female and male respondents during winter season respectively, therefore an increase of 2.4, 1.8, 2 and 2.1 respectively in T_{op} will increase TSV by one unit. Kumar et al., (S. Kumar et al., 2019a) found slope of 0.34 during investigation in Indian hostel building during monsoon season. Likewise, Dahlan et al., (Nur Dalilah Dahlan, Phil Jones, D.K. Alexander, Elias Salleh, 2008) investigated high rise Malaysian hostel buildings during summer season and found slope of 0.42. Slopes of linear equations of present study were found higher than other previously reported studies focusing on gender based thermal comfort (Z. Wang, 2006), reflecting less adaptation of subjects with outdoor changing conditions.

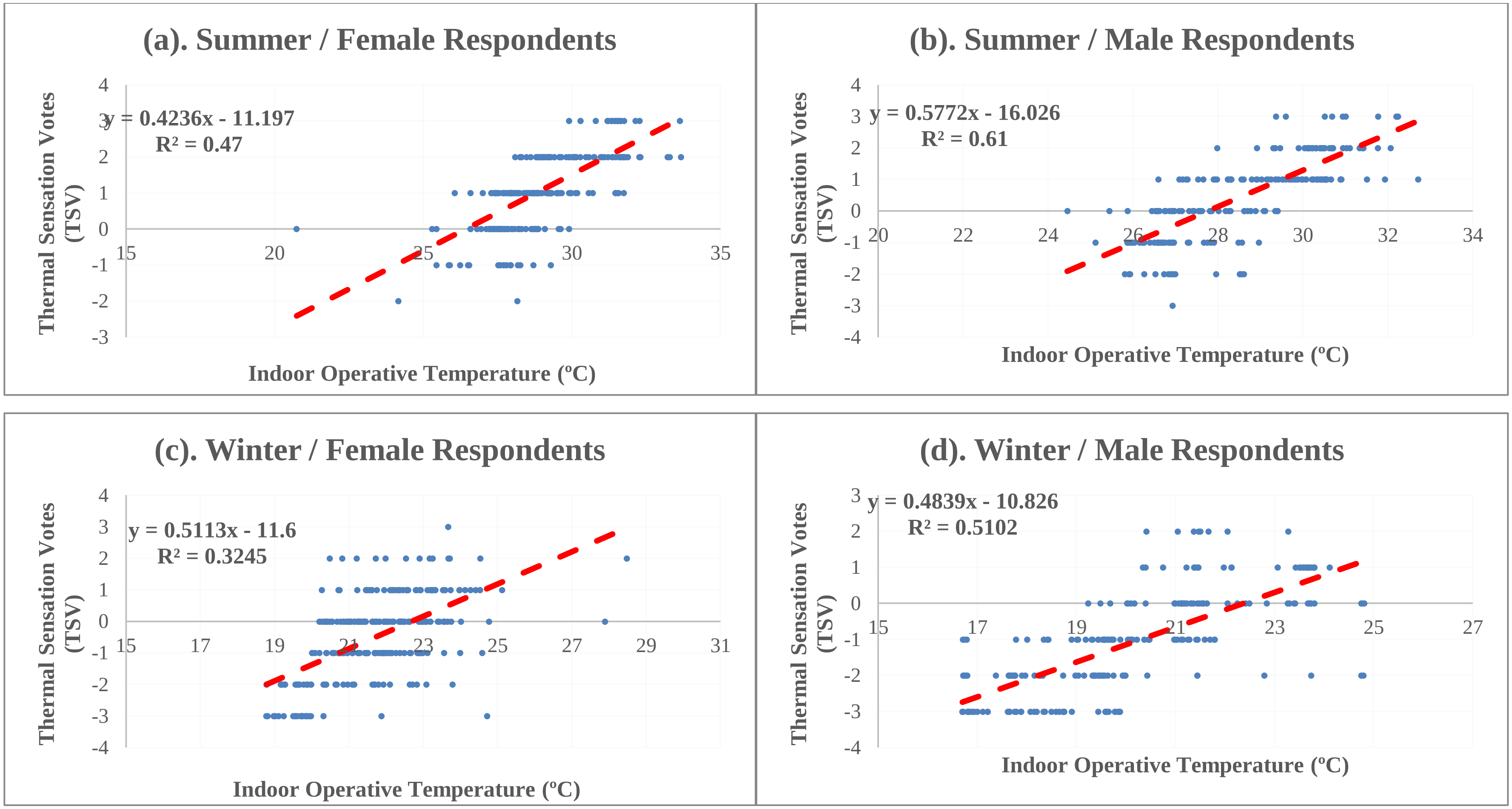
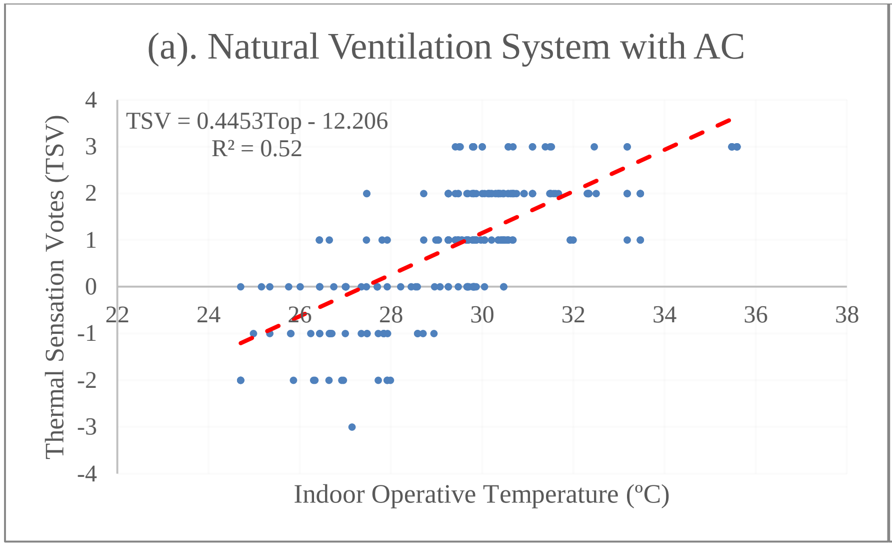
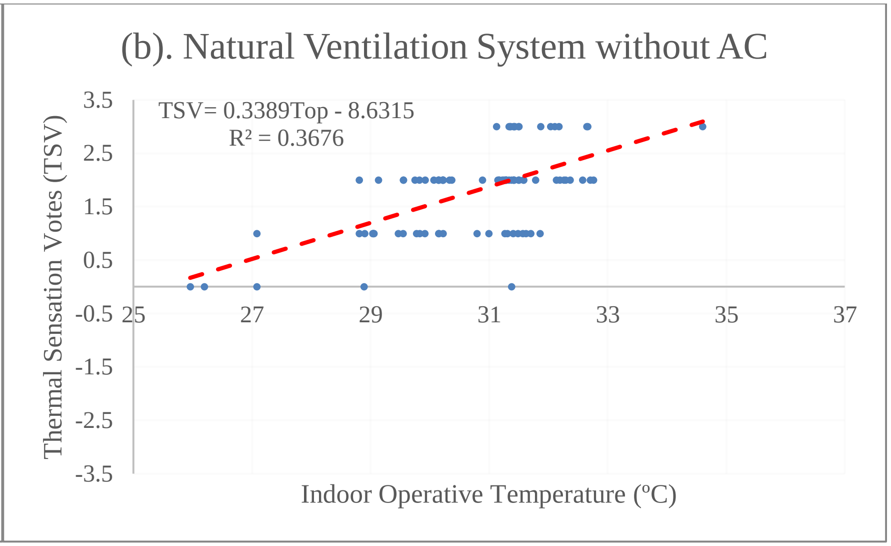


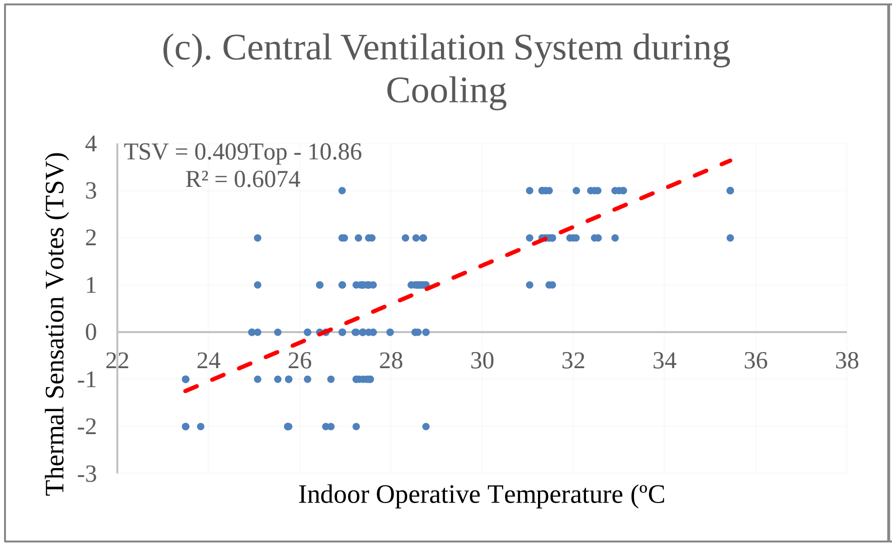
Fig. 8.11: Linear regression analysis between indoor operative temperature and thermal sensation votes for (a) female respondents during summer, (b) male respondents during summer, (c) female respondents during winter and (d) male respondents during winter

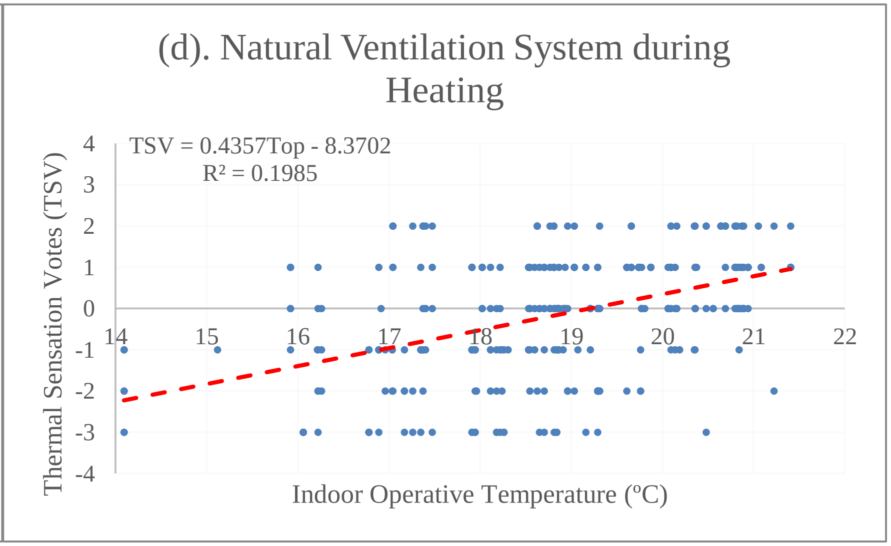
(b). Offices

Fig. 4.12 exhibit scatter plots of TSV against T_{op} in all five modes of ventilation in offices. By substituting TSV=0 in regression equations, T_c were calculated as 27.4, 25.5, 26.6, 19.2 and 19.3ºC ºC for N_{ACon}, N_{ACoff}, CS_C, N_H and CS_H modes respectively. T_c results were compared with previously reported studies of comparable ambience. Singh et al., (Singh et al., 2017) estimated T_c as 27.3ºC during their work on adaptive thermal comfort in Indian offices during autumn season which was almost similar to that calculated in N_{ACon} mode. However, in other summer modes calculated T_c were found a bit lower. Likewise, Thapa et al., (Thapa, Bansal, Panda, et al., 2018) calculated T_c for different buildings located in Tiger Hills, India as 19.1ºC during winter season which is in conformity with the winter observations of present study. Moreover, comfort bandwidth corresponding to TSV±1 for N_{ACon}, N_{ACoff}, CS_C, N_H and CS_H modes comes out to be 25.2-29.7, 22.5-28.4, 24.1-28.9, 16.9-21.5 and 15.8-22.7ºC respectively. López-Pérez et al., (López-Pérez et al., 2019) investigated thermal comfort in educational buildings under tropical climate facilitated with air conditioning systems (AC) and natural ventilation (NV). Results exhibited comfort range as 23.7-29.0ºC (T_c=26.4ºC) and 22.5–28.7°C (T_c=25.6ºC) for AC and NV modes respectively using linear regression method. On comparing the findings of AC mode with N_{ACon} and CS_C modes, less difference was found. Similar observations were recorded while comparing NV mode with N_H mode. Likewise, Trebilcock et al., (Trebilcock et al., 2017) analyzed thermal comfort in school buildings of Chile and found comfort bandwidth of 14.7-15.6ºC during winter season. These observations are lower than the winter findings of current study. Possible reasons of this difference could be the outdoor climatic conditions and difference in adaptive behavior of subjects. Furthermore, slopes of regression equations (Fig. 4.12) for N_{ACon}, N_{ACoff}, CS_C, N_H and CS_H modes were 0.4453, 0.3389, 0.409, 0.4357 and 0.2902ºC respectively which show that TSV will increase by one unit if a change of 2.3, 3, 2.5, 2.4 and 3.5ºC respectively will be observed in the T_{op}. Moreover, these slopes also show sensitivity of thermal responses due to change in T_{op}. It was found that TSV of subjects in CS_H mode are less sensitive to changing T_{op} in comparison to other modes under study.


(a). Natural Ventilation System with AC


(b). Natural Ventilation System without AC


(c). Central Ventilation System during Cooling


(d). Natural Ventilation System during Heating

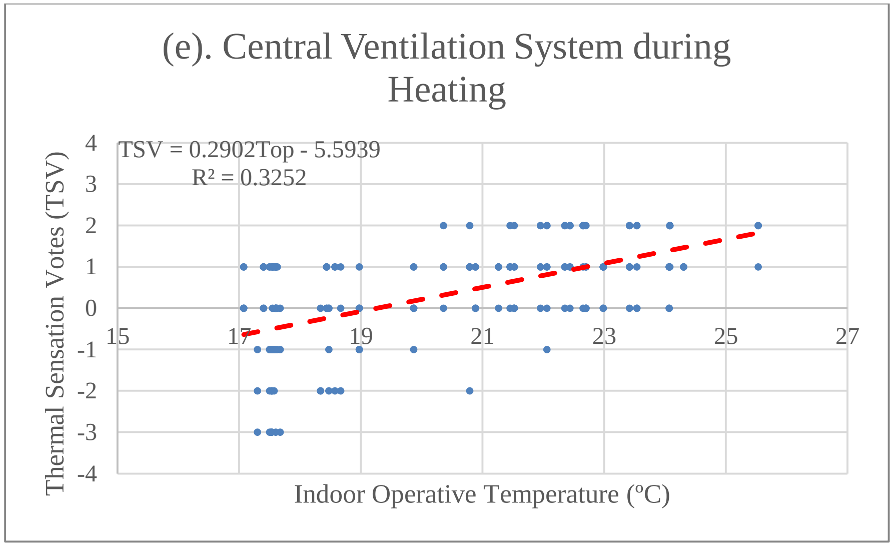


Fig. 8.12: Correlation between thermal sensation votes and indoor operative temperature in (a) natural ventilation system with air-conditioner, (b) natural ventilation system without air-conditioner, (c) central mechanical ventilation system during cooling, (d) natural ventilation system during heating and (e) central mechanical ventilation system during heating

4.1.2.2. Griffths Method

In addition to the linear regression method, T_c was also estimated using Griffths method. Humphreys et al., (M. A. Humphreys et al., 2013) proposed three values of constant G_C in eq. 3.6 i.e. 0.25, 0.33 and 0.5) and T_c was calculated accordingly. Additionally, T_c was calculated for all Ts ($T_{a,}$ T_{gt} and T_{op}) and detailed description of results are presented in below sub-sections.

(a). Dormitories

Descriptive statistics of estimated T_c for all the above-mentioned case scenarios in dormitories is presented in Table 4.9. Mean T_{op} for neutrality (TSV=0) was also analyzed which were found in agreement with T_c calculated using slope of 0.5. Similar results have been reported in a previous study (S. Kumar et al., 2019a).

Table 8.8: Calculated mean comfort temperatures using Griffths method

Modes	**G_C**	**N**	**$^aT_{aC}$**		**$^bT_{gtC}$**		**$^cT_{opC}$**	
			Mean	**Sd**	**Mean**	**Sd**	**Mean**	**Sd**
Females Respondents (Summer)	0.25	250	24.82	3.45	24.68	3.24	24.68	3.24
	0.33		25.86	2.49	25.72	2.33	25.72	2.34
	0.5		26.97	1.55	26.83	1.51	26.82	1.53
Males Respondents (Summer)	0.25	215	25.83	4.51	26.54	4.18	26.51	4.04
	0.33		26.37	3.27	27.08	2.99	27.05	2.83
	0.5		26.94	2.00	27.65	1.86	27.62	1.67
Females Respondents (Winter)	0.25	276	23.73	4.86	23.72	4.57	23.67	4.65
	0.33		23.24	3.62	23.23	3.36	23.18	3.44
	0.5		22.72	2.38	22.71	2.15	22.66	2.23
Males Respondents (Winter)	0.25	230	23.89	4.45	24.43	4.44	24.43	4.44
	0.33		22.86	3.19	23.40	3.17	23.40	3.17
	0.5		21.76	2.02	22.30	1.99	22.30	1.99

^aT_aC = indoor air comfort temperature

$^bT_{gt}C$ = indoor globe comfort temperature

$^cT_{op}C$ = indoor operative comfort temperature

In the present study a minute difference in T_c of both genders is observed which is in agreement with previously reported study conducted in India (Indraganti et al., 2015), focusing on office environments for all four seasons (T_c= 27.0ºC and 26.7ºC females and males Similarly, Maykot et al., (Maykot et al., 2018a), found similar T_c values of 24.0ºC and 23.2ºC for females and males respectively while working on thermal comfort assessment in office buildings from March 2014 to March 2016. Moreover, results of both tests showed no difference ($p>0.05$) in T_c between two genders during both seasons.

(b). Offices

Descriptive statistics of T_c calculated for all modes of office under study is given in Table 4.10.

Table 8.9: Descriptive statistics for comfort temperature calculated by Griffiths method in all studied modes of offices

Modes	**G_C**	**N**	**T_{aC}**		**T_{gtC}**		**T_{opC}**	
			Mean	**Sd**	**Mean**	**Sd**	**Mean**	**Sd**
N_{ACon}	0.25	268	25.41	4.14	25.12	4.21	25.64	4.06
	0.33		26.39	2.97	26.10	3.02	26.62	2.90
	0.5		27.44	1.92	27.14	1.90	27.66	1.86
N_{ACoff}	0.25	91	22.54	2.73	23.50	2.54	23.59	2.58
	0.33		24.28	2.01	25.23	1.91	25.33	1.92
	0.5		26.12	1.30	27.08	1.39	27.18	1.35
CS_C	0.25	153	24.96	4.36	24.59	4.14	25.37	4.09
	0.33		25.69	3.11	25.33	2.90	26.11	2.87
	0.5		26.48	2.04	26.11	1.89	26.89	1.91
N_H	0.25	320	19.07	5.65	19.30	5.59	19.55	5.55
	0.33		18.88	4.22	19.11	4.18	19.36	4.14
	0.5		18.67	2.77	18.90	2.76	19.15	2.72
CS_H	0.25	184	18.38	4.26	18.98	4.14	19.10	4.15
	0.33		18.69	3.16	19.29	3.16	19.41	3.15
	0.5		19.01	2.12	19.61	2.38	19.73	2.31

Thapa et al., (Thapa, Bansal, & Panda, 2018) calculated T_{gtC} for each month in naturally ventilated offices of Darjeeling, India. The estimated T_{gtC} in that study for summer months i.e., July, August and September were 24.4, 23.07 and 22.87ºC respectively. Moreover, for winter months i.e., December, January and February, T_{gtC} were reported as 17.34, 16.94 and 16.36ºC respectively. On comparing with the results of present study, it was found that due adaptive behavior of subjects in cold and cloudy climatic conditions of Darjeeling, India, T_{gtC} was lower. Likewise, Singh et al., (Singh et al., 2017) estimated T_c as 27, 27.3 and 27.5ºC for slopes 0.25, 0.33 and 0.5 respectively for the offices of North-East India during autumn season which is in consonance with the results of present study for summer months.

4.1.2.3. Comparison of Comfort Temperature with Standards

Calculated results of T_c were compared with ASHRAE 55-2013 Standard (for thermal comfort) (ASHRAE, 2013) according to which indoor temperature should be in the range of 22.5-25.5 ºC for maintaining a comfortable indoor thermal environment. The results of dormitories (calculated using Griffiths method for slope 0.5) suggested that the acceptable thermal comfort conditions by occupants during winter season were much closer to the minimum suggested limit by ASHRAE. However, occupants felt comfortable at lower temperatures during winter season in offices. Besides, summer observations for both studied areas were higher than the standard limits.

Results were also compared with building energy codes of Pakistan 1990 (ENERCON, 1990) according to which design temperatures for indoor environments during summer and winter season are 26ºC and 21ºC respectively. Analysis shows that the calculated indoor operative comfort temperature for all the summer and winter cases under study doesn’t meet Pakistani regulations.

4.1.3. Thermal Comfort Models

Below subsections present proposed PMV-PPD models for mechanically ventilated offices modes and adaptive models for naturally ventilated offices modes and dormitories.

4.1.3.1. PMV-PPD Model

Descriptive statistics of calculated PMV and PPD for the mechanically ventilated offices modes under study is presented in Table 4.11.

Table 8.10: Descriptive statics of PMV and PPD

		Max	Min	Mean	Median	Stdev
CS_C	**PMV**	3.5	-2.6	0.79	0.62	1.18
	PPD	80	5	36.67	22	32.25
CS_H	**PMV**	1.08	-1.8	-0.28	-0.23	0.61
	PPD	67	5	14.4	9	12.68

In a comparable study of thermal adaptation in heated and unheated buildings in Shanghai and Beijing, China, range of mean PMV in four studied groups was found as -1.8 to -0.1 (Luo et al., 2019). In another study of thermal comfort and adaptive actions for modern and traditional naturally ventilated hostel buildings during monsoon season in India, mean PMV and PPD were 1.4 and 49 respectively (S. Kumar et al., 2019b).

Furthermore, TSV and PMV were linearly regressed against T_{op} scatter plots of which are depicted in Fig. 4.13; however, regression equations are given below:

CS_C Mode:

$$TSV = 0.44T_{op} - 12.035 \; (R^2 = 0.70) \qquad (4.1)$$

$$PMV = 0.36T_{op} - 9.497 \; (R^2 = 0.88) \qquad (4.2)$$

CS_H Mode:

$$TSV = 0.37T_{op} - 7.4141 \quad (R^2 = 0.4) \qquad (4.3)$$

$$PMV = 0.25T_{op} - 5.5121 \quad (R^2 = 0.71) \qquad (4.4)$$

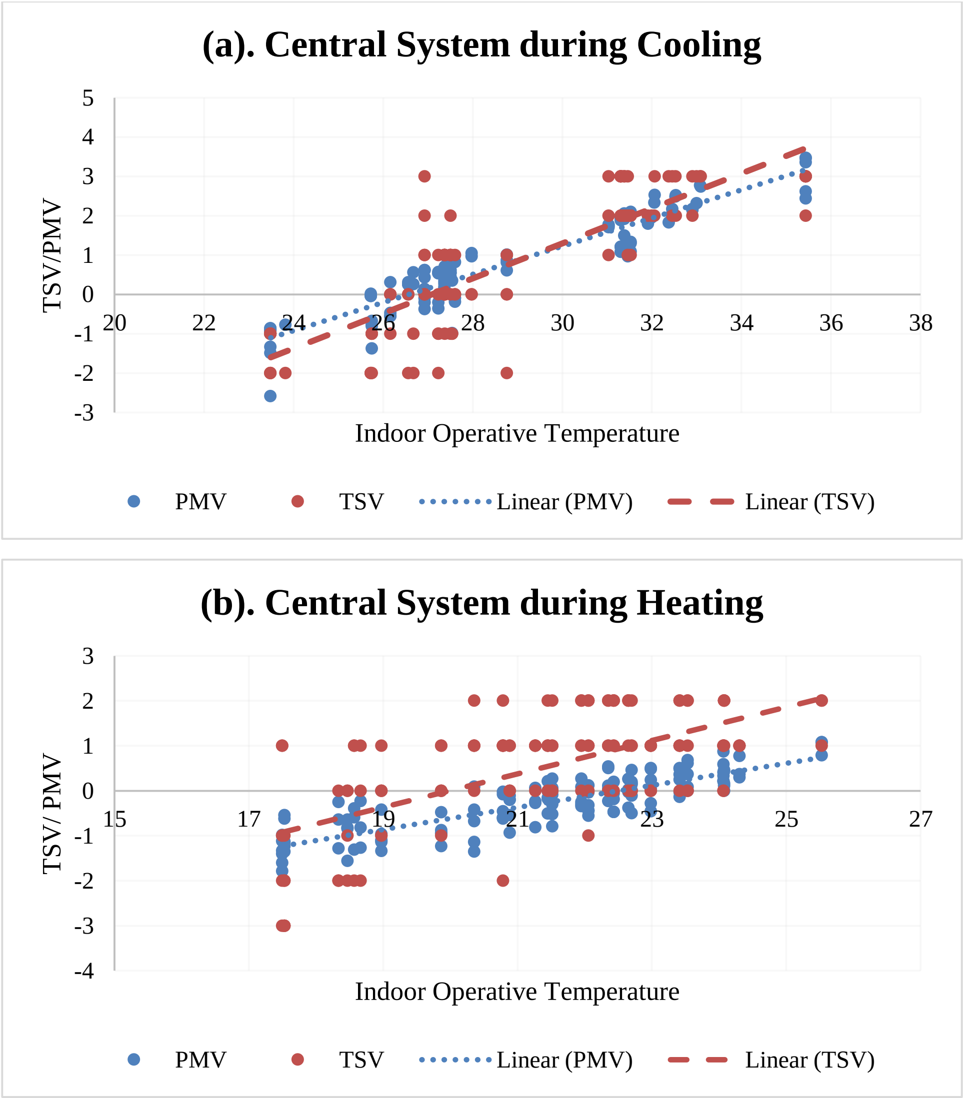
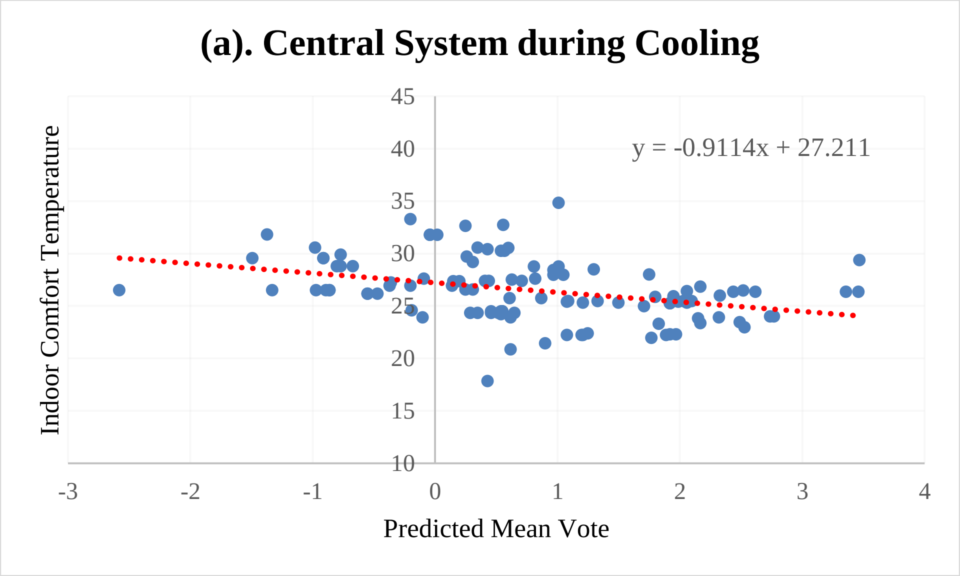


Fig. 8.13: Scatter plots of TSV and PMV against Top in (a). central system during cooling and (b). central system during heating

Slopes of the regression equations for subject's actual thermal sensation showed a change in thermal sensation by one unit if T_{op} will increase or decrease by approximately 2.28 and 2.71°C for CS_C and CS_H modes respectively. Furthermore, a change in T_{op} of 2.78 and 4.00°C for CS_C and CS_H modes respectively will increase or decrease PMV levels by one unit. These results could be interpreted as subjects during summer season were more sensitive to change in T_{op} in comparison to winter season. Similar observations were reported in previously published studies (Thapa, Bansal, Panda, et al., 2018)

Besides, PMV was also linearly regressed against T_c for prediction purpose as presented in Fig. 4.14 along with their respective linear equations.



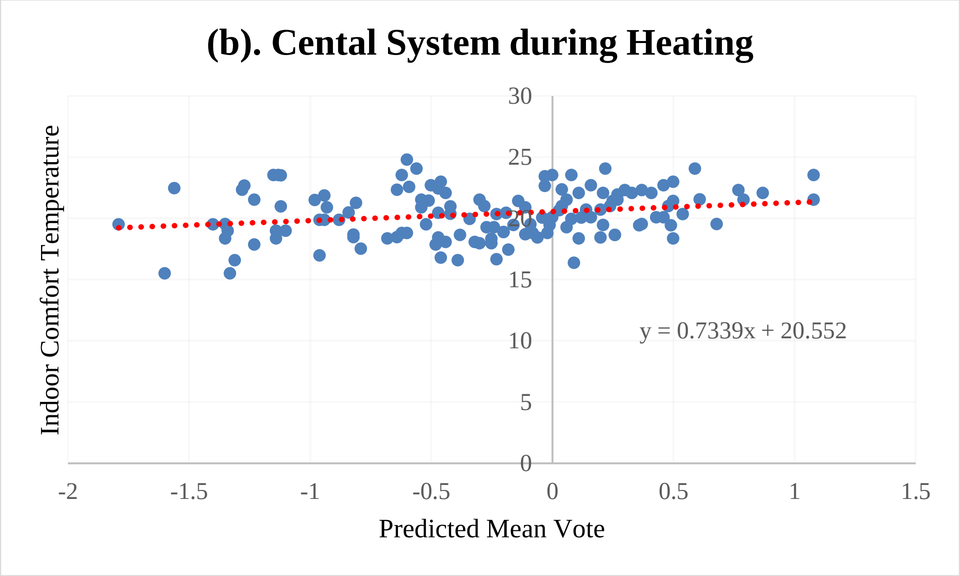


Fig. 8.14: Linear regression analysis of indoor comfort temperature and predicted mean vote in (a). central system during cooling and (b). central system during heating

4.1.3.2. Adaptive Thermal Comfort Model

Main assumption of process of adaptation is that subjects are active towards changing outdoor environmental conditions. Thus, calculated indoor comfort operative temperatures during both seasons against 0.5 slope for offices and dormitories, were linearly, cubically and logistically regressed with T_{rm} (calculated using eq. 3.5) following previous literature (Khalid et al., 2019). Detailed description is presented in the following subsections.

(a). Linear Regression Model

Dormitories

Fig. 4.15 shows scatter plots and linear regression lines of training data set of female and male dormitories during summer and winter seasons. Linear regression equations along with sample size and regression coefficient, are given below.

Female Dormitories (Summer):

$$T_C = -0.1499T_{rm} + 29.773 \quad \text{(n= 175, r=0.089)} \tag{4.5}$$

Male Dormitories (Summer):

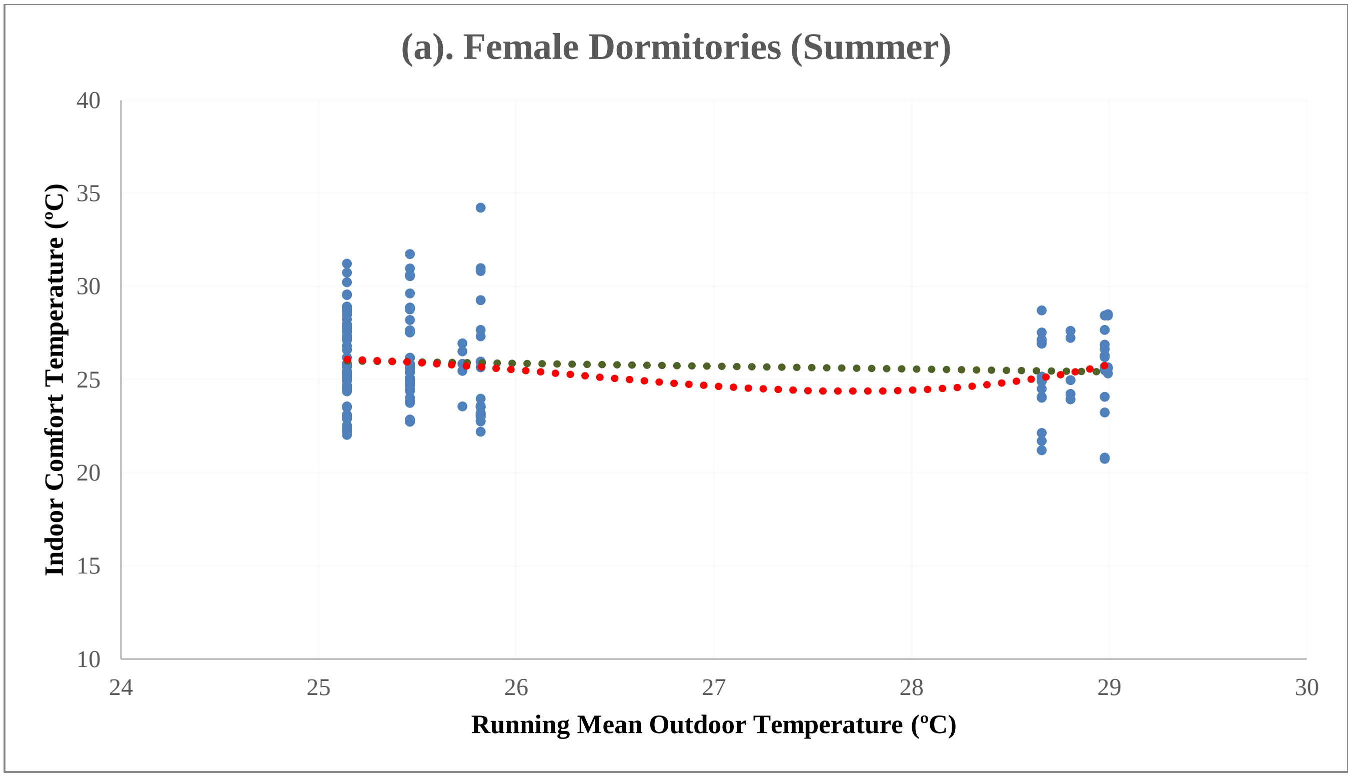
$$T_C = -0.7252T_{rm} + 46.18 \quad \text{(n=150, r=0.32)} \tag{4.6}$$

Female Dormitories (Winter):

$$T_C = -0.403T_{rm} + 26.912 \quad \text{(n=186, r=0.28)} \tag{4.7}$$

Male Dormitories (Winter):

$$T_C = 0.266T_{rm} + 19.761 \quad \text{(n=162, r=0.18)} \tag{4.8}$$


(a). Female Dormitories (Summer)
Indoor Comfort Temperature (°C)
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29
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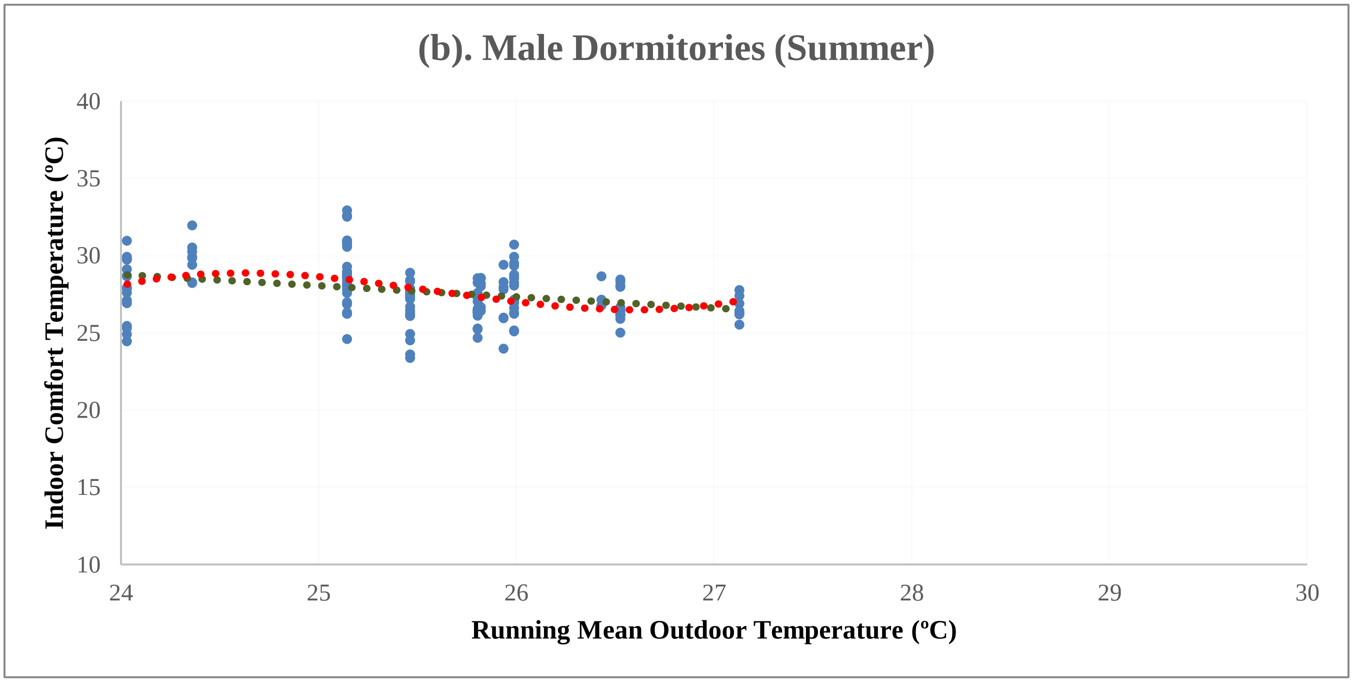
Running Mean Outdoor Temperature (°C)


(b). Male Dormitories (Summer)
Indoor Comfort Temperature (°C)
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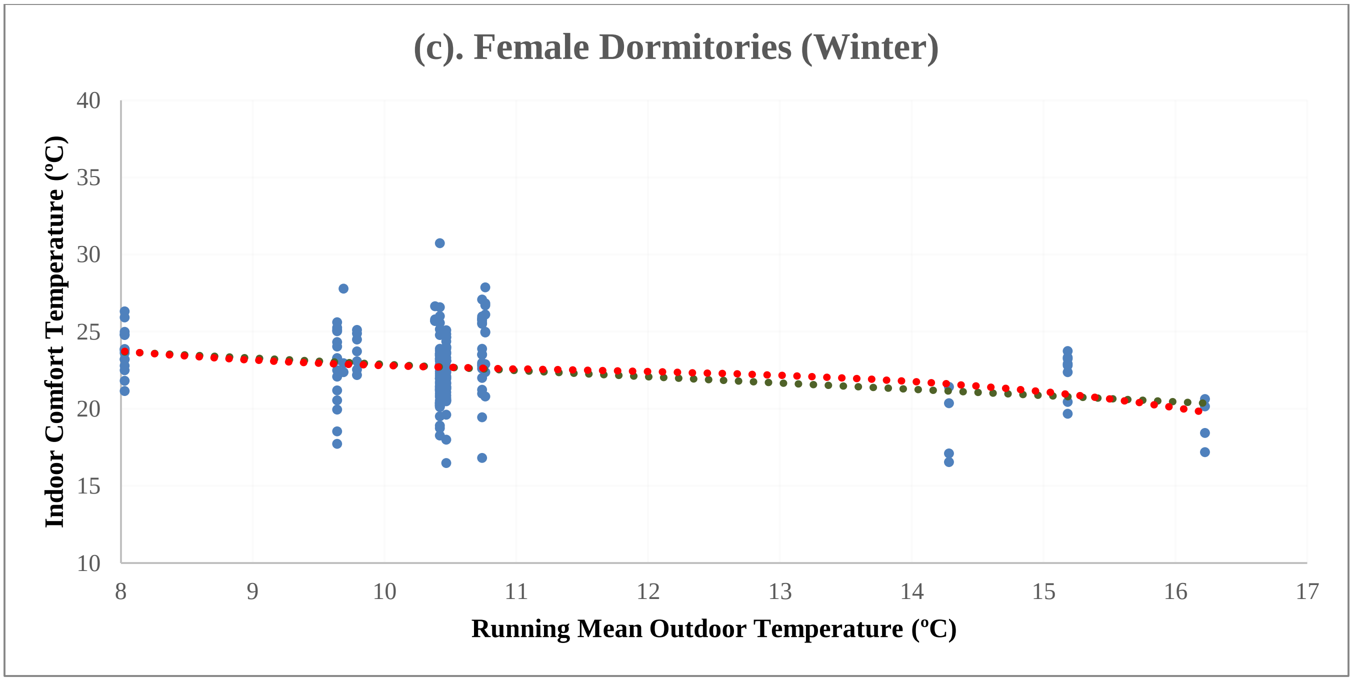
Running Mean Outdoor Temperature (°C)



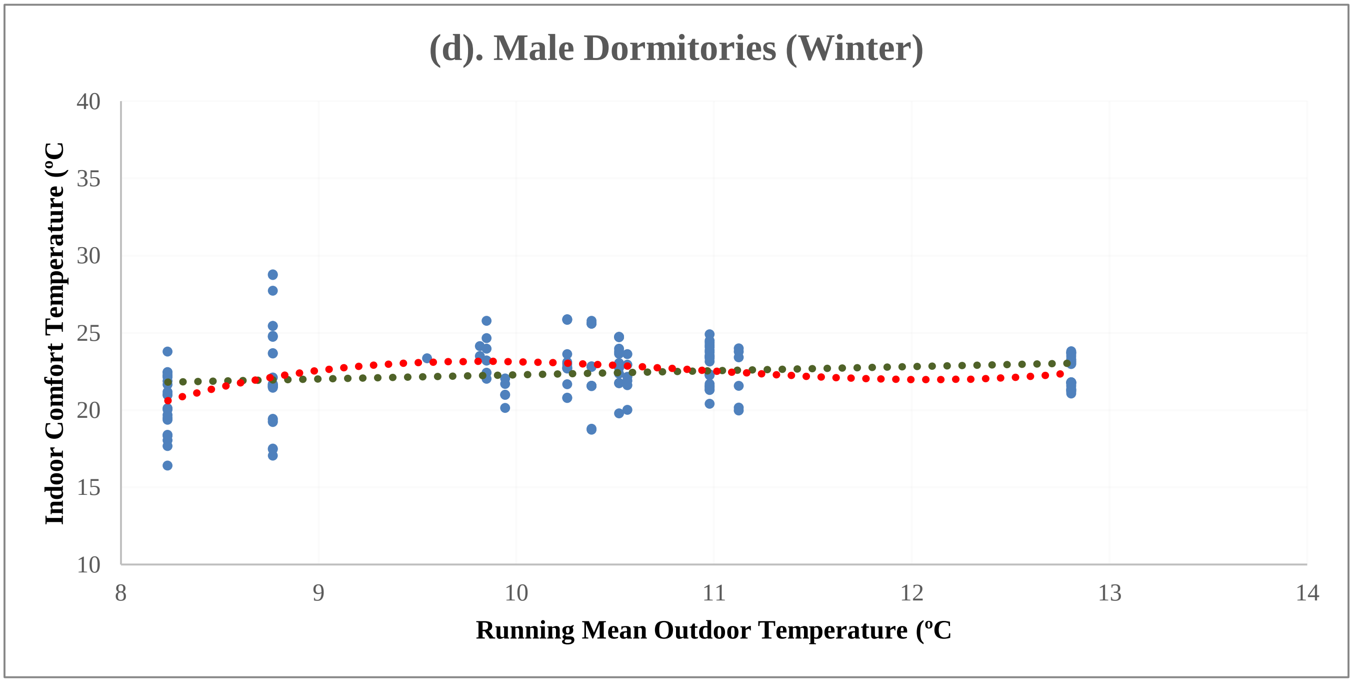


Fig. 8.15: Linear and cubic adaptive models of (a). female dormitories during summer, (b). male dormitories during summer, (c). female dormitories during winter and (d). male dormitories during winter season

Optimal T_c range using linear regression lines in female and male dormitories during summer season are 25.4-26.0 and 26.5-28.5°C respectively and during winter season are 20-23.5 and 21.8-23.0°C respectively.

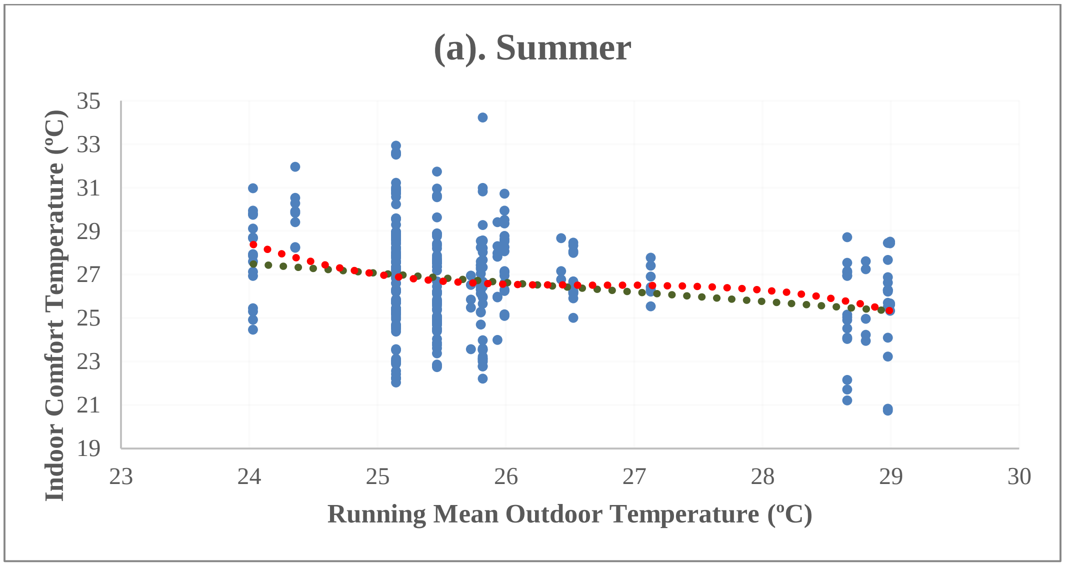
In addition to this data for summer and winter seasons without gender segregation was also linearly modeled (Fig.4.16) and the equations are as follows;

Summer:

$$T_C = -0.4337T_{rm} + 37.907 \qquad \text{(n= 325, r=0.23)} \qquad (4.9)$$

Winter:

$$T_C = -0.0954Trm + 23.488 \qquad \text{(n=348, r=0.07)} \qquad (4.10)$$



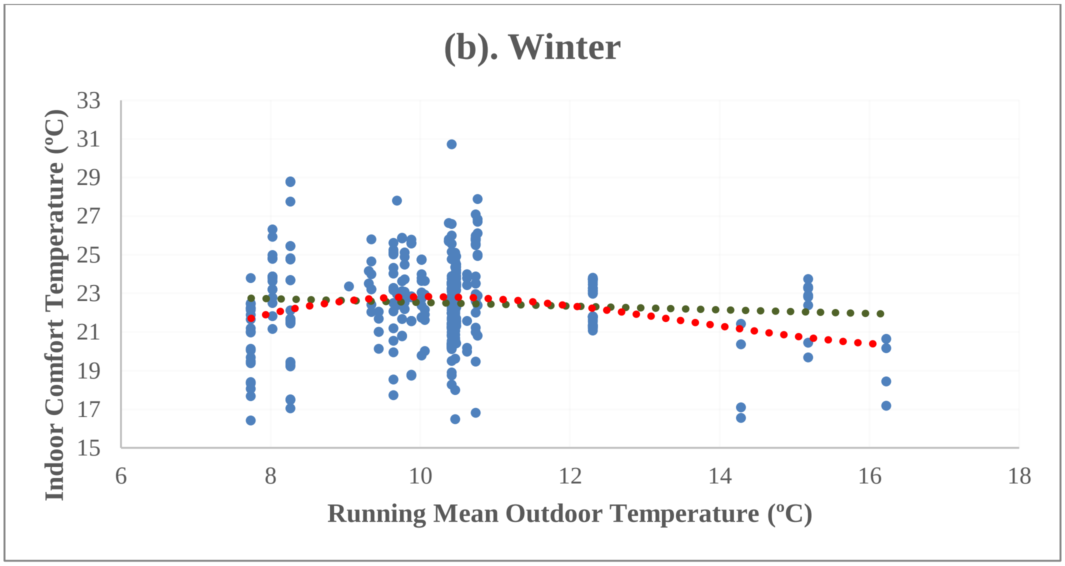
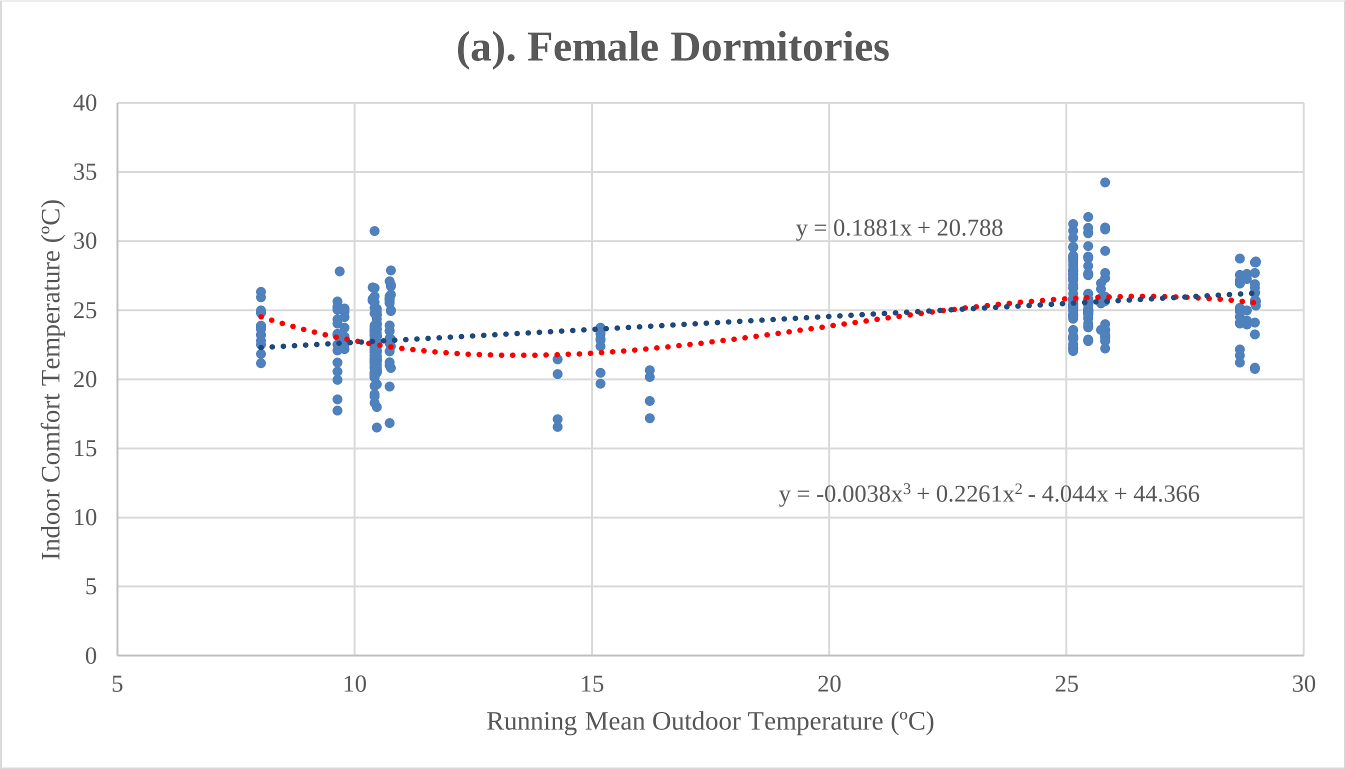


Fig. 8.16: Linear and cubic adaptive models during (a). summer, (b). winter seasons

Optimal T_c range for summer and winter seasons on combined data were found as 25.33- 27.48 and 22.03-22.9 respectively.

Considering the principles of adaptive thermal comfort, occupants adapt to their changing outdoor climatic conditions by adjusting their clo levels and opening/ closing windows and doors. Due to this reason T_c should increase with the increase in temperature and vice versa, thus resulting in positive regression correlation between T_c and T_{rm} as reported in many previously reported studies (Indraganti et al., 2014; Indraganti and Boussaa, 2017). However, in the present study contradictory results can be seen with negative regression coefficients most of the time. This could be attributed to the fact that the present study reports seasonal adaptive thermal models with very less variation in T_{rm}. In this regard, further regression analysis on combined data of two seasons for male and females was performed and presented in Fig. 4.17 which supported the above-mentioned fact with positive correlation coefficients.



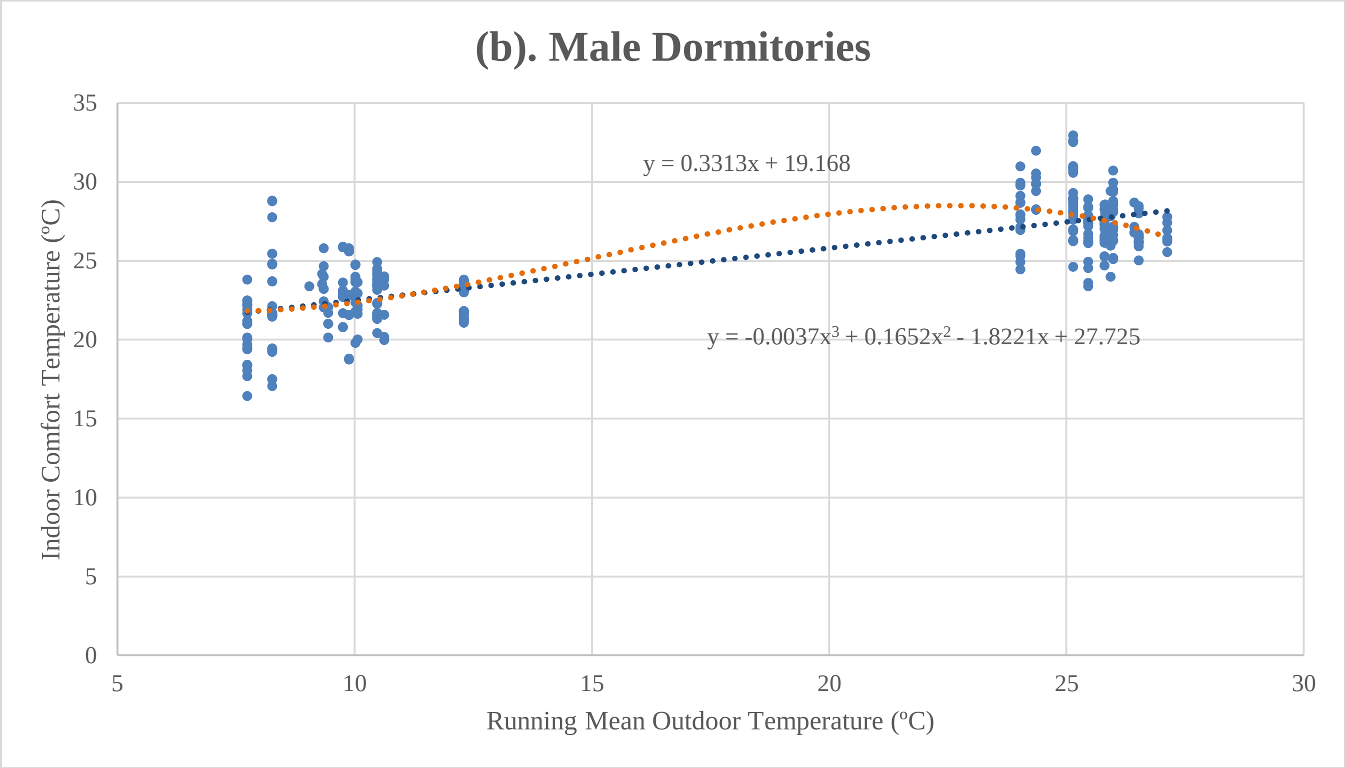


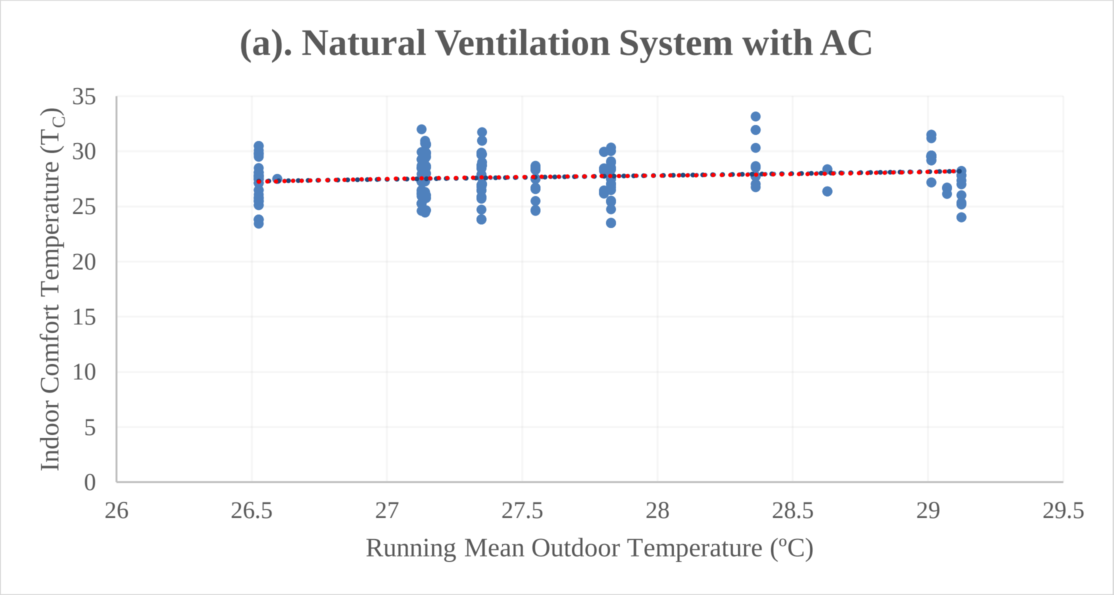
Fig. 8.17: Linear and cubic adaptive models of female (a) and male dormitories(b)

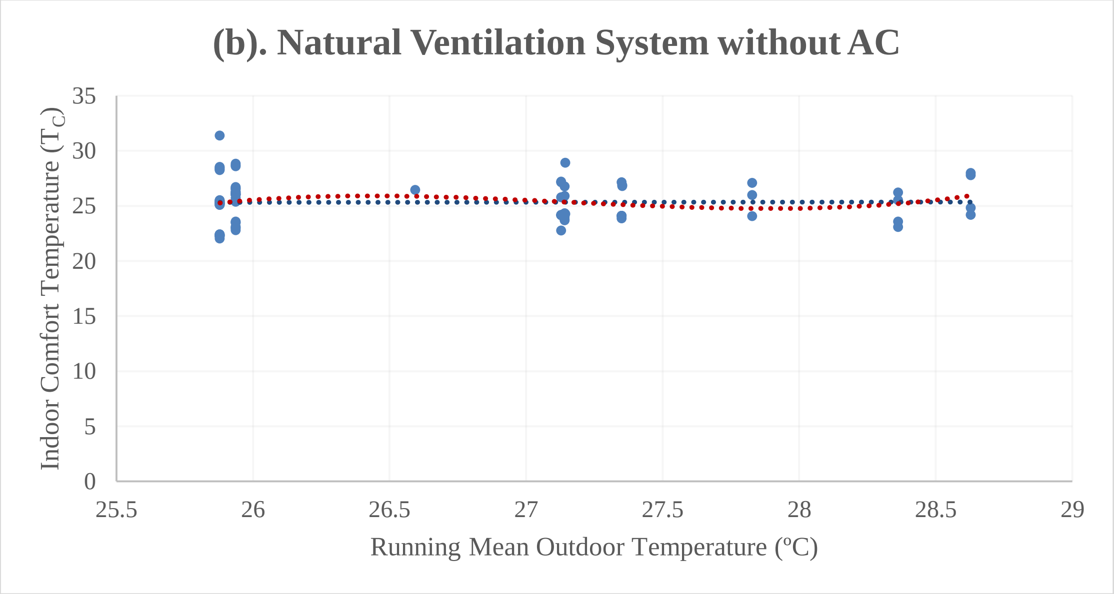
Offices

Scatter plots and linear regression lines of training datasets models for the three naturally ventilated modes in offices are depicted in Fig. 4.18. Below are the equations of the proposed adaptive models.

- Natural System with AC: $T_c = 0.34T_{rm} + 18.17$ (4.11)
- Natural System without AC: $T_c = 0.014T_{rm} + 24.958$ (4.12)
- Natural System during Heating: $T_c = 0.13T_{rm} + 17.975$ (4.13)

Slopes of adaptive model manifest human comfort sensitivity to the changing outdoor climatic conditions. Hereby, it was found that subjects in N_{ACoff} mode are less sensitive to changing outdoor conditions in comparison to the other two modes. Slopes of the equations for N_{ACon}, N_{ACoff} and N_H modes are 0.34, 0.014 and 0.13 respectively, thus, it illustrates that on 1ºC change in outdoor temperature, T_c in offices would also change by 0.34, 0.014 and 0.13ºC respectively. Besides, range of optimal T_c for N_{ACon}, N_{ACoff} and N_H modes were observed as 27.3-28.2, 25.3-26.4 and 19.1-19.6ºC respectively.





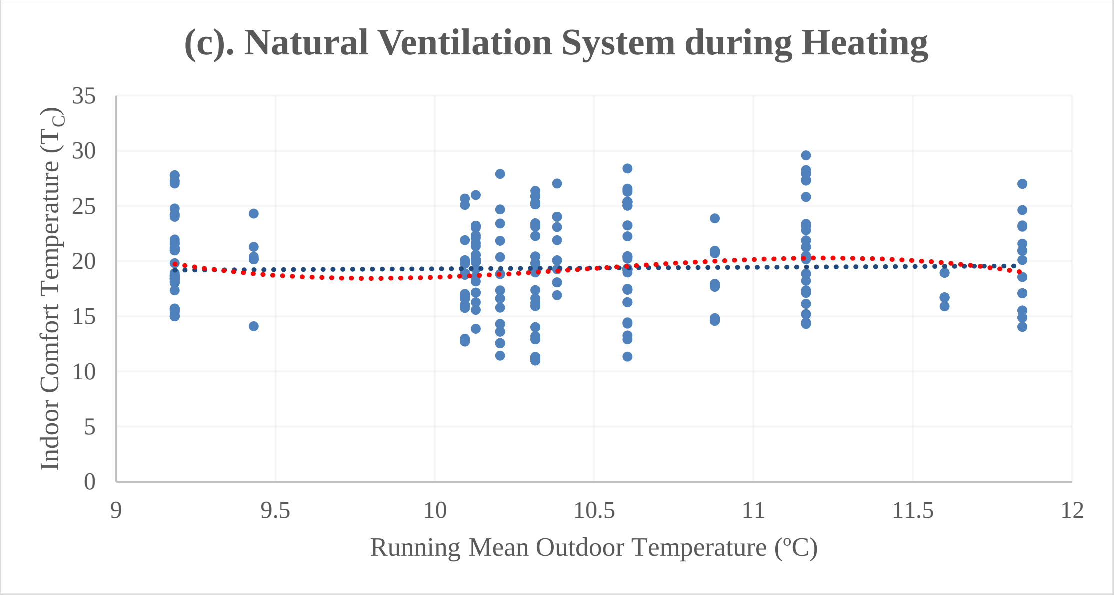


Fig. 8.18: Adaptive thermal comfort models of (a) natural ventilation system with air-conditioner, (b) natural ventilation system without air-conditioner, (c) central mechanical ventilation system during cooling, (d) natural ventilation system during heating and (e) central mechanical ventilation system during heating in offices

(b). Cubic Regression Model

Dormitories

Scatter plots and cubic regression curves of training data set of female and male dormitories during summer and winter seasons are shown in Fig. 4.15. Cubic regression equations are given below;

Female Dormitories (Summer):

$$T_C = 0.1545T_{rm}^3 - 12.185T_{rm}^2 + 319.47T_{rm} - 2758.6 \quad \text{(n=175, r=0.12)} \quad (4.14)$$

Male Dormitories (Summer):

$$T_C = 0.602T_{rm}^3 - 46.244T_{rm}^2 + 1182.3T_{rm} - 10032 \quad \text{(n=186, r=0.38)} \quad (4.15)$$

Female Dormitories (Winter):

$$T_C = -0.0167T_{rm}^3 + 0.5707T_{rm}^2 - 6.6656T_{rm} + 49.114 \quad \text{(n=150, r=0.28)} \quad (4.16)$$

Male Dormitories (Winter):

$$T_C = 0.203T_{rm}^3 - 6.3676T_{rm}^2 + 65.807T_{rm} - 201.39 \quad \text{(n=162, r=0.36)} \quad (4.17)$$

The lower and upper limits of optimal T_c using cubic regression curves in female and male dormitories during summer season are observed as 26-26.5 and 27.0-29.0°C respectively and during winter season are 20-23.7 and 20.5-23.0°C respectively.

Equations of cubic regression model for summer and winter without gender segregation is given below;

Summer:

$$T_c = -0.0954T_{rm}^3 + 7.6446T_{rm}^2 - 204.18T_{rm} + 1844.4 \quad \text{(n=325, r=0.25)} \tag{4.18}$$

Winter:

$$T_C = 0.0154T_{rm}^3 - 0.6271T_{rm}^2 + 7.9733T_{rm} - 9.5617 \quad \text{(n=248, r=0.24)} \tag{4.19}$$

Offices

Cubic regression models for the training datasets of three naturally ventilated offices modes are depicted in Fig. 4.18 and regression equations are given below.

- Natural System with AC:

$T_C = 0.083T_{rm}^3 - 6.99T_{rm}^2 + 195.26T_{rm} - 1793.6$ (4.20)

- Natural System without AC:

$T_C = 0.74T_{rm}^3 - 60.58T_{rm}^2 + 1644.2T_{rm} – 14841$ (4.21)

- Natural System during Heating:

$T_C = -1.25T_{rm}^3 + 39.38T_{rm}^2 - 412.15T_{rm} + 1450.4$ (4.22)

Range of optimal T_c using cubic regression equations for N_{ACon}, N_{ACoff} and N_H modes were noted as 26.7-27.6, 24.5-25.3 and 19.1-19.8ºC respectively.

(c). Logistic Regression Model

Dormitories

Logistic regression model was developed with T_{rm} as a predictor variable. Results of α and β values of all the cases under study in dormitories with their standard error and p-values are presented in Table 4.12.

Table 8.11: Summary of logistic regression model for indoor comfort temperature prediction in dormitories

Coefficients	Female Dormitories (Summer)			Male Dormitories (Summer)			Female Dormitories (Winter)			Male Dormitories (Winter)			Summer			Winter		
	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value
ß	0.07	0.08	0.00	0.67	0.16	0.00	0.25	0.08	0.00	-0.23	0.10	0.03	0.26	0.07	0.00	0.05	0.06	0.37
α_1	-5.83	2.21	0.00	-22.14	4.32	0.00	-7.95	1.36	0.00	-2.91	1.40	0.04	-11.42	1.96	0.00	-5.71	0.95	0.00
α_2	-4.48	2.16	0.00	-20.74	4.23	0.00	-6.30	1.02	0.00	-1.50	1.09	0.17	-10.09	1.90	0.00	-4.19	0.71	0.00
α_3	-3.40	2.14	0.00	-19.28	4.20	0.00	-5.67	0.97	0.00	-0.77	1.04	0.46	-9.02	1.88	0.00	-3.53	0.67	0.00
α_4	-2.75	2.14	0.00	-17.95	4.17	0.00	-5.19	0.95	0.00	0.00	1.01	1.00	-8.39	1.87	0.00	-2.92	0.65	0.00
α_5	-1.86	2.13	0.00	-17.10	4.15	0.00	-4.22	0.91	0.00	0.52	1.00	0.60	-7.54	1.86	0.00	-2.19	0.64	0.00
α_6	-1.24	2.13	0.00	-16.07	4.12	0.00	-3.33	0.89	0.00	1.22	1.00	0.22	-6.80	1.85	0.00	-1.41	0.63	0.03
α_7	-0.75	2.13	0.00	-15.06	4.11	0.00	-2.77	0.88	0.03	2.45	1.01	0.02	-6.22	1.84	0.00	-0.57	0.63	0.37
α_8	0.01	2.13	0.00	-14.52	4.10	0.00	-1.86	0.87	0.15	3.18	1.03	0.00	-5.38	1.84	0.00	0.24	0.63	0.70
α_9	0.66	2.13	0.00	-13.40	4.11	0.00	-1.27	0.87	0.46	4.13	1.05	0.00	-4.57	1.84	0.01	0.98	0.63	0.12

Coefficients	Female Dormitories (Summer)			Male Dormitories (Summer)			Female Dormitories (Winter)			Male Dormitories (Winter)			Summer			Winter		
	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value
α_{10}	1.14	2.14	0.00	-13.17	4.12	0.00	-0.65	0.87	0.55	4.89	1.07	0.00	-4.07	1.84	0.03	1.64	0.64	0.01
α_{11}	2.68	2.23	0.00	-	-	-	0.54	0.92	0.13	6.24	1.18	0.00	-2.82	1.87	0.13	2.87	0.69	0.00
α_{12}	3.38	2.34	0.00	-	-	-	1.55	1.02	0.04	6.65	1.25	0.00	-2.47	1.88	0.19	3.49	0.74	0.00
α_{13}	-	-	-	-	-	-	2.66	1.31	0.00	-	-	-	-0.85	2.08	0.68	4.19	0.84	0.00
α_{14}																5.30	1.17	0.00

Offices

Like dormitories, logistic regression analysis was also performed in the three naturally ventilated offices modes under study. Table 4.13 depicts results of α and β values along with standard error and p-values.

Table 8.12: Summary of logistic regression model for indoor comfort temperature prediction in offices

Coefficients	N_{ACon}			N_{ACoff}			N_H		
	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value	Estimate	Std. Error	P-value
B	0.552	0.87	0.524	-0.332	0.75	0.658	-0.231	0.672	0.732
α_1	13.504	3.91	0.572	-10.88	2.67	0.599	-4.753	3.199	0.509
α_2	14.43	3.96	0.547	-9.97	2.62	0.629	-3.946	3.153	0.581
α_3	15.188	4.05	0.528	-9.32	2.58	0.65	-3.405	3.13	0.633
α_4	15.993	4.12	0.507	-8.765	2.55	0.67	-2.972	3.114	0.676
α_5	17.017	4.22	0.482	-8.178	2.51	0.69	-2.59	3.101	0.715
α_6	-	-	-	-7.309	2.49	0.721	-2.211	3.089	0.755
α_7	-	-	-	-	-	-	-1.817	3.079	0.797
α_8	-	-	-	-	-	-	-1.395	3.073	0.844
α_9	-	-	-	-	-	-	-0.879	3.073	0.901
α_{10}	-	-	-	-	-	-	-0.09	3.097	0.99

(i). Comparison of Proposed Adaptive Models with Previously Reported Studies

Adaptive relations assessed through linear, cubic and logistic methods were compared with models reported in previous studies. It was found that linear regression is the most practiced method in literature for the T_c prediction. Some of the previously reported linear and cubic regression thermal comfort models are summarized in Table 4.14. Z. Wu et al., (2019) developed a linear adaptive model for naturally ventilated dormitories in China. The data was collected in summer season and was combined for male and female subjects. Comparison of the model with the respective results of the present study shows the optimal T_c range of 27.17-28.12ºC (as compared to 25.33-27.48 (dormitories), 26.7-27.6 and 24.5-27.6 (offices) of this study) when upper and lower limits of T_{rm} of the present study were used, for comparison purposes. Likewise, Dhaka et al., (2013) developed the adaptive model for naturally ventilated hostels during summer season in India which showed optimal $T_c$range as 24.78-29.77 ºC when T_o of present study were used. The slight differences among these studies reflect those models developed in different geographic regions (cultures, clothing etc.) under same season and building characteristics couldn't be accurate representation of thermal comfort demands of all regions. Likewise, the studies on linear adaptive models with different building characteristics were also compared with linear models of present study. Khalid et al., (2019) developed an adaptive model for patients and visitors while working on T_c and thermal adaptation for patients and visitors in hospitals. It was found that the upper and lower limits of optimal T_c during summer and winter season were 32.2-36.5ºC and 23.2-27.4ºC respectively when T_{rm} (of this study) were input in patients' model.

However, model limits were 22.9-25.6 ºC and 14.1-18.1 ºC for the visitors during summer and winter seasons respectively. In another study, Indraganti et al., (2014) developed linear adaptive models for office workers for natural ventilation (NV) and air-conditioning (AC) modes from their 14 months long survey. Optimal T_c ranges for AC and NV modes were 27.6-29.6ºC and 25.7-26.8ºC respectively under T_o of this study, during summer season. However, only NV mode was compared for winter season which indicated that ranges are not in agreement with the model results of the present study. Thus, it was concluded adaptive behaviors and thermal comfort demands of occupants will be different for buildings with different characteristics and therefore adaptive model will also be different.

Although, cubic regression modelling technique is commonly used in different areas of research. However, limited literature is available in the field of thermal comfort assessment

(Takasu et al., 2017). Using T_{rm} range in eqs. 4.14 and 4.15, optimal T_c ranges for summer and winter seasons were 16.3-29.0 ºC and 20.8-21.7 ºC respectively for dormitories. Furthermore, limits for offices were discussed in Section 4.1.3.2. However, the limits of optimal T_c in Takasu et al., (2017) cubic adaptive model for offices were 23.8-24.1 ºC and 23.4-23.7 ºC for free running (FR) and mixed mode respectively. Comparison indicated that the results of the developed model for dormitories and offices were not in agreement with Takasu et al., (2017) results for offices.

Table 8.13: Linear and cubic adaptive thermal comfort models in previous literature

Reference	**Regression Equations**	**Country**	**Adaptive Model Type**	**Survey Time**
Z. Wu et al., 2019	$T_c = 0.19T_{rm} + 22.6$	China	Linear	Summer
Dhaka et al., 2013	$T_n = 0.6478T_o + 9.368$	India	Linear	Summer
Khalid et al., 2019	$T_c = 0.56T_{rm} + 18.9$ (patients)	Malaysia	Linear	January 2016-March 2017
	$T_c = 0.54T_{rm} + 9.9$ (visitors)			
Indraganti et al., 2014	$T_c = 0.26T_{rm} + 21.4$ (NV mode)	India	Linear	January 2012-February 2013
	$T_c = 0.15T_{rm} + 22.1$ (AC mode)			

Reference	Regression Equations	Country	Adaptive Model Type	Survey Time
Takasu et al., 2017	$T_c = -0.0007T_o^3 + 0.046T_o^2 - 0.78T_o + 27.7$ (FR mode)	Japan	Cubic	2012-2016
	$T_c = -0.0008T_o^3 + 0.048T_o^2 - 0.78T_o + 27.3$ (mixed mode)			

T_n = neutral temperature
NV = natural ventilation
AC = air conditioning
FR = free running

In most of the previously reported studies on logistic regression analysis of thermal comfort, TSV were predicted instead of T_c. Ji and Wang, (2019) reported thermal adaptation and logistic regression analysis in severe cold regions. They divided the data into three groups on the basis of TSV and developed separate models for cool and hot thermal comfort conditions for the prediction of TSV. Likewise, Rehman et al., (2020) developed personalized thermal comfort models for the prediction of TSV. However, Takasu et al., (2017) developed models for the prediction of T_c. Thermal comfort, being a subjective concept varies according to the climatic conditions and the model equations in all the above mentioned studies were developed according to the outdoor conditions of that region. Due to this reason, the model equations couldn't be used in the present scenario for comparison.

(ii). Comparison of Adaptive Models Predictive Capability

Three adaptive models developed for training datasets in section 4.1.3.2 were used to predict individual T_c for the testing datasets which were then compared with the actual T_c calculated using eq. 3.6. Afterwards, accuracy of models was appraised by dividing the number of correct predictions by total observations. Comparison of accuracy of three models is presented in Table 4.15.

Table 8.14: Percentage accuracies of the predicted Tc from developed linear, cubic and logistic models

Location		Linear Model (%)	Cubic Model (%)	Logistic Model (%)
Dormitories	**Summer Females**	21.33	24	30.67
	Winter Females	17.5	18.75	21.25
	Summer Males	18.46	32.31	35.38
	Winter Males	23.19	21.74	34.78
	Summer (Both Genders)	17.86	22.86	26.43
	Winter (Both Genders)	16.11	17.45	24.83
Offices	**Natural System with AC**	19.24	22.13	29.42
	Natural System without AC	20.38	21.91	31.28
	Natural System during Heating	16.35	18.47	36.39

On comparing models' accuracy, it was found that in all observed cases logistic regression model predicts T_c better than linear and cubic models. On contrary, linear regression method is the widely accepted and practiced method for the prediction of $T_{c.}$ Use of cubic regression in thermal comfort prediction studies is rarely reported and logistic regression is commonly used for the prediction of TSV and not the T_c. Furthermore, authors also found that there are only a few studies in literature comparing the percentage accuracy of developed models. Lai and Chen, (2019) compared linear, ordinal/logistic and multinomial regression models for TSV prediction. The percentage accuracies calculated using linear and ordinal/logistic regression analysis were 39% and 45% respectively. Although logistic regression performs better than linear regression in the present study, it was found that percentage accuracies were lesser than that reported by Lai and Chen, (2019). One of the possible reasons could be in Lai and Chen, (2019) study five respondents from each area were recruited, who recorded the data over different times, under different conditions. However, in the present study each respondent participated only once. Likewise, Chaudhuri et al., (2017) incorporated multiple variables in the logistic model and found percentage accuracy as 76.81% and 70.28% for mechanically and naturally ventilated building respectively. Thus, it could be concluded that alone T_{rm} has a limited contribution towards determination of T_c whereas percentage accuracies could be increased if multiple variables will be considered in the models.

4.1.3.3. Thermal Comfort Models with Multiple Variables

In continuation of previous section, further analysis was performed on dormitories data to check the impact of different variables (T_o, T_a, T_{gt}, T_{op}, Rh_o, Rh_i and clo) on the percentage accuracies. In addition to this combine effect of all variables was also investigated. Build-in MATLAB functions for KNN and logistic regression algorithm were used to predict individual TSV for the testing data set of each dormitory building. Afterwards, comparison was made between the actual and predicted levels which is presented in Table 4.16 and 4.17 for KNN and logistic regression respectively, as percentage accuracies for all the cases under study.

Table 8.15: Percentage accuracies of the predicted TSV using KNN algorithm

Variables	**Dormitories**			
	Summer Boys	**Summer Girls**	**Winter Boys**	**Winter Girls**
Outdoor Temperature	39.06	43.33	40.58	32.91
Outdoor Relative Humidity	40.63	46.67	31.88	29.11
Air Temperature	48.44	50.67	42.03	50.63
Indoor Relative Humidity	39.06	38.67	28.99	40.51
Globe Temperature	46.88	50.67	43.48	41.77
Dressing	29.69	40.00	28.99	34.18
Indoor Operative Temperature	48.44	50.67	43.48	41.77
All variables	54.69	56.00	54.93	51.90

Table 8.16: Percentage accuracies of the predicted TSV using logistic regression

Variables	**Dormitories**			
	Summer Boys	**Summer Girls**	**Winter Boys**	**Winter Girls**
Outdoor Temperature	35.94	34.67	18.84	39.24
Outdoor Relative Humidity	26.56	33.33	15.94	35.44
Air Temperature	51.56	48.00	33.33	37.97
Indoor Relative Humidity	35.94	29.33	21.74	35.44
Globe Temperature	45.31	45.33	39.13	41.77
Dressing	32.81	34.67	17.39	31.65
Indoor Operative Temperature	42.19	50.67	40.58	39.24
All variables	68.75	61.33	59.42	60.76
Simplified Model	75.24	70.51	65.73	72.35

As in adaptive thermal comfort studies, T_o or T_{rm} were taken as an independent variable for the prediction of TSV or T_c. However, in the present study percentage accuracies were noted less than 50% when T_o was taken independently in both models (KNN and logistic). Moreover, less impact of indoor/ outdoor relative humidity and dressing on TSV during one season was also evident. Furthermore, higher percentage accuracies (>50%) could be noticed in Table 4.16 and 4.17 when all variables were input in the model in comparison to individual variables as independent variable. Thus, it could be concluded as predictive power of thermal comfort models could be increased by considering the impact of all the possible variables or factors. Current observations were supported by previously reported studies (Chaudhuri et al., 2017). Furthermore, comparison of logistic and KNN models showed that logistic approach performed better than KNN as percentage accuracies of latter are more.

Further analysis was performed for the simplification of combined logistic regression model. For this purpose interaction between independent variables were checked as a factor of mean square error (MSE) using multiple input combinations in Wingamma software. Results indicated lowest MSE levels when outdoor relative humidity and dressing were eliminated from the input combination. Thus, a logistic regression model was developed using outdoor temperature, air temperature, indoor relative humidity, globe temperature and indoor operative temperature as independent variables and percentage accuracies were checked. Results indicated better performance of simplified model in comparison to the combined model (Table 4.17)

4.2. Phase 2: IAQ, AERS and Airborne Infection Risk Assessment

Present section is divided into four subsections where first subsection presents results and discussion for indoor CO_2 levels in all the indoor microenvironments under study. Percentage exceedance of monitored indoor parameters from ASHRAE standard is depicted in second subsection. Furthermore, findings of ventilation/ air exchange rates and airborne infection risk assessment is provided in third and fourth subsections respectively.

4.2.1. Indoor CO_2 Levels

Indoor CO_2 levels have been taken as a universal surrogate of IAQ and ventilation (Branco et al., 2015). Thus the present section depicts trends in indoor CO_2 levels along the day i.e., between occupancy and non-occupancy hours in the four monitored indoor environments. Moreover, significant variation of indoor CO_2 between two or more datasets (between seasons or along day or between ventilation modes/scenarios) was also checked. Detailed description is presented in below sub-sections.

4.2.1.1. NCLS Classrooms

Detailed descriptive statistical analysis of indoor CO_2 levels of all the monitored classrooms (occupancy + non-occupancy hours) during both seasons in NCLS has been summarized in Fig. 4.19. CO_2 is a function of two major factors i.e., occupancy and ventilation which depends on degree of opening and closing of windows and doors. Although CR07 had the highest occupancy level (Table 3.6), opening frequency of doors and windows during summer season was found more than winters which resulted in less built-up of indoor CO_2 levels during summer season.

No significant variation ($p>0.05$) in indoor CO_2 levels has been observed between the two monitored seasons for all classrooms during weekends, which may be attributed to the same level of air tightness during the two seasons. Besides, mean indoor CO_2 values in all classrooms (as shown in Fig. 4.19) were almost equal to 400 ppm (outdoor CO_2 concentration) on weekends during both seasons. On weekdays, the mean values of CO_2 concentration varied significantly ($p<0.05$) among the rooms and seasons for CR06, CR07, CR08, CR09 and CR10. However, for all other cases variation was not significant among seasons. .

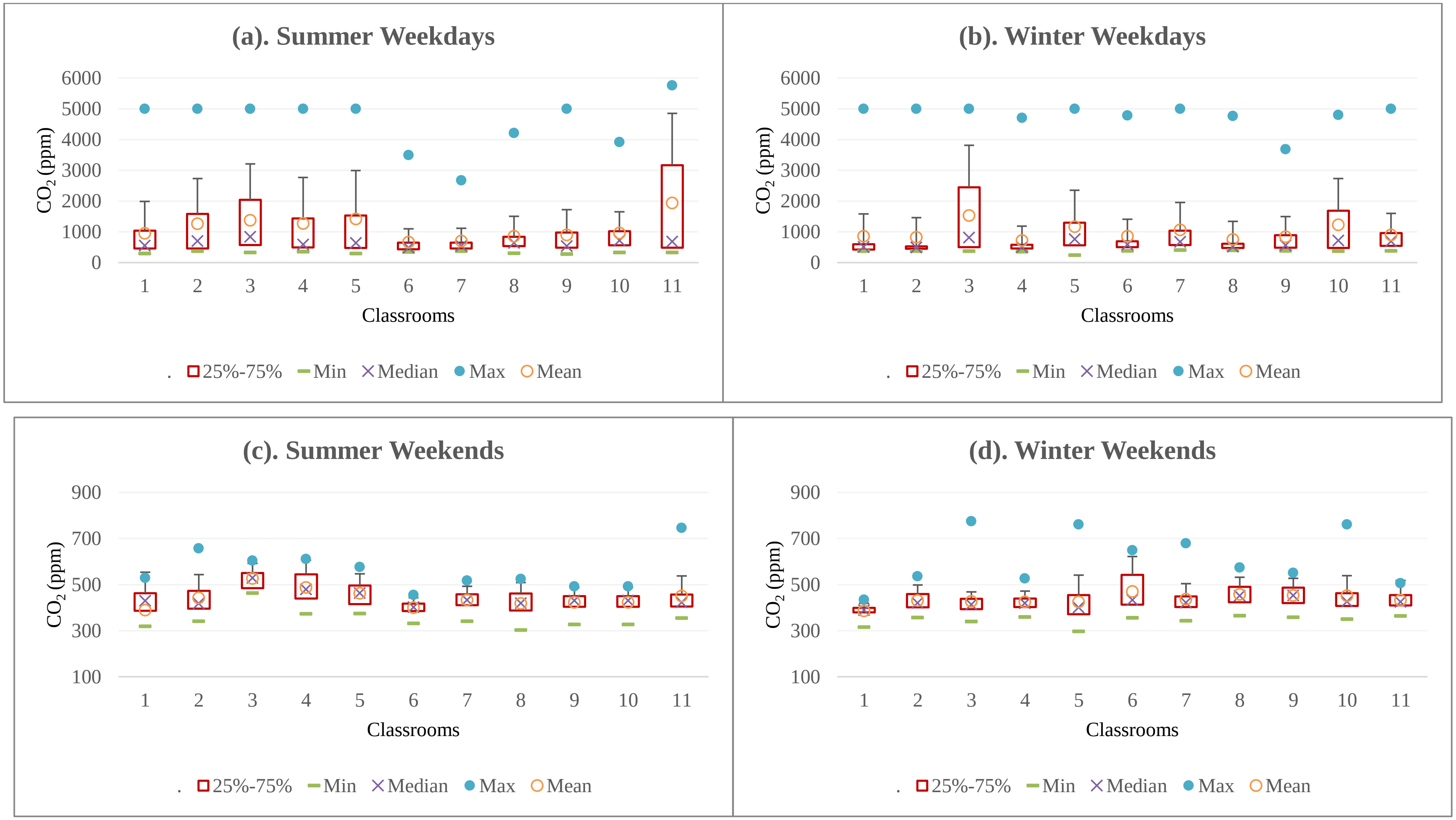
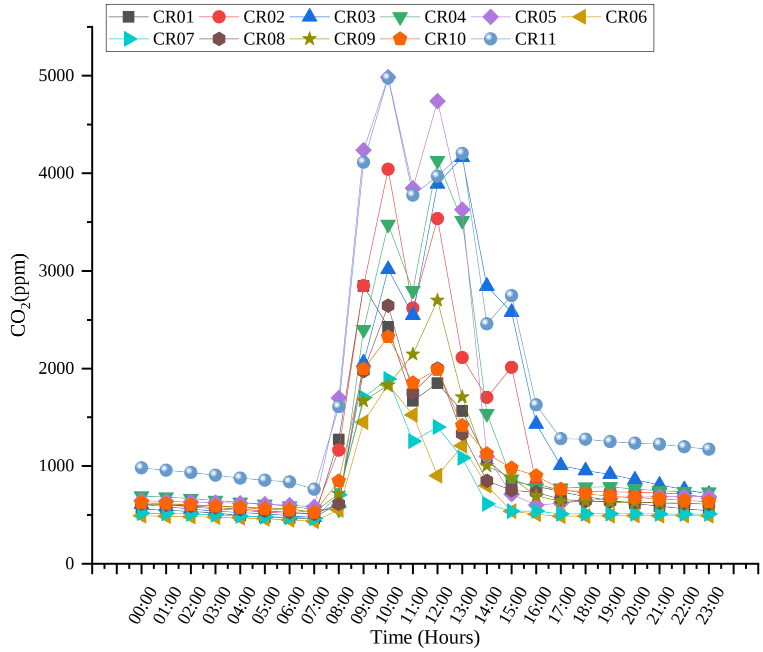


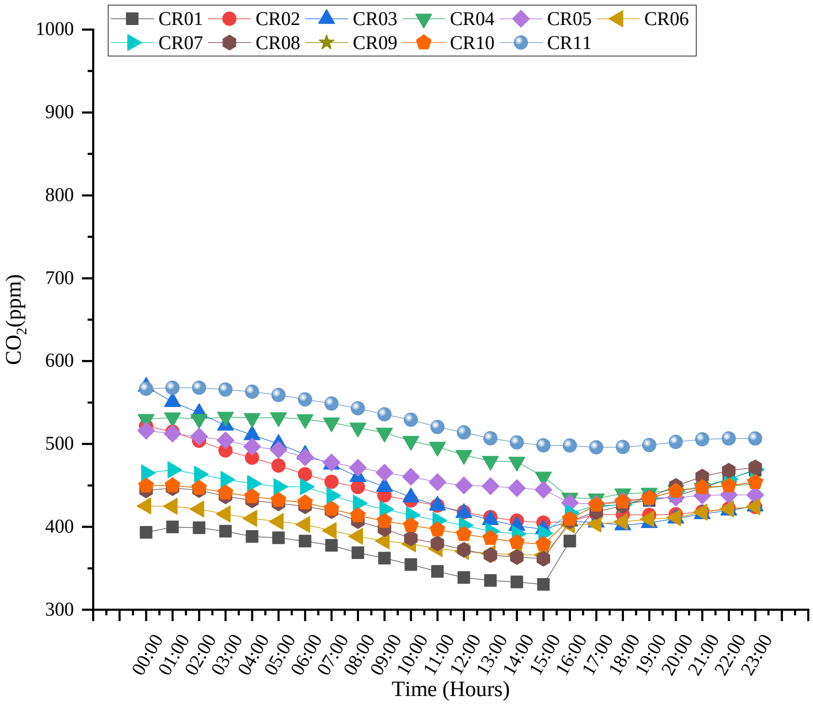
Fig. 8.19: Descriptive statistics of indoor CO2 during (a) Summer Weekdays, (b) Winter Weekdays, (c) Summer Weekends, (d) Winter Weekends in NCLS

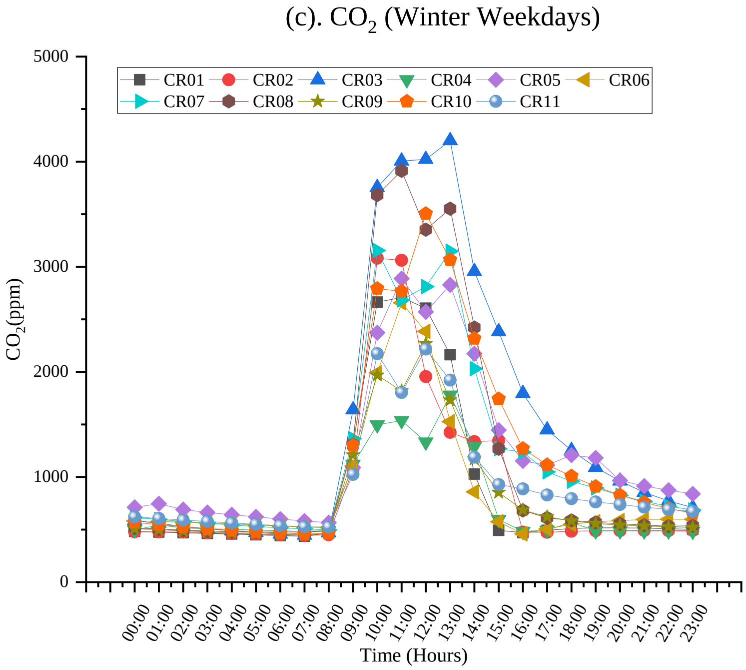
The 24-hour mean hourly concentration profiles of indoor CO_2 levels observed in the monitored classrooms of NCLS obtained by averaging all minute-by-minute data records are shown in Fig. 4.20. Fig. 4.20(a) and 4.20(b) show the CO_2 concentration profiles for summer (weekdays and weekends) while Fig. 4.20(c) and 4.20(d) shows results for winter (weekdays and weekends) season respectively. Indoor CO_2 levels are observed to be stable (almost equal to ambient) during the weekends. On weekdays, class sessions start at 08:30 am resulting in gradual increase in indoor CO_2 levels in each classroom. The concentrations varied significantly ($p<0.05$) between occupancy and non-occupancy hours on weekdays of both seasons. During break time, from 10:20 to 10:45 am, classrooms were vacant resulting in slight decrease in indoor CO_2 levels. CO_2 concentration again starts to rise after break session till 01:00 pm for junior and 02:00 pm for senior classes (as shown in Table 3.5). After class sessions, CO_2 levels again start to decline and become equal to ambient (taken as 400 ppm) in most of the cases with time. In some rooms, occasionally, an additional session was held between 02:00 pm till 04:00 pm which results in a third peak in profiles. Maximum levels (per minute basis) were recorded higher during weekdays for both seasons with maximum value in CR11 (5764 ppm) and CR03 (5000 ppm) during summer and winter respectively. Minimum levels during weekdays on the other hand, were observed in CR06 (408 ppm) and in CR01 (426 ppm) during summer and winter respectively. During weekends, indoor levels were found lower due to no occupancy hours with highest value in CR03 (746 ppm) and CR11 (775 ppm) during summer and winter respectively. Minimum levels on the other hand, were found in CR08 (306 ppm) and CR05 (302 ppm) during summer and winter respectively.

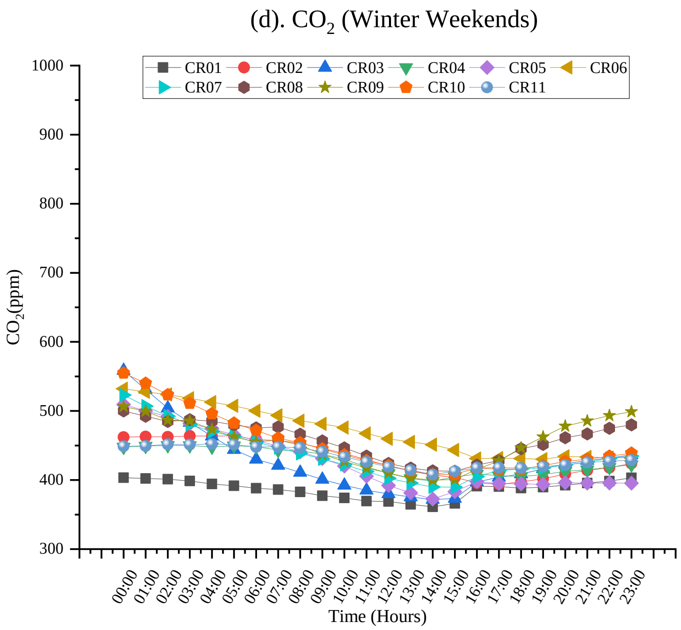
(a). CO$_2$ (Summer Weekdays)



(b). CO$_2$ (Summer Weekends)




(c). CO$_2$ (Winter Weekdays)
CR01
CR02
CR03
CR04
CR05
CR06
CR07
CR08
CR09
CR10
CR11
CO$_2$(ppm)
5000
4000
3000
2000
1000
0
00:00
01:00
02:00
03:00
04:00
05:00
06:00
07:00
08:00
09:00
10:00
11:00
12:00
13:00
14:00
15:00
16:00
17:00
18:00
19:00
20:00
21:00
22:00
23:00
Time (Hours)



(d). CO_2 (Winter Weekends)

Fig. 8.20: 24-Hour mean hourly CO_2 concentration profiles during (a) Summer weekdays, (b) Summer weekends, (c) Winter weekdays and (d) Winter weekends in NCLS classrooms

4.2.1.2. IESE Classrooms

Detailed descriptive statistics of indoor CO_2 levels for all IESE classrooms under study are given in Fig.4.21. It was noticed that among different ventilation scenarios considered, indoor CO_2 levels varied significantly ($p<0.05$) for all classrooms. In addition, concentrations were also significantly ($p<0.05$) different between occupancy and non-occupancy hours and among classrooms, within same ventilation scenarios.

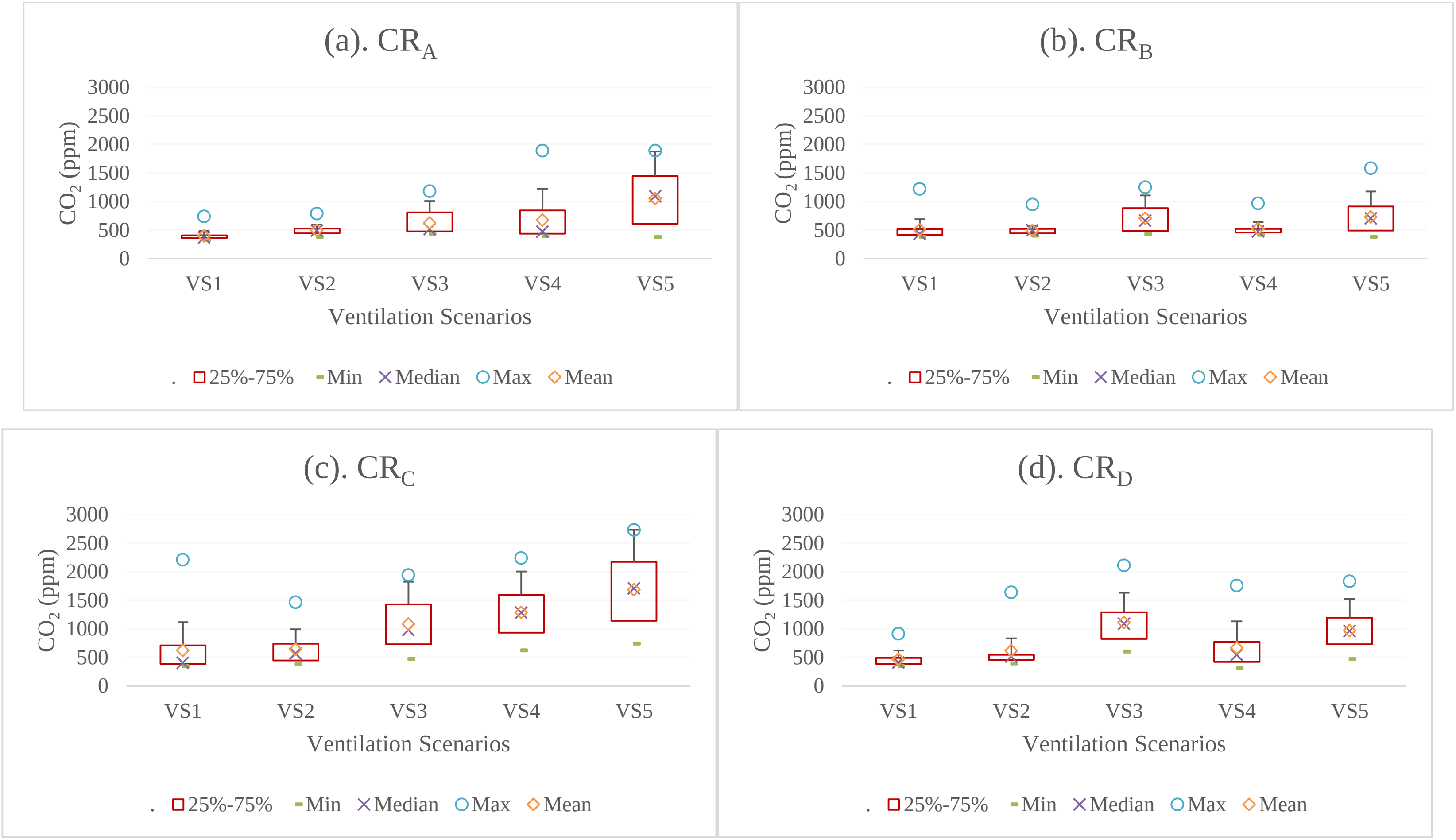


Fig. 8.21: Descriptive statistics of indoor CO_2 in (a). CRA, (b). CRB, (c). CRC and (d). CRD under five ventilation scenarios in IESE classrooms

Fig. 4.22 depicts trends of indoor CO_2 levels in all classrooms under different ventilation scenarios along with the occupancy levels. It was observed that indoor CO_2 levels varied along the day under same ventilation scenario of all monitored classrooms. This could be explained by variation in occupancy along the day and between two or more sampling days of same or different classrooms during monitoring as could be seen in Fig. 4.22. Besides, although ventilation was controlled through opening and closing of windows and ventilators, doors opening and closing was not taken into account during analysis. In first ventilation scenario (VS1), all windows and ventilators were open, resulting in comparatively less build-up of indoor CO_2 concentrations (<1000ppm) in CR_A and CR_D during occupancy hours. However, during evening session in CR_B and CR_C, CO_2 levels rose to 1219 and 2213 ppm respectively. This can be explained by the fact (observed in CCTV footages) that during morning sessions, there is always 10-15 minutes break between two consecutive lectures, in which most of the students leave classrooms, leading to lower CO_2 levels build-up. In contrast, during evening sessions, on that particular day in CR_B and CR_C, the classes starting at 05:00 got extended till 07:00 (rather than 06:30), leading to 3.5-hour long evening session without any break, thus, resulting in higher CO_2 levels. Sharp decline in indoor CO_2 levels was evident after end of each session. Besides, there was no extra class during break session in CR_A and CR_D and the classrooms had comparatively less occupancy levels due to which indoor CO_2 levels were always below 1000 ppm.

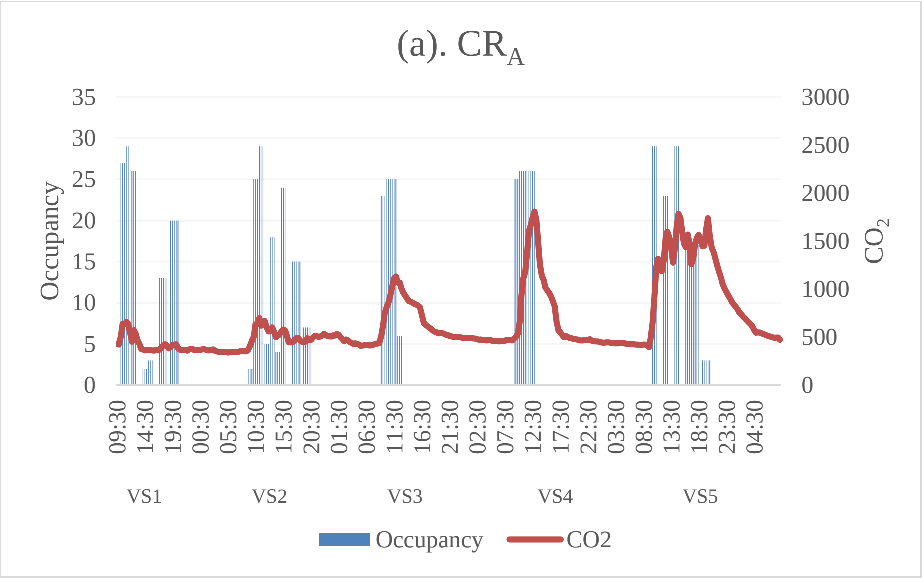
During the second ventilation scenario (VS2), front window of all classrooms was kept closed while the back window and ventilators were kept open. It was observed that during this scenario, indoor CO_2 levels were always less than 1000 ppm in CR_A and CR_B. However, in CR_C, there were continuous lecture sessions from 10:00 am to 12:00 pm and 5:00 to 8:30 pm, due to which indoor CO_2 levels rose to 1496 and 1177 ppm respectively. Similar, trend was observed during the morning session of CR_D, during which indoor CO_2 levels rose to 1643 ppm.

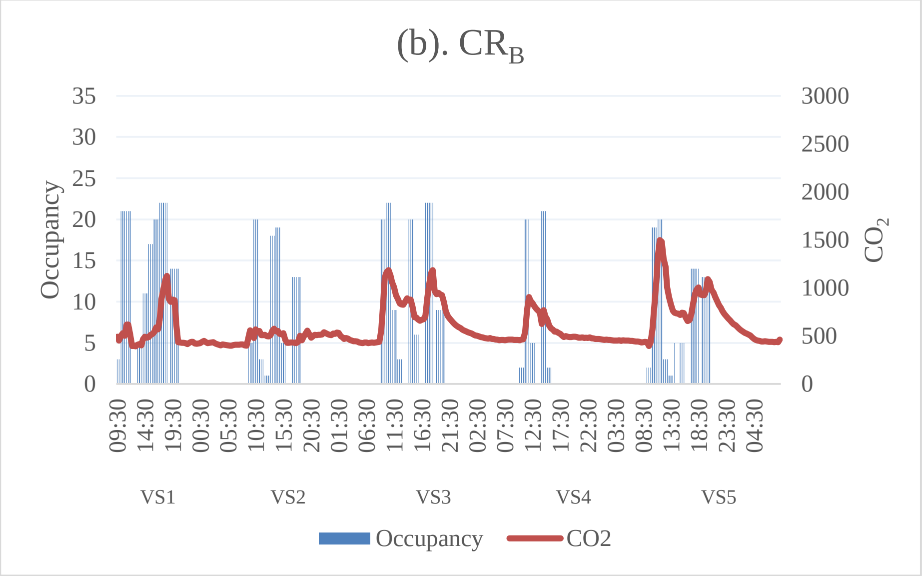
In third ventilation scenario (VS3), all windows were kept closed and ventilators were open. In this case, all four classrooms showed buildup of indoor CO_2 levels above 1000 ppm. Highest levels were observed in CR_D as 2112 ppm while lowest in CR_A as 1180 ppm.

The difference in CO_2 levels between classrooms can be explained due to difference in occupancy levels and duration of lecture sessions which are evident from Fig. 4.22.

All windows and one ventilator were kept closed during the fourth ventilation scenario (VS4) in all classrooms. Higher indoor CO_2 concentrations were observed in comparison to the previously discussed scenarios for CR_A and CR_C. However, in CR_B, continuous breaks in between lecture sessions were observed resulting in less CO_2 concentrations than expected. Although during break hours 2-5 students stayed in the classroom but their presence won't impact significantly in build-up of CO_2 levels. Additionally, in CR_D, less levels were observed in comparison to VS3 which can be again attributed to comparatively low occupancy levels.

All windows and ventilators were kept closed for the fifth ventilation scenario (VS5) in all classrooms under study. Highest levels among all other scenarios were observed in CR_B and CR_C. In CR_A and CR_D, trends of CO_2 build-up with increase in occupancy in VS4 and VS5 were found almost similar. Moreover, in CR_D, build-up in VS3 was highest due to high occupancy levels. Highest indoor CO_2 level was observed in VS5 of CR_C as 2733 ppm and lowest in VS1 of CR_A as 413 ppm.


(a). CR_A
Occupancy
CO_2
35
30
25
20
15
10
5
0
3000
2500
2000
1500
1000
500
0
09:30
14:30
19:30
00:30
05:30
10:30
15:30
20:30
01:30
06:30
11:30
16:30
21:30
02:30
07:30
12:30
17:30
22:30
03:30
08:30
13:30
18:30
23:30
04:30
VS1
VS2
VS3
VS4
VS5
Occupancy
CO2


(b). CR_B
Occupancy
CO_2
35
30
25
20
15
10
5
0
3000
2500
2000
1500
1000
500
0
09:30
14:30
19:30
00:30
05:30
10:30
15:30
20:30
01:30
06:30
11:30
16:30
21:30
02:30
07:30
12:30
17:30
22:30
03:30
08:30
13:30
18:30
23:30
04:30
VS1
VS2
VS3
VS4
VS5
Occupancy
CO2

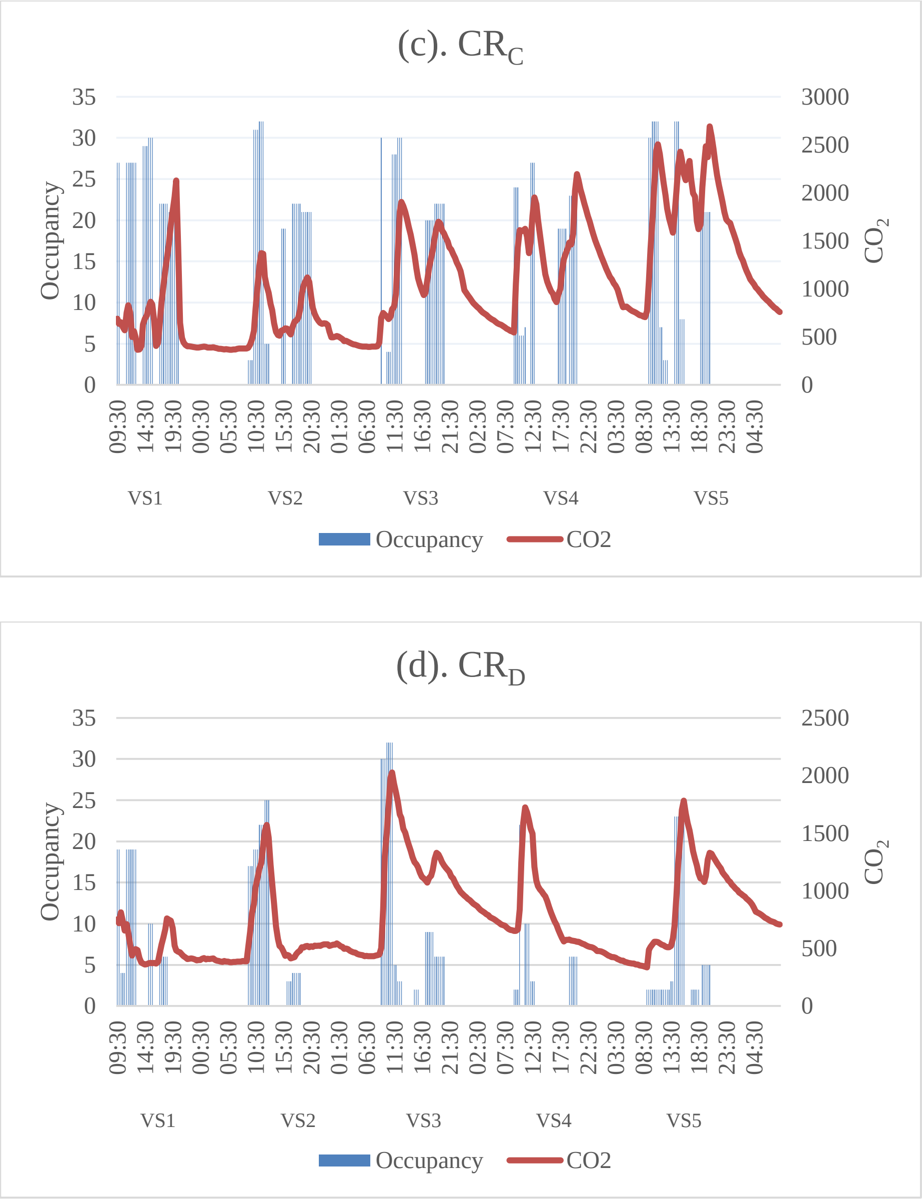


Fig. 8.22: Indoor CO_2 levels in (a). CRA, (b). CRB, (c). CRC and (d). CRD under five ventilation scenarios along with occupancy levels in IESE classrooms

4.2.1.3. NUST Offices

Fig. 4.23 summarizes detailed descriptive statistical analysis of indoor CO_2 levels of all the monitored offices during both seasons. Overall naturally ventilated offices showed higher indoor CO_2 levels with highest mean value in R3B which could be attributed to the absence of windows in that office.

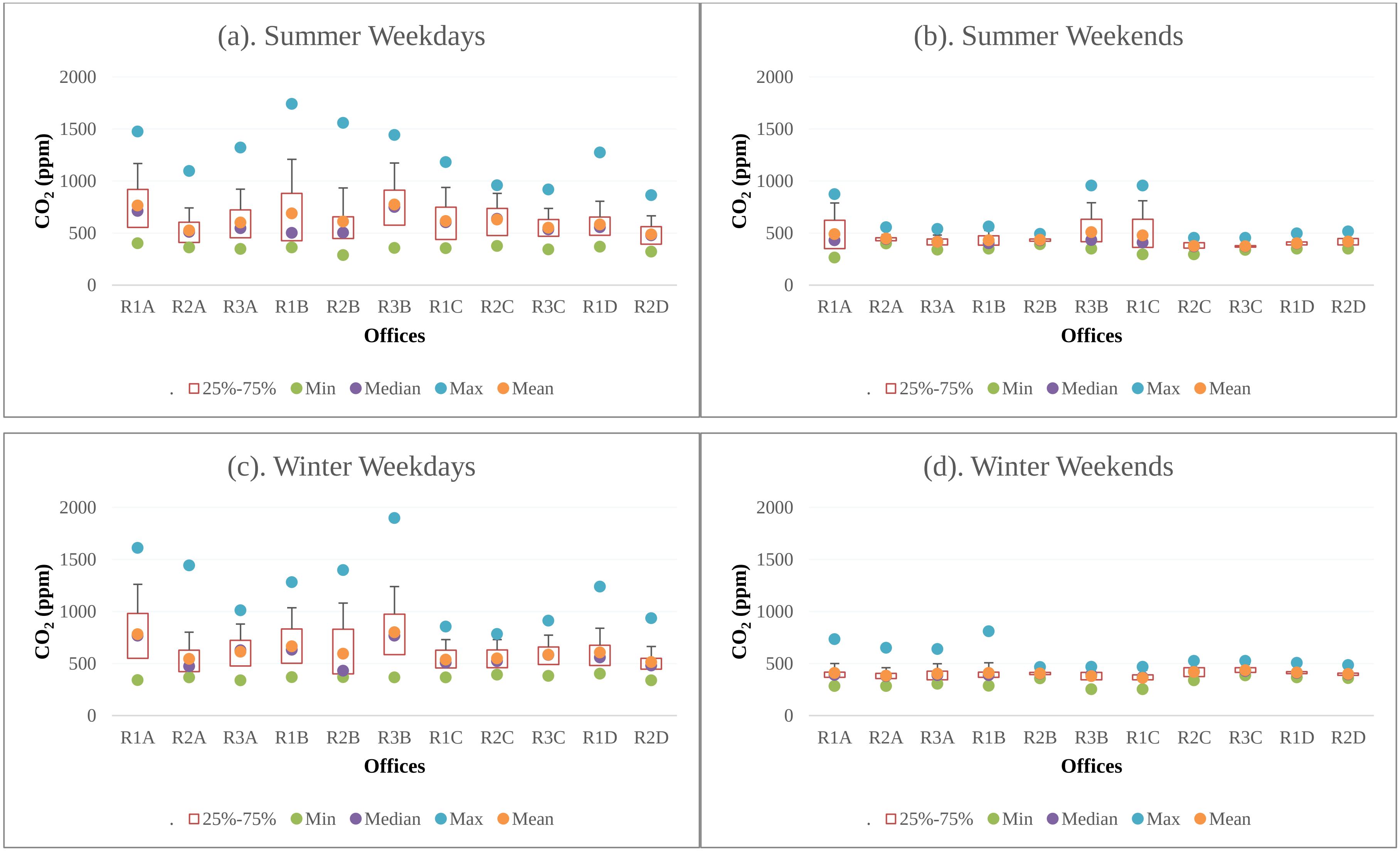
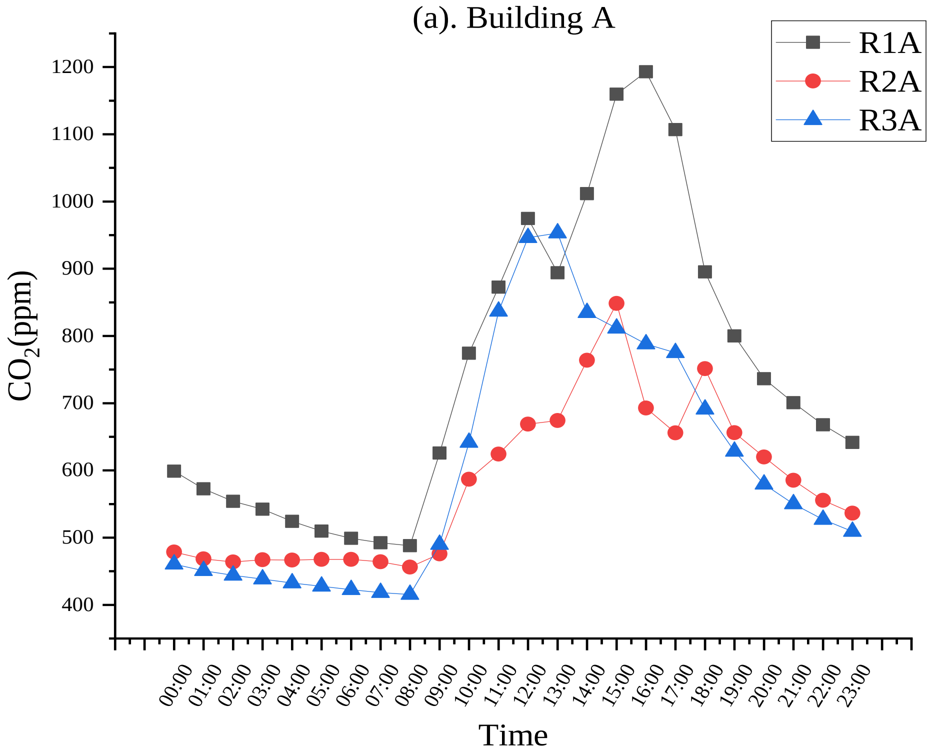
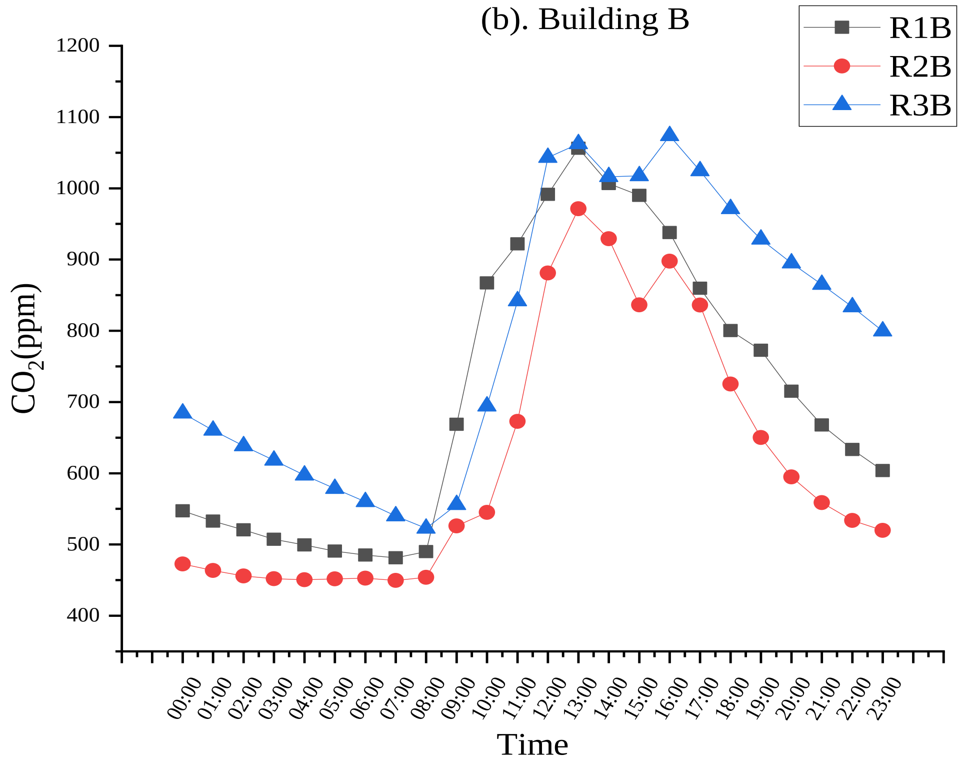


Fig. 8.23: Descriptive statistics of indoor CO_2 levels in the monitored offices during (a) summer weekdays, (b) summer weekends, (c) winter weekdays and (d) winter weekends

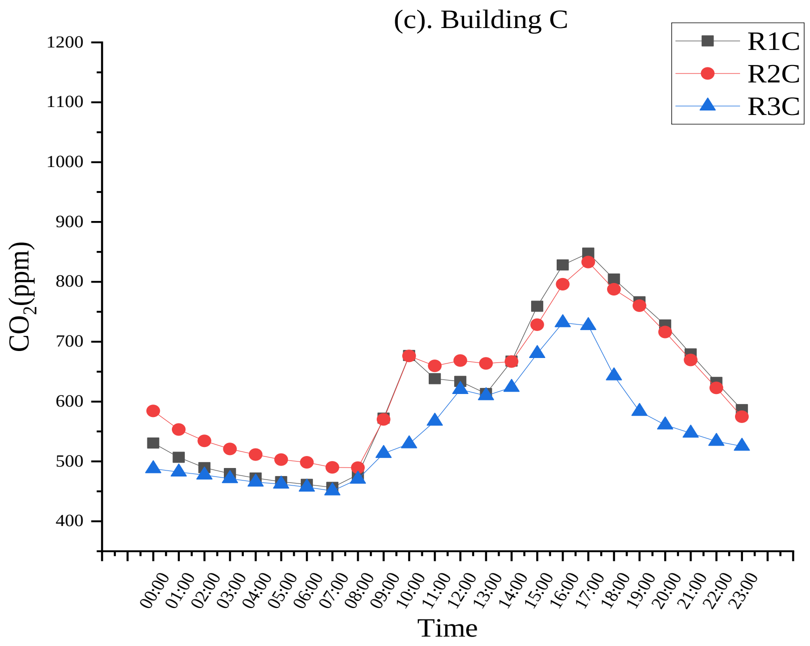
24-hour mean hourly concentration profiles of indoor CO_2 for weekdays and weekends in the monitored offices are shown in Fig. 4.24-4.27. Significant variation ($p<0.05$) was observed along the day during weekdays monitoring of all the offices in both seasons. Profiles of summer season showed two peaks of indoor CO_2 levels during weekdays; first one starting from 09:00 am along with start of office hours lasting till 01:00 pm and the other starting from 02:00 pm which lasts till the end of office hours i.e., 05:00 pm. The possible reason for this occurrence could be the lunch break from 01:00 pm to 02:00 pm. Anomaly was observed in office R2A which showed 3 peaks. This could be explained as the occupants overstayed in the office till 06:00 pm with frequent openings of door (Fig. 4.24). Moreover, indoor CO_2 levels were observed decreasing after occupancy hours in naturally ventilated buildings (Building A and B) till they attain a stable level which was almost equal to ambience i.e., 400 ppm. However, it was found that mechanically ventilated buildings attain ambience earlier after occupancy hours then natural systems. Moreover, during weekends some offices of building A and B showed significant variation ($p<0.05$) along the day which could be the result of less VRs during the decay phase and thus slower decrease in CO_2 concentration to finally achieve ambient levels after long hours (Fig. 4.25). However, due to appropriate VRs in mechanically ventilated offices during the decay phase, no significant variation ($p>0.05$) was observed along the day. Similar trend was observed in the weekdays and weekends profiles of indoor CO_2 levels during winter season (Fig. 4.26 to 4.27). Overall, more indoor CO_2 levels were observed in naturally ventilated buildings in comparison to mechanical systems. Maximum indoor CO_2 level during summer observation was observed in R1B i.e., 1742 ppm and minimum in R2D i.e., 423 ppm. However, during winter season maximum level was observed in R3B i.e., 1898 ppm and minimum in R2D i.e., 438 ppm.



(a). Building A



(b). Building B



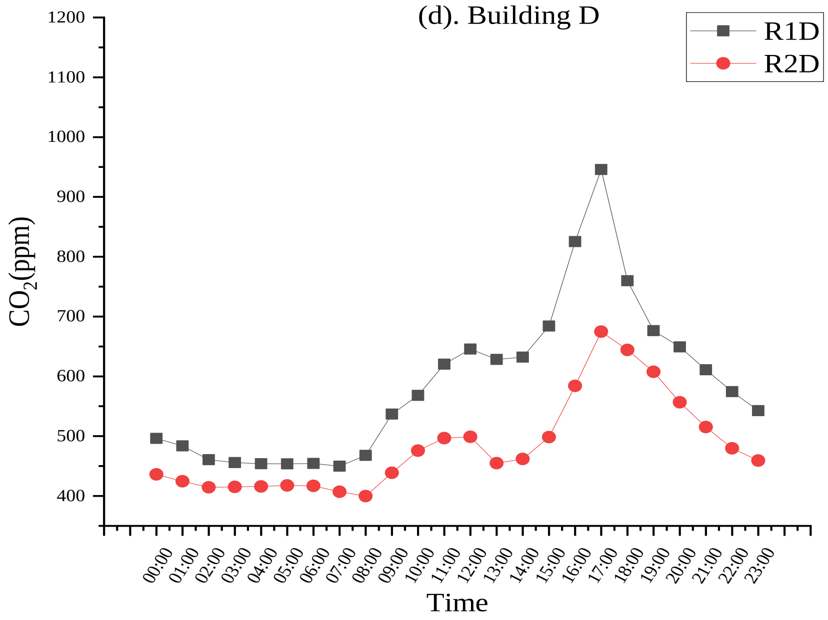
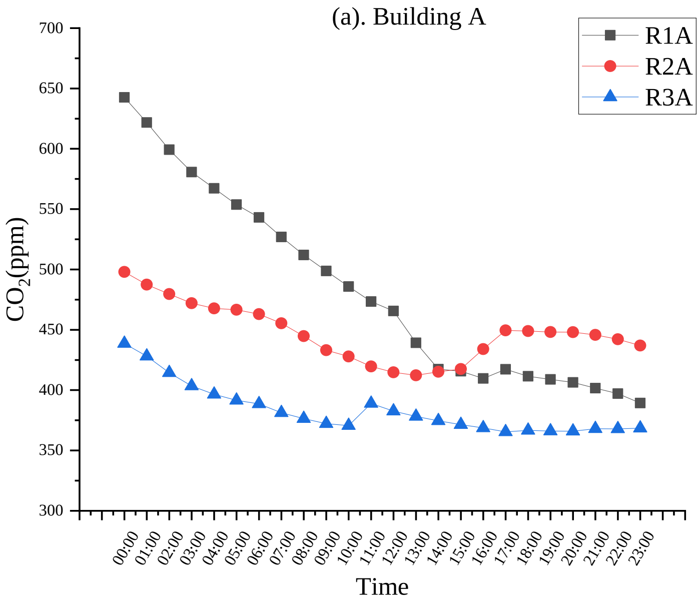
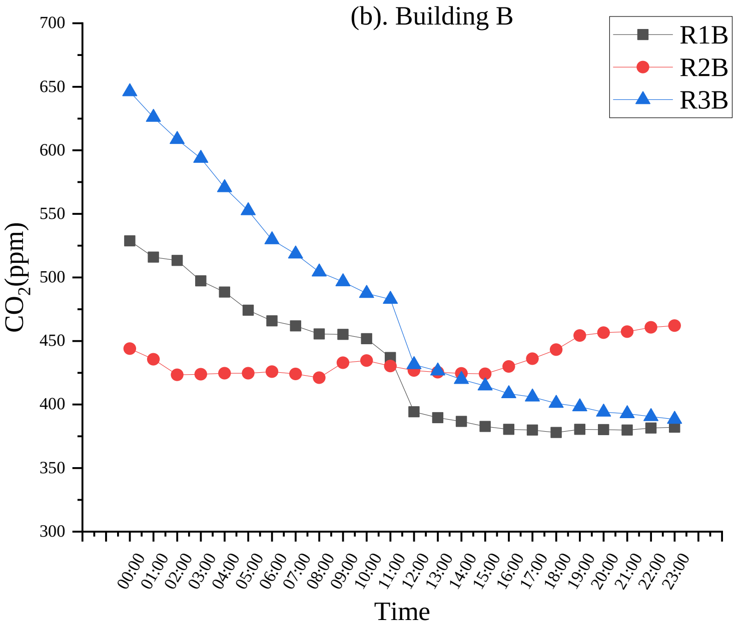


Fig. 8.24: 24-hour mean hourly concentration profiles of indoor CO$_2$ levels in Building A (a), Building B (b), Building C (c) and Building D (d) during summer weekdays in offices



(a). Building A



(b). Building B

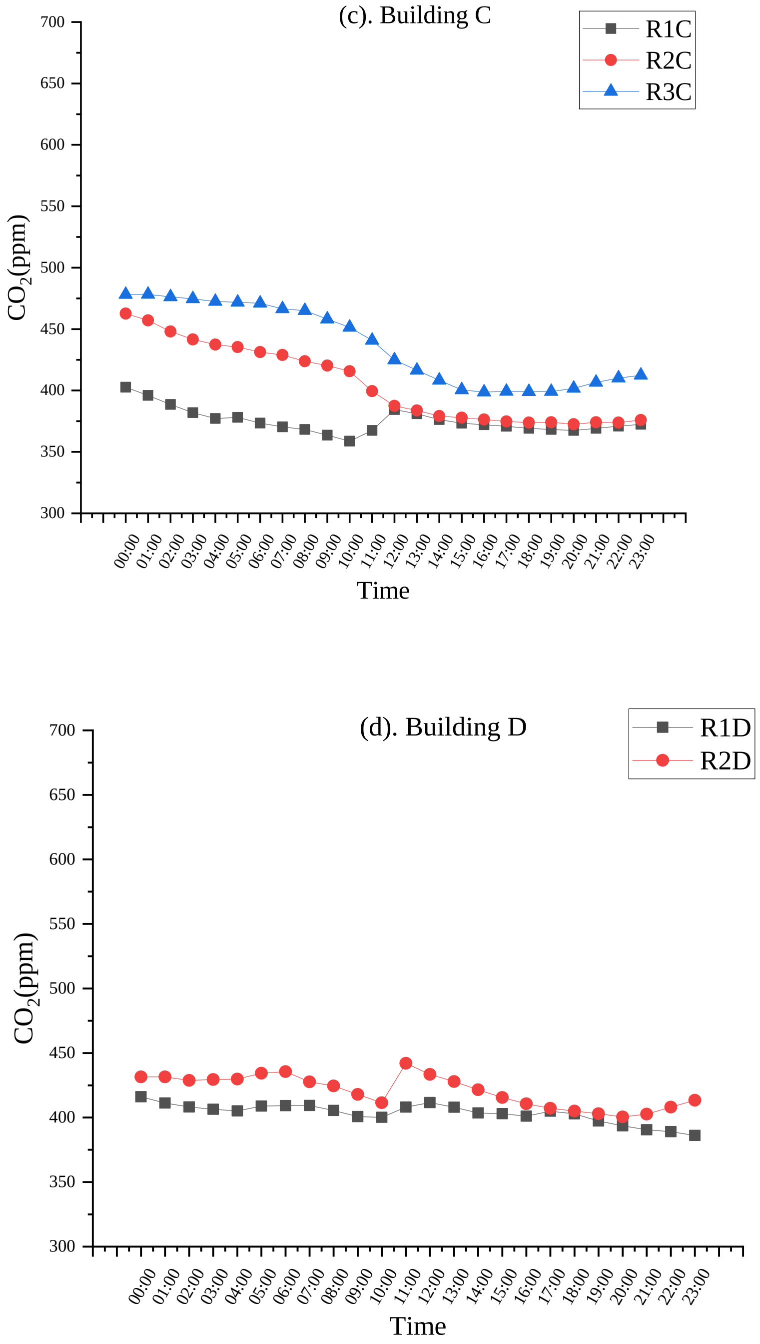
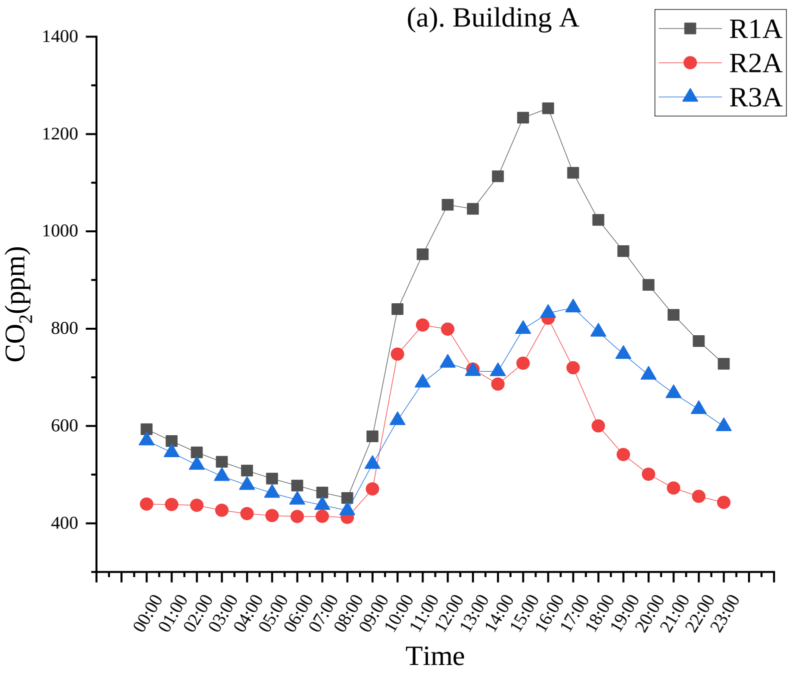
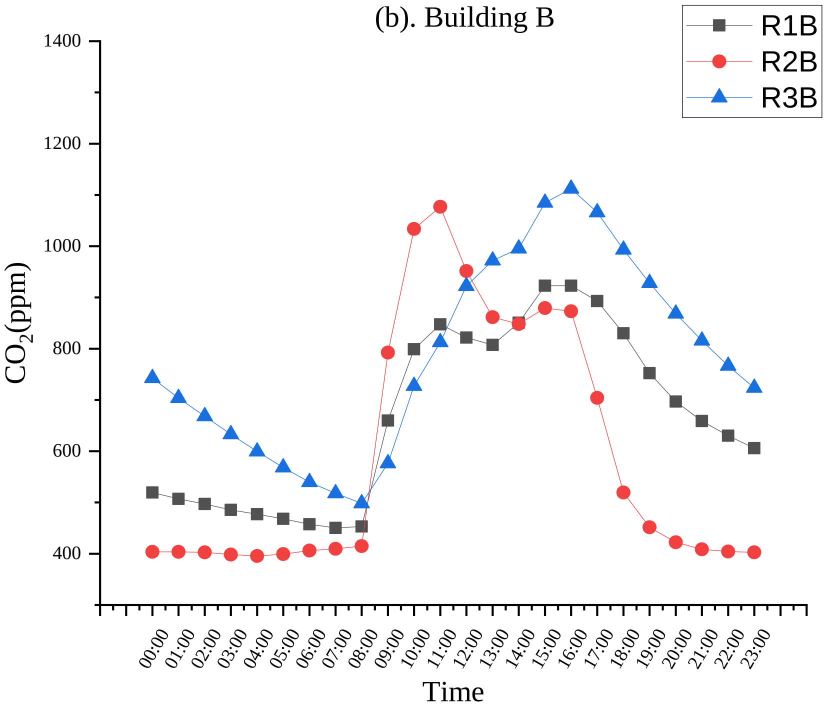
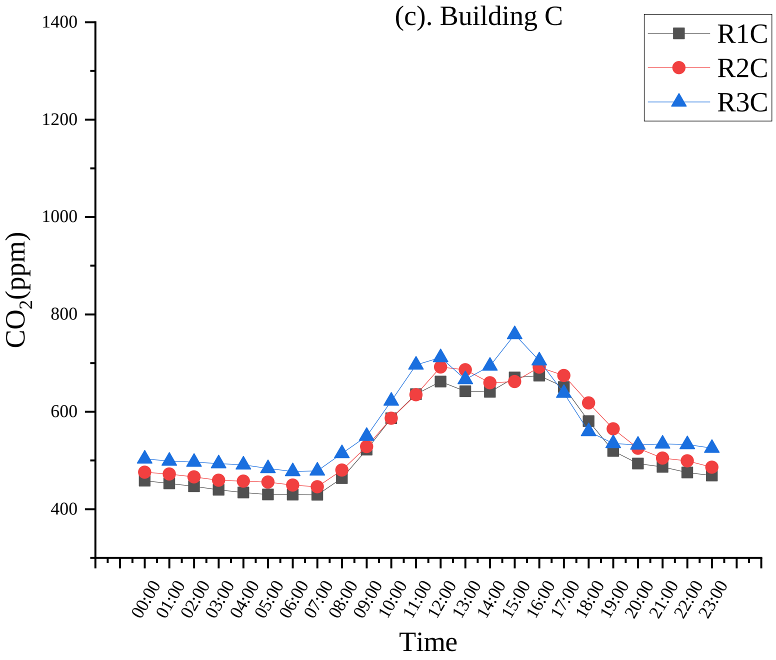


Fig. 8.25: 24-hour mean hourly concentration profiles of indoor CO_2 levels in Building A (a), Building B (b), Building C (c) and Building D (d) during summer weekends in offices


(a). Building A


(b). Building B



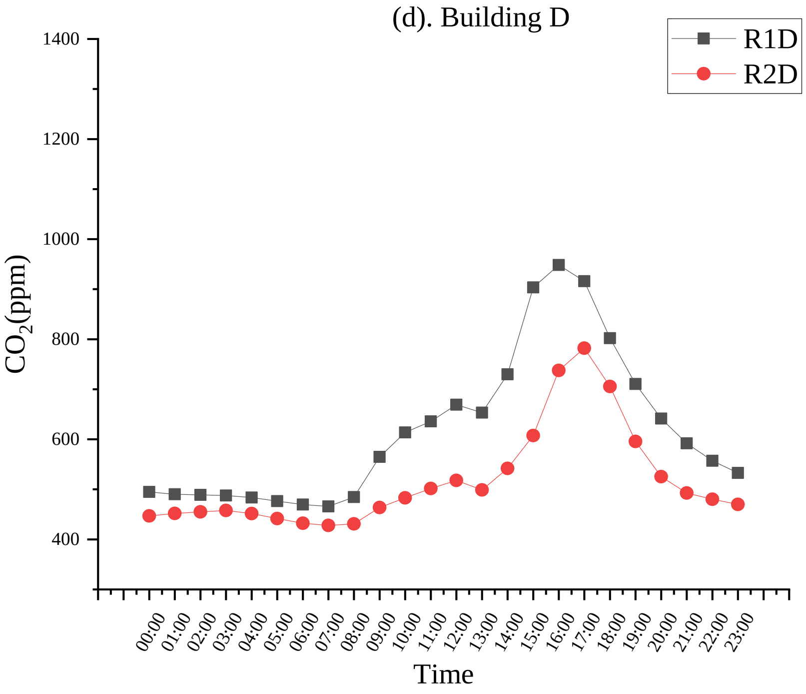
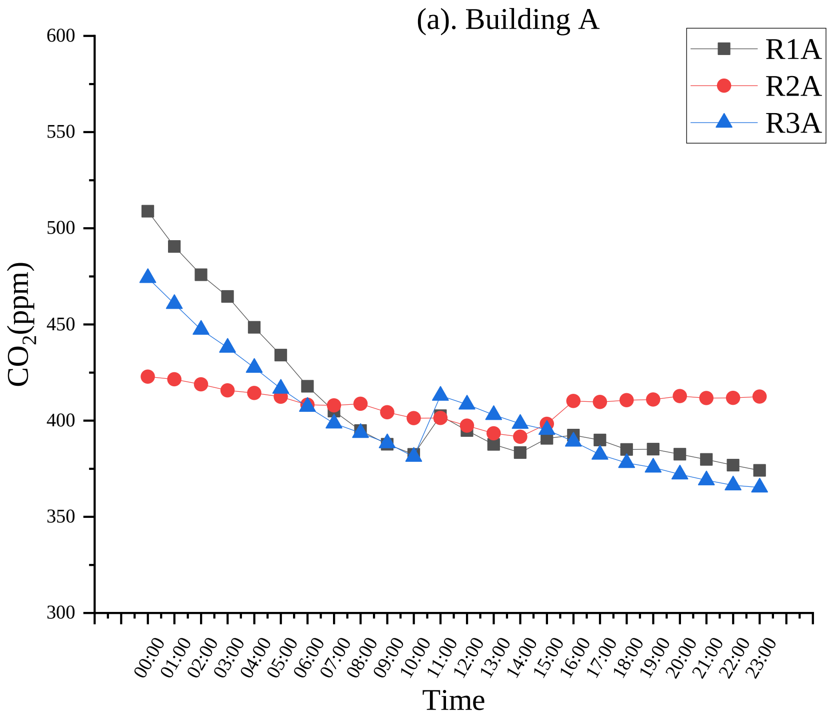
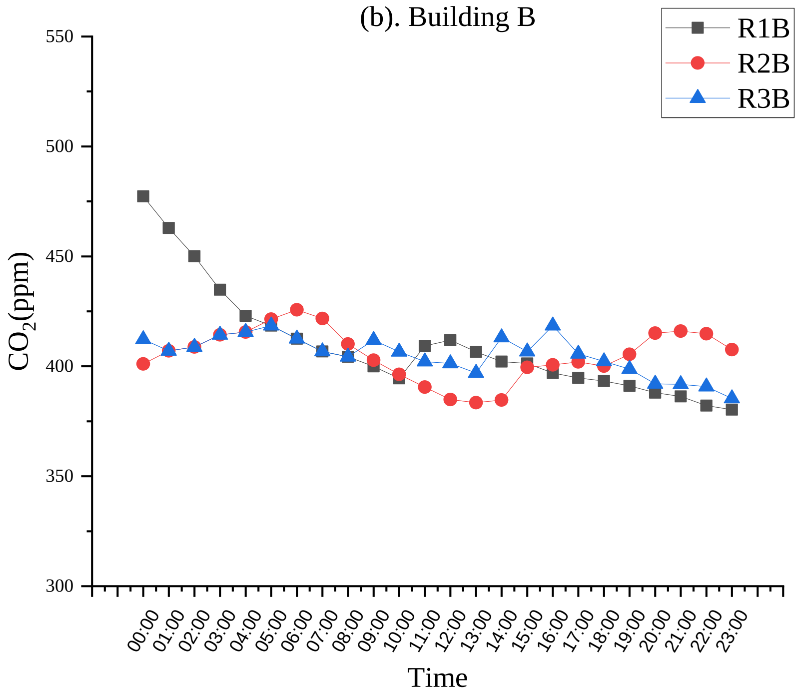


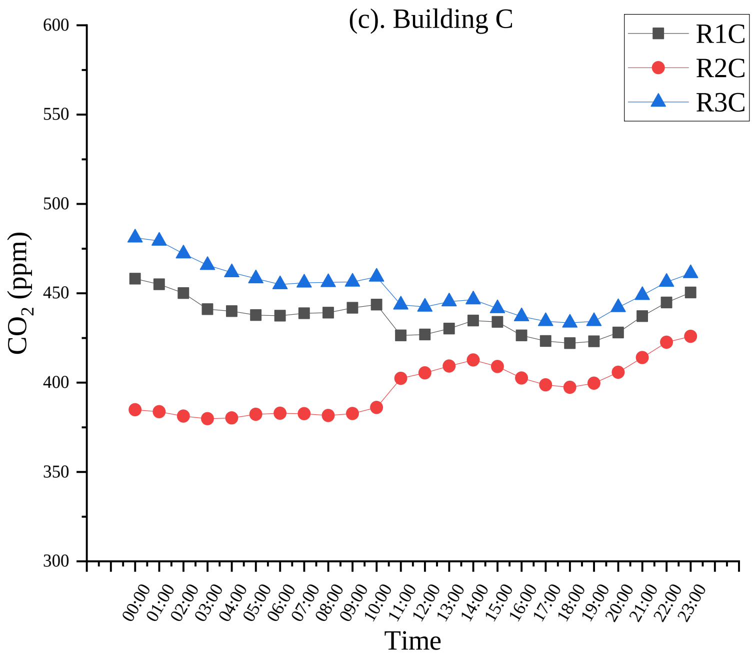
Fig. 8.26: 24-hour mean hourly concentration profiles of indoor CO_2 levels in Building A (a), Building B (b), Building C (c) and Building D (d) during winter weekdays.



(a). Building A



(b). Building B



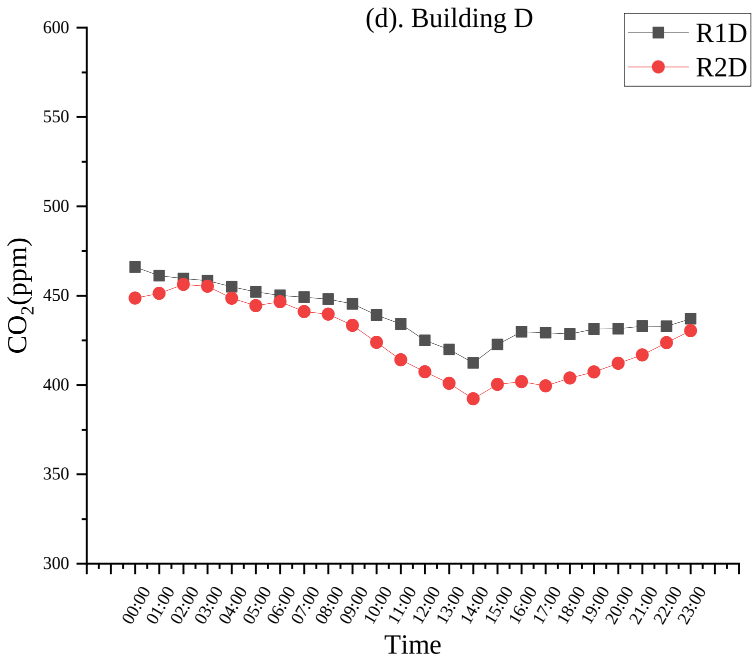


Fig. 8.27: 24-hour mean hourly concentration profiles of indoor CO_2 levels in Building A (a), Building B (b), Building C (c) and Building D (d) during winter weekends

4.2.1.4. NUST Dormitories

Descriptive statistical analysis of indoor CO_2 in all the monitored dormitories is depicted in Fig. 4.28. Statistical results of indoor CO_2 monitoring in selected dormitories showed significant difference ($p<0.05$) between sleep hours and non-sleep hours and between different categories of dormitories i.e., cubical, bi-seater and tri-seater for all cases.

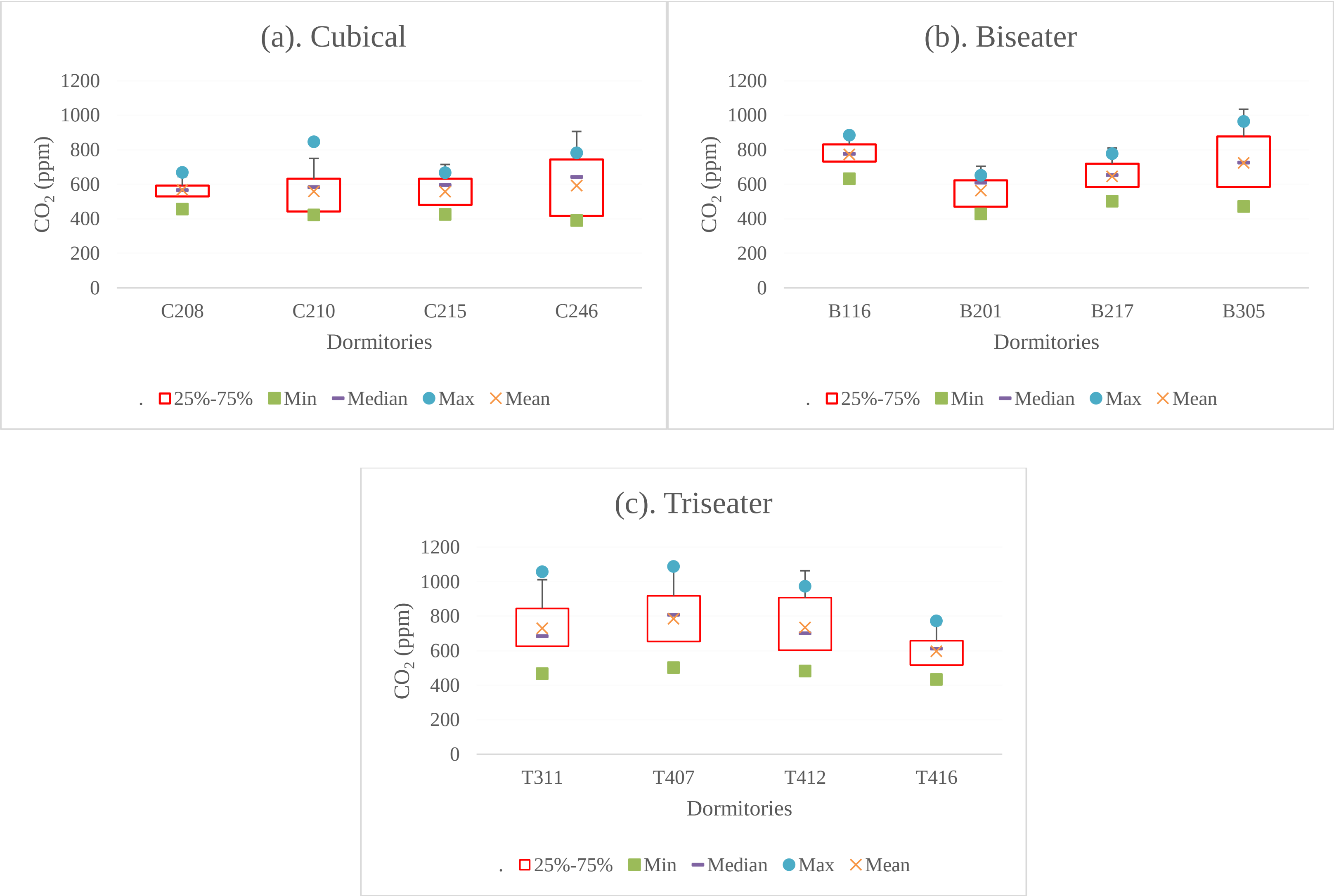
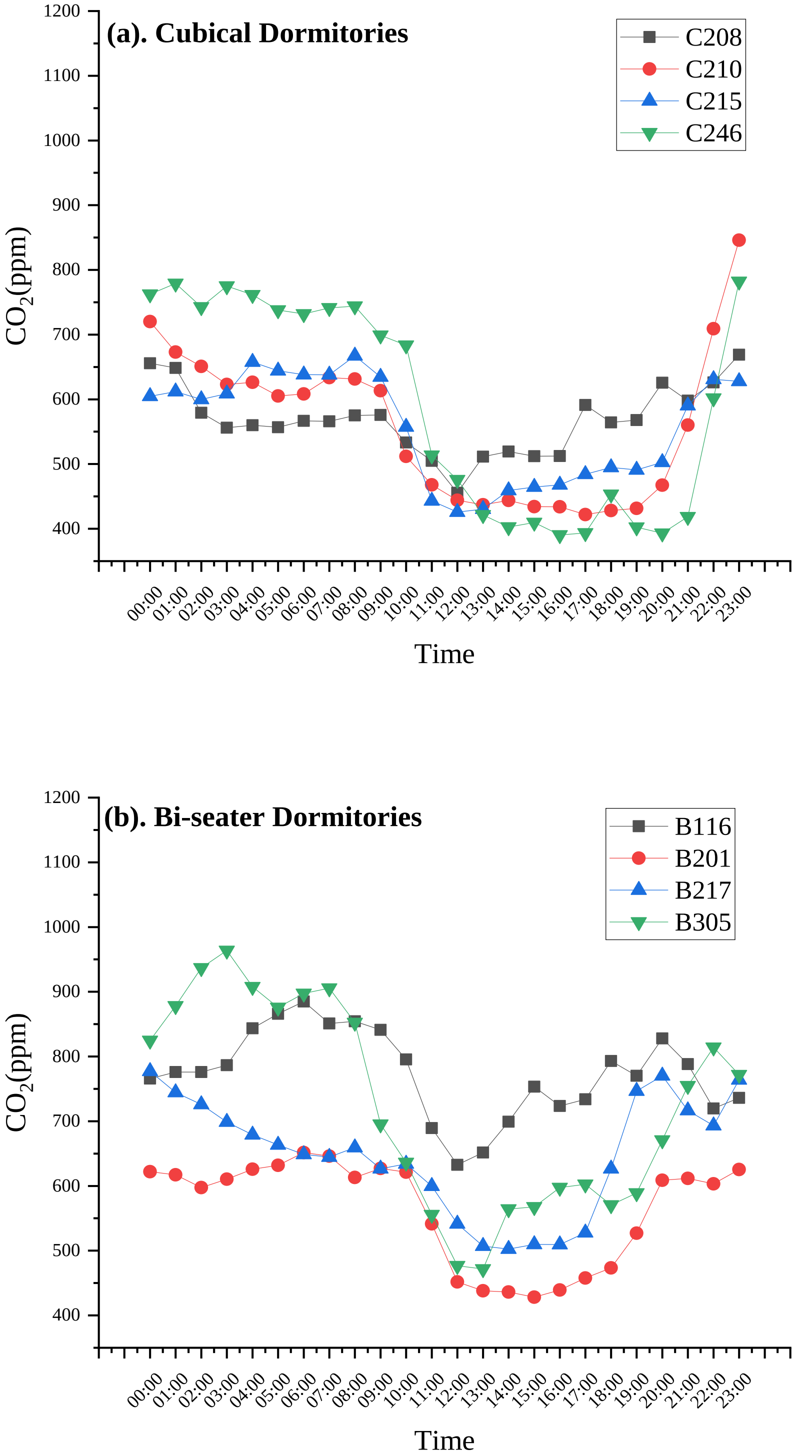


Fig. 8.28: Descriptive statistics of indoor CO_2 levels in (a). cubical, (b). biseater and (c). triseater dormitories

24-hour mean hourly profiles of indoor CO_2 levels in the monitored dormitories are depicted in Fig. 4.29. A significant contribution of occupancy level and duration in the build-up of indoor CO_2 levels can't be repudiated. However, it was noted that students residing in the monitored dormitories had different timings of lecture sessions and thus, used to visit dormitories on and off. Due to this reason, indoor CO_2 levels were observed varying during daytime in all dormitories. However, there was a curfew time from the administration of dormitories from 09:00 pm onwards, after which students were not allowed to leave their dormitory building. Thus, data records were divided into two parts for analysis i.e., sleep hours and non-sleep hours. Generally, class sessions of students residing in dormitories were scheduled at 09:00 am thus, resulting a decrease in indoor CO_2 levels as evident from Fig. 4.29. As cubical dormitories had attached washrooms facility due to which students used to leave dormitories just before their lecture sessions (09:00 am). However, bi-seater and tri-seater dormitories had community washroom facility, thus students frequently open and close door of dormitory while getting ready in the morning, resulting in decrease in indoor CO_2 levels before 09:00 am. Moreover, no noticeable trend in indoor CO_2 levels was evident after 09:00 am till 09:00 pm after which maximum students were found in their dormitories which can be evident from the rising trend of indoor CO_2 levels (Fig. 4.29). Comparison of indoor CO_2 levels in different categories of dormitories showed less levels of indoor CO_2 in cubical dormitories than others. However, windows were found open in B201 and T416 during sleep hours which resulted in less build-up of indoor CO_2 levels in comparison to other dormitories. Maximum levels were observed in T407 as 1088 ppm and minimum in C246 as 390 ppm.


(a). Cubical Dormitories
C208
C210
C215
C246
CO$_2$(ppm)
1200
1100
1000
900
800
700
600
500
400
00:00 01:00 02:00 03:00 04:00 05:00 06:00 07:00 08:00 09:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00
Time
(b). Bi-seater Dormitories
B116
B201
B217
B305
CO$_2$(ppm)
1200
1100
1000
900
800
700
600
500
400
00:00 01:00 02:00 03:00 04:00 05:00 06:00 07:00 08:00 09:00 10:00 11:00 12:00 13:00 14:00 15:00 16:00 17:00 18:00 19:00 20:00 21:00 22:00 23:00
Time

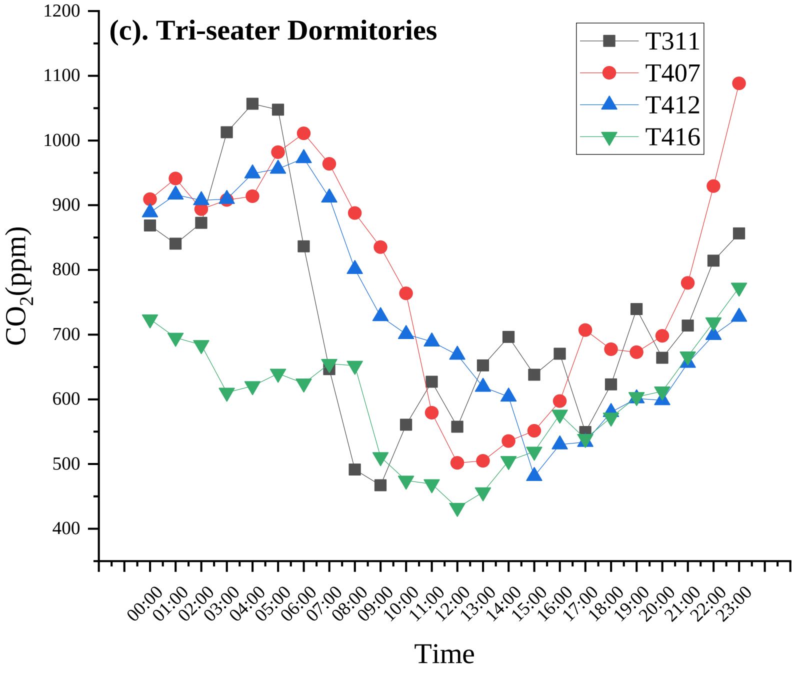


Fig. 8.29: Mean hourly indoor CO_2 levels in (a). cubical, (b). bi-seater and (c). tri-seater dormitories

4.2.2. Exceedance from Standards

Following ASHRAE 62.1-2016 Standard (for ventilation), percentage exceedance of the per-minute data records for indoor $CO_2$from standards was calculated for all the monitored sites and is shown in Table 4.18- 4.21. Indoor CO_2 levels depend upon number of occupants, thus no exceedance from reference standards was found during weekends for all cases under study.

Moreover, in IESE classrooms (Table 4.19) comparatively less exceedance of indoor CO_2 levels was noticed with open windows (VS1 and VS2) for all classrooms. Highest exceedance was found in VS5 when all windows and ventilators were closed for all classrooms except CRD where highest exceedance was in VS3. The anomaly can be explained in terms of high occupancy level during that monitoring day. Furthermore, significantly less exceedance of indoor CO_2 in mechanically ventilated offices was also evident during weekdays and occupation period of both seasons (Table 4.20). In cubical and bi-seater dormitories, indoor CO_2 levels were below recommended limits most of the time (Table 4.21). However, levels in tri-seater dormitories exceeded the limits during sleep hours for all cases except T416. This anomaly could be due to open window in the respective dormitory during monitoring.

Table 8.17: Exceedance of CO_2 levels observed values from Standards in NCLS classrooms

	CO_2 (>1000 ppm)					
	WD[a]		**WE[b]**		**OP[c]**	
	S[d]	**W[e]**	**S**	**W**	**S**	**W**
CR01	26.5	14.7	0	0	71.5	52.1
CR02	36.5	12.1	0	0	85.0	41.1
CR03	48.5	22.5	0	0	91.3	59.7
CR04	32.5	12.7	0	0	72.1	42.7
CR05	30.8	28.9	0	0	93.1	42.5
CR06	11.6	17.1	0	0	59.3	60.1
CR07	11.1	24.9	0	0	60.6	60.3
CR08	11.6	9.2	0	0	53.6	37.5
CR09	16.6	24.1	0	0	60.0	74.9
CR10	22.3	37.7	0	0	78.3	76.4
CR11	34.7	43.1	0	0	84.1	78.9

[a] Weekday

[b] Weekend

[c] Occupancy Period

[d] Summer

[e] Winter

Table 8.18: Exceedance (%) to relevant standards for per-minute data records of indoor CO_2 levels in IESE classrooms

		CO_2
	Ventilation Scenarios	**>1000 ppm**
CRA	VS1	0
	VS2	0
	VS3	7.6
	VS4	18.3
	VS5	52.4
CRB	VS1	3.1
	VS2	0
	VS3	11.6
	VS4	0
	VS5	12.8
CRC	VS1	11.7
	VS2	13.8
	VS3	48.4
	VS4	69
	VS5	82.1
CRD	VS1	0
	VS2	13
	VS3	57.3
	VS4	15.5
	VS5	45.7

Table 8.19: Percentage (%) exceedance of indoor CO_2 levels from ASHRAE standard limits in offices

Building	**Room**	**ASHRAE Standards**					
		CO_2 (>1000 ppm)					
		WDs[a]		**WEs**[b]		**OP**[c]	
		S[d]	**W**[e]	**S**	**W**	**S**	**W**
A	R1A	19.3	21.3	0	0	41.6	49.1
	R2A	0.3	1.7	0	0	1	5.8
	R3A	5.1	0.1	0	0	15.3	0.2
B	R1B	18.2	7.5	0	0	42.8	11.3
	R2B	14.5	6.7	0	0	36.7	20.2
	R3B	17.6	27.7	0	0	35.9	38.5
C	R1C	3.6	0	0	0	12.4	0
	R2C	0	0	0	0	0	0
	R3C	0	0	0	0	0	0
D	R1D	2.7	3.4	0	0	3	8
	R2D	0	0	0	0	0	0

[a] Weekdays

[b] Weekends

[c] Occupation Period

[d] Summer

[e] Winter

Table 8.20: Exceedance of CO_2 observed values from Standards in dormitories

Dormitories	**Room**	**ASHRAE Standards**
		CO_2 (>1000 ppm)
Cubical	C208	2.62
	C210	0
	C215	0
	C246	10.75
Bi seater	B116	2.03
	B201	0
	B217	0
	B305	2.56
Tri seater	T311	15.06
	T407	24.05
	T412	17.36
	T416	1.42

4.2.3. Ventilation and Air Exchange Rates

AERs and VRs were calculated for all the monitored sites under study during occupancy hours. These minute-by-minute values were later averaged arithmetically as average VRs. The calculations were performed using eqs. 3.16 and 3.17 and are presented in below sub-sections for all the monitored sites.

4.2.3.1. NCLS Classrooms

Table 4.22 shows averaged VRs per person and AERs for each monitored classroom of primary school. Values of VRs were found in range of 1.1-6.3 l/s/person, while that of AERs in range of 1.4-10.6 hour^{-1}. Since all classrooms were naturally ventilated, the variation of VRs among the rooms can be associated to multiple factors including the ventilation area, door/window opening frequencies/practices as well as other ambient parameters including wind speed and direction with respect to the orientation of rooms (and thus doors and windows). Results show that average VRs were below the minimum ASHRAE recommended limits i.e. 8 l/s/person (ASHRAE, 1999a) for all classrooms. According to REHVA Guidebook (REHVA, 2010), VRs should be above 3 l/s/person during full occupation. It has been found that VRs in CR02, CR05 and CR11 didn't even meet recommendations of REHVA Guidebook[1].

Table 8.21: Ventilation and air exchange rates in the classrooms of primary school

Classrooms	**Volume** (m^3)	**Ventilation Rates** (l/s/person)	**Air Exchange Rates** (1/hour)
CR01	71.6	5.6	7.8
CR02	71.6	1.8	1.8
CR03	102.4	3.6	3.6
CR04	61.7	4.2	5.9
CR05	61.7	1.1	1.4
CR06	79.6	7.7	9.0
CR07	62.5	6.3	10.6
CR08	61.9	6.3	9.2
CR09	61.9	5.3	7.5
CR10	61.9	4.03	5.9
CR11	61.7	1.6	1.7

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[1] ASHRAE's and REHVA's standards for mechanically ventilated rooms are used because during lessons air-conditioning or heating fans were turned on.

4.2.3.2. University Classrooms

VRs and AERs for all five ventilation scenarios under study were calculated for occupancy hours and are presented in Table 4.23. As expected, opening of windows and ventilators facilitate in increasing VRs and AERs. On comparing results with ASHRAE recommended minimum limits (8 l/sec/person), it was concluded that average VRs meet the standard limits for VS1 and VS2 for all classrooms. However, for VS3, average VRs of CR_C and CR_D didn't meet the standards. Moreover, for VS4 and VS5, limits never meet for any classroom under study. Up-to authors knowledge, currently, less guidelines are available for VRs and AERs to limit airborne spread of COVID-19. Park et al., (Park et al., 2021) while working on natural ventilation strategies to prevent airborne transmission of COVID-19, found that infection probability could be reduced to below 1% by 15% opening of windows (AER= $6.51h^{-1}$) and use of face masks. Moreover, Ho (Ho, 2021), while working on the spread of pandemic concluded that airborne infection transmission could be minimized by increasing ventilation. However, in an already published study on airborne transmission of tuberculosis, it was concluded that AERs of $8h^{-1}$ is indispensable to avoid the spread of virus. (Mushayabasa, 2013b)

Table 8.22: Ventilation and air exchange rates for all ventilation scenarios in university classrooms

	VS1		**VS2**		**VS3**		**VS4**		**VS5**	
	l/sec/person	**1/hr**	**l/sec/person**	**1/hr**	**l/sec/person**	**1/hr**	**l/sec/person**	**1/hr**	**l/sec/person**	**1/hr**
CR_A	22.1	8.2	13.4	3.9	9.0	2.9	7.3	2.5	5.2	1.5
CR_B	19.4	4.9	14.0	3.4	8.2	2.1	6.6	1.6	6.0	1.4
CR_C	15.4	5.1	10.6	3.1	6.8	2.0	5.6	1.8	4.5	1.3
CR_D	21.3	5.3	14.5	2.3	7.9	1.7	6.8	1.3	4.6	1.4

4.2.3.3. NUST Offices

Minute-by-minute VRs and AERs calculated during occupancy hours for each office were averaged and are reported in Table 4.24. According to ASHRAE standards and recent guidelines of Chartered Institute of Building Services Engineers (CIBSE) (CIBSE, 2020b) after COVID-19 pandemic, minimum VRs should be 8 and 10 l/sec/person respectively. On comparing results with standards, it was found that VRs in all offices were above the ASHRAE standards. Moreover, similar results were found during comparison with CIBSE limits except in R1A where average VRs were slightly lower than the standards. Overall, higher VRs were observed in mechanically ventilated offices in comparison to naturally ventilated offices.

Table 8.23: Average ventilation and air exchange rates in monitored offices

Offices	**Volume**	**Occupancy**	**Ventilation Rate**	**Air Exchange Rates**
	(m^3)		**(l/s/person)**	**(1/hour)**
RIA	65.14	3	9.93	1.65
R2A	35	2	12.12	2.49
R3A	135.59	1	10.11	0.27
R1B	83.42	3	10.67	1.38
R2B	70.44	4	11.69	2.39
R3B	55.55	2	11.35	1.47
R1C	37.12	2	17.52	3.4
R2C	37.12	2	17.01	3.3
R3C	42.94	2	19.45	3.26
R1D	258.44	5	17.16	1.19
R2D	217.54	4	19.03	1.26

4.2.3.4. NUST Dormitories

Minute-by-minute AERs and VRs were calculated for sleep hours in dormitories which were later averaged and are presented in Table 4.25. Difference in AERs and VRs among same category of dormitories is evident from table which could be due to different activity patterns. In some dormitories windows was found open during sleep hours which resulted in less CO_2 build-up and higher AERs and VRs. Overall average AERs and VRs were found in the range of 1.6-4.2 hr^{-1} and 9.8-32 l/sec/person. On comparing the levels with ASHRAE minimum recommended limits i.e., 8 l/sec/person (ASHRAE, 1999a), it was observed that all the dormitories were well ventilated and meet the recommended criteria.

Table 8.24: Air exchange and ventilation rates in dormitories

	Dormitory	**Volume**	**Air Exchange Rates**	**Ventilation Rates**
		m^3	**1/hr**	**l/sec/person**
Cubical	C208	27.2	4.2	32.0
	C210	27.2	3.9	29.4
	C215	27.2	3.7	27.7
	C246	27.2	3.2	24.1
Bi-seater	B116	54.4	2.5	19.0
	B201	54.4	3.3	25.0
	B217	54.4	2.9	21.9
	B305	54.4	2.6	19.5
Tri-seater	T311	64.6	2.1	12.7
	T407	64.6	1.7	10.3
	T412	64.6	1.6	9.8
	T416	64.6	3.0	17.9

4.2.4. Airborne Infection Risk Assessment

Although IAQ and ventilation quality was assessed in four different indoor environments, airborne infection risk of COVID-19 was estimated in IESE classrooms only. This could be explained by the fact that airborne transmission risk of COVID-19 is highly dependent upon VRs, occupancy and exposure durations (eq. 3.20) and in all other monitored sites (except IESE classrooms) different ventilation conditions and variation occupancy along the day were not assessed.

Results showed that enhanced ventilation (by opening of windows and ventilators), lowers the infection transmission risk, which is supported by previously reported literature (Di Gilio et al., 2021). Values of airborne transmission risk for all classrooms under five ventilation scenarios were in range between 1.9-11.9% and are presented in Fig. 4.30. Maximum transmission risk was observed in VS5 (all windows and ventilators close) for CR_A, CR_B, CR_C and CR_D as 9.9, 10.7, 11.9 and 11.32% respectively and minimum in VS1 as 1.9, 3.2, 3.1 and 2.9 respectively.

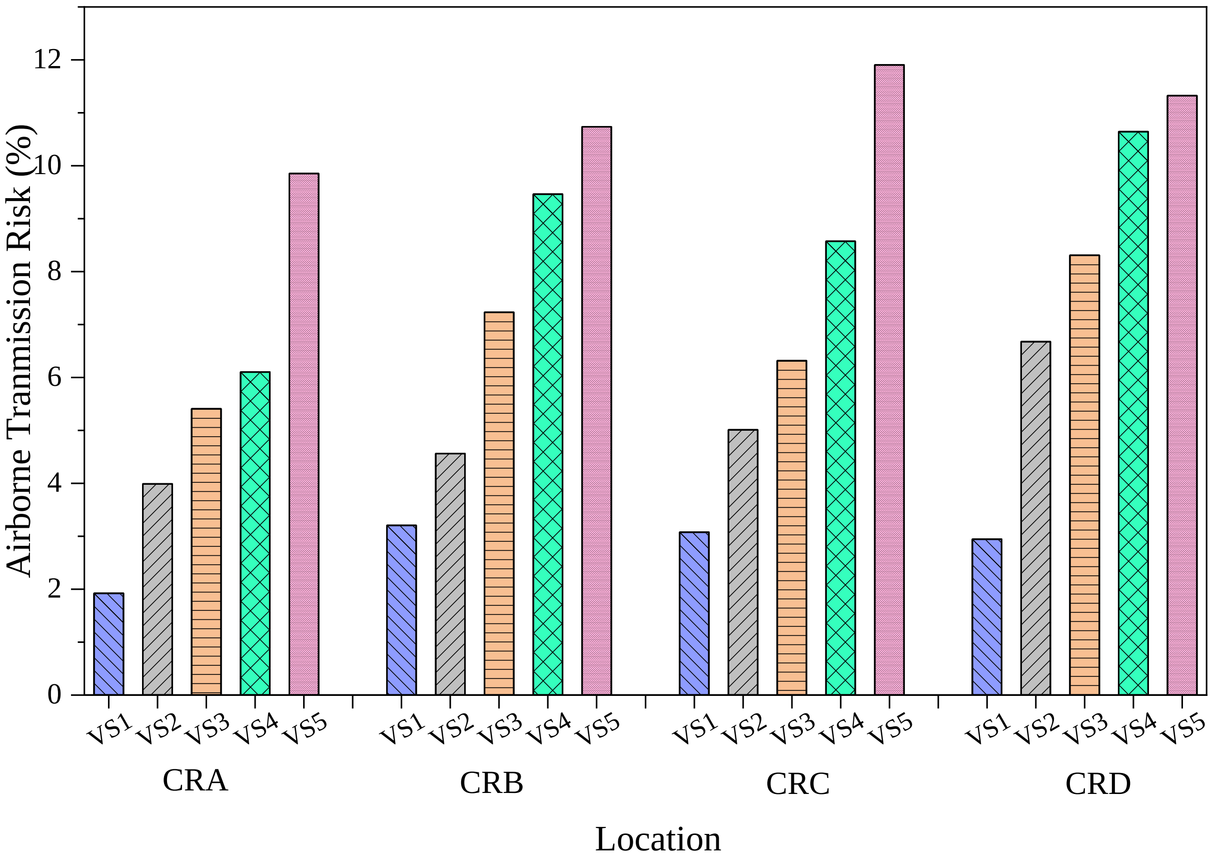

Fig. 8.30: Airborne transmission risk of COVID-19 in classrooms under different ventilation scenarios[2]

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[2] VS1= Front window open + back window open + front ventilator open + back ventilator open
VS2= Front window close + back window open + front ventilator open + back ventilator open
VS3= Front window close + back window close + front ventilator open + back ventilator open
VS4= Front window close + back window close + front ventilator close + back ventilator open
VS5= Front window close + back window close + front ventilator close + back ventilator open

4.3. Phase 3: System Dynamics Based Modeling for Air Exchange Rates

Section for results and discussion of Phase 3 has been divided into three sub-sections. First sub-section presents simulation results of indoor CO_2 levels by using VRs calculated in Phase 2 as an input in developed SD based model. Besides, results of VRs optimization has been presented in second sub-section and limitations of the model in third subsection. Detailed description of each sub-section is presented below.

4.3.1. Simulation of Indoor CO_2 Concentration Utilizing Calculated VRs as Input

Phase 2 of the dissertation involved calculation of VRs using transient mass balance, steady-state and decay method (Section 4.2.3) for all the monitored indoor environments i.e., NCLS classrooms, offices, IESE classrooms and dormitories. Those VRs were input in SD based model and results were compared with the monitored data. Results of one of the monitoring days for R1A are shown in Fig. 4.31. Multiple statistical tests were conducted using the monitored and simulated indoor CO_2 data to check the accuracy of the methods for VRs calculation. Results of spearman correlation test showed strong correlation (coefficient>0.90) between monitored and simulated levels for all offices when minute-by-minute VRs estimated using transient mass balance methods were input. However, as steady-state and decay method present average VRs, lower correlation (coefficient <0.60) was noted between measured and simulated levels most of the time. Results of root mean square error (RMSE) test showed similar observations.

Moreover, decay method overlooked actual ventilation conditions and occupancy during the occupancy hours and thus over estimated indoor CO_2 levels. Although these issues were addressed in steady state method but as the method use average VRs, it underestimated indoor levels. Hence, it was concluded that using VRs calculated by following steady-state and decay approaches couldn’t be a good representative of actual ventilation conditions in an indoor space and are thus more susceptible to inaccuracies in comparison to transient mass balance method.

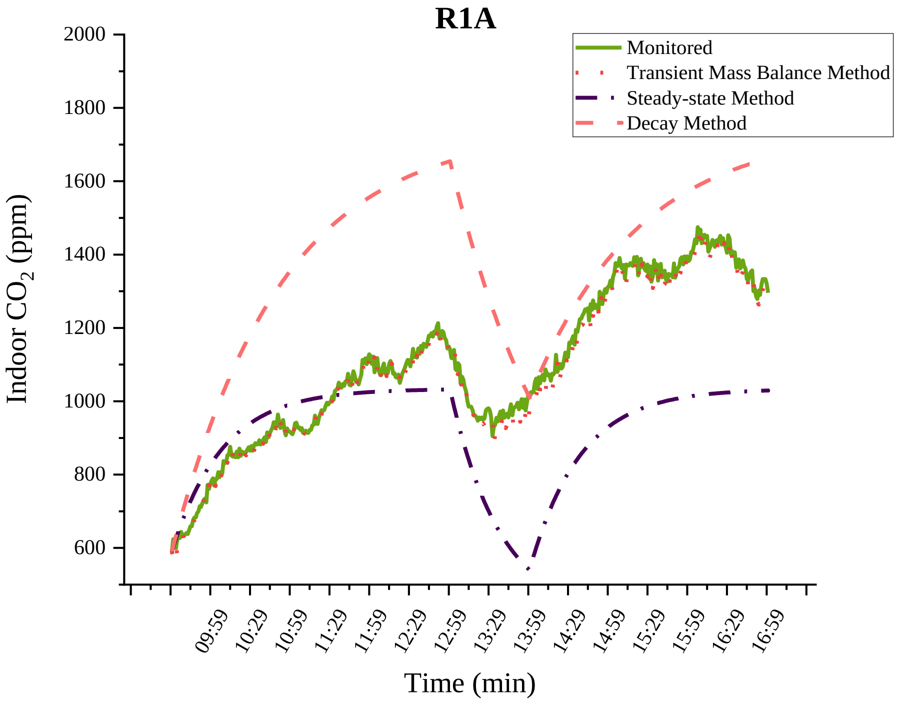

Fig. 8.31: Monitored and simulated indoor CO_2 levels in R1A

4.3.2. Optimization of VRs

COVID-19 pandemic, which emerged in late 2019, has affected almost every aspect of human life including indoor ventilation requirements. According to ASHRAE standards, indoor CO_2 levels must not exceed 700 ppm (ASHRAE, 2016) above the outdoor levels and minimum ventilation requirements are 8 l/sec/person (ASHRAE, 1999b). Keeping in view, strict regulations have been imposed in European countries (REHVA, 2020), limiting indoor CO_2 levels below 800 ppm. Additionally, national recommendations of Spain in pandemic era suggested limiting level of indoor CO_2 as 700 ppm in well mixed spaces to reduce the spread of virus (Marr, L., Miller, S., Prather, K., Haas, C., Bahnfleth, W., Corsi, R., Tang, J., Herrmann, H., Pollitt, K., Ballester, J., Jim´enez, 2020). Moreover, recent guidelines of Chartered Institute of Building Services Engineers (CIBSE) (CIBSE, 2020a), suggested minimum ventilation requirements as 10 l/sec/person. Thus, in the present study, different VRs i.e., 6, 8, 10, 12, 14, 16, 18 and 20 l/sec/person were input in the SD model and results were compared with the standards and regulations as presented in Fig. 4.32. It was found that to restrict indoor CO_2 levels to 1100 ppm (ASHRAE standard), minimum VRs should be 10 l/sec/person. However, to meet the European and Spanish regulations minimum VR requirements were found as 16 and 20 l/sec/person respectively.

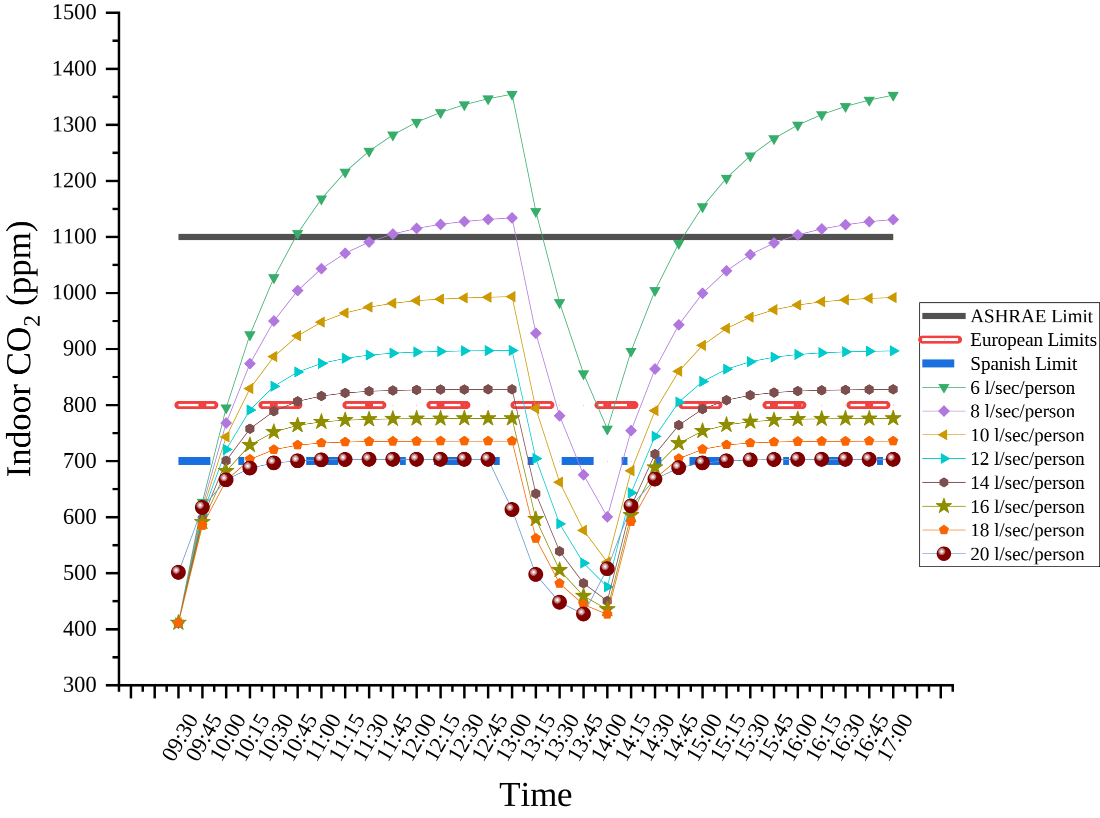

Fig. 8.32: Simulated indoor CO_2 levels using different ventilation rates

4.3.3. Limitations of System Dynamics Modeling

Although SD is a robust modeling approach for understanding and analyzing complex engineering system, however, the approach has some limitations. SD based model can’t handle complex systems accurately and generally have less predictive power (Cabrera, 2023). In addition , model users might struggle in understanding and trusting model results if not closely involved in the process of model development (Currie et al., 2018).

4.4. Phase 4: Association of Indoor CO_2 with Particulate Matter

Firstly, IAQ in the monitored classrooms was assessed followed by calculation of VRs in this phase of dissertation (section 4.4.1). Afterwards, Dylos particle number has been converted into mass number (section 4.4.2) and correlation of PM with indoor CO2 levels was checked (section 4.4.3). Detailed results of each part has been depicted in below sub-sections.

4.4.1. Indoor Air Quality and Ventilation Rates

Average levels of AERs, ventilation, ventilation per person and PM are depicted in Table 4.26. In addition, data was also analyzed to check the possible source of buildup of indoor CO_2 levels. The results showed strong influence of occupancy level and indoor activities on indoor CO_2 levels as I/O ratio was found greater than 1 for all classrooms under study as illustrated in Table 4.26. However, indoor PM levels were found more influenced by outdoor activities as could be seen by less I/O ratios. These results are supported by previous literature (Schibuola & Tambani, 2020).

Table 8.25: Average levels of AERs, ventilation, ventilation per person and the monitored parameters

	CR01	**CR02**	**CR03**	**CR107**	**CR203**
AER	0.80	1.62	1.93	1.31	5.06
Ventilation (l/sec)	61.45	124.62	148.46	107.92	417.32
Ventilation per Person (l/sec/person)	2.29	5.23	5.41	4.32	17.28
Indoor CO_2	2152.46	1434.08	907.85	1433.63	967.24
I/O CO_2	5.01	3.51	2.23	3.46	1.91
Indoor $PM_{\geq 2.5}$	42924.54	23708.52	30291.25	45442.25	75164.36
I/O $PM_{\geq 2.5}$	0.65	0.34	0.43	0.65	1.00
Indoor $PM_{\geq 0.5}$	592373.13	565547.90	657950.18	764177.03	904886.56
I/O $PM_{\geq 0.5}$	0.55	0.53	0.62	0.70	0.69

4.4.2. Conversion of Dylos Particle Number to Mass Concentration

PNC for $PM_{2.5}$ recorded using dylos was plotted against PMC obtained by using nephelometer as presented in Fig. 4.33. Strong correlation between the two data sets was evident as R^2 value is >0.95. Based on results, PMC was modelled linearly by taking PMC as a dependent variable. General model equation is provided in Fig. 4.33.

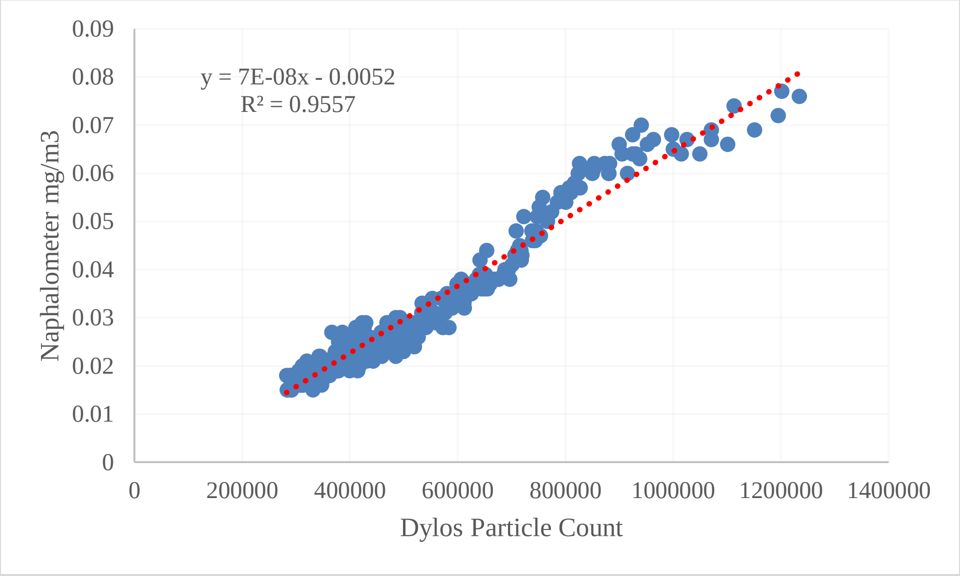

Fig. 8.33: Fitted curves between dylos PNC and naphalometer PMC

In the end validation of the linear model was performed by inputting actual monitored data in the developed linear relationship as presented in Fig. 4.34. Results of Pearson correlation test showed strong correlation (coefficient> 0.90) between the modelled and monitored levels. Similar methods were presented in many previous research studies. Franken et al., (Franken et al., 2019) developed fit curves and compared the conversion method with previously published literature studies. Likewise, Dacunto et al., (Dacunto et al., 2015) developed fit curves while working on indoor environments where different types of foods were cooked using similar approach. Furthermore, Semple et al., (Semple et al., 2013), compared the response of Dylos 1700 with TSI Sidepak Personal Aerosol Monitor which is commonly used to monitor $PM_{2.5}$. Furthermore,

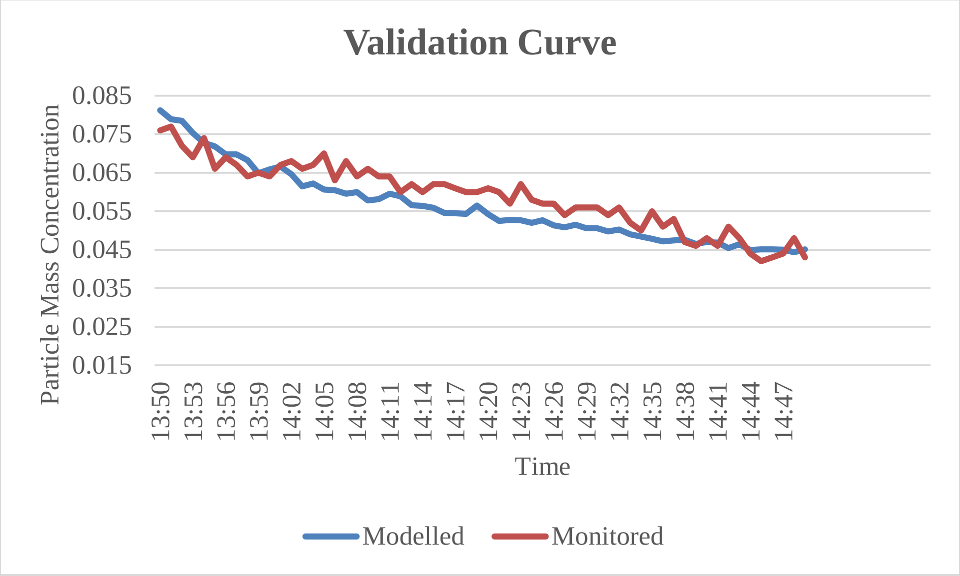

Fig. 8.34: Linear model validation curve

4.4.3. Correlation of Indoor CO_2 with $PM_{\geq 0.5}$, $PM_{\geq 2.5}$ and $PM_{2.5}$

Present section presents correlation results of indoor CO_2 with $PM_{2.5}$ and two sizes of PM i.e., $PM_{\geq 0.5}$ and $PM_{\geq 2.5}$. Results of Pearson correlation test showed strong weak correlation (coefficient<0.5) was evident for all cases (Table 4.27). These results could be attributed to the fact that indoor build-up of CO_2 levels is strongly dependent upon indoor occupancy level as could be seen from Table 4.26. However, although source of PM levels in an indoor space could be indoor activities but are more influence by outdoor PM levels (Table 4.26). These observation are also supported by ASHRAE recent position document on indoor CO_2 (ASHRAE, 2022).

Table 8.26: Pearson correlation of indoor CO_2 with indoor monitored parameters

	$PM_{2.5}$	**$PM_{\geq 0.5}$**	**$PM_{\geq 2.5}$**
CR01	0.37	0.33	0.13
CR02	0.45	0.03	0.14
CR03	0.27	0.20	0.27
CR107	0.41	0.44	0.47
CR203	0.36	0.30	0.22

Chapter 5

Conclusions and Recommendations

5.1. Conclusions

The humans exposure to indoor environment is significantly higher than the outdoor environment, (Ai et al., 2016) and this trend is escalating as more people are adopting urban lifestyle, which is intensively based on the indoor activities. This in turn, is leading to unprecedented increase in energy requirements of the buildings. Many studies reported that maintenance of favorable indoor environmental conditions i.e., indoor air quality (IAQ) and thermal comfort by building heating, ventilation and air-conditioning (HVAC) systems is directly linked with occupants' productivity, satisfaction, health and well-being (Kalimeri et al., 2016). Moreover, HVAC systems contribute around 20% of total energy consumption in developed and majority of developing countries (Aghniaey et al., 2019). Thus, the evaluation of thermal comfort and IAQ in the dissertation lead us to following conclusions.

5.1.1. Indoor Thermal Comfort in Dormitories and Offices

Existing thermal comfort conditions were assessed in dormitories and offices belonging to NUST Islamabad, followed by prediction of comfort temperature (T_c). Data from dormitories was analyzed for gender and seasonal differences. However, different modes of ventilation were considered for the analysis of offices data. In dormitories, subject's thermal and humidity sensation votes of both genders were statistically significant ($p<0.05$) while air speed sensation votes were not significant ($p>0.05$). However, all sensation votes (thermal, humidity and air speed) were statistically significant ($p<0.05$) when compared for two seasons. In addition, results of spearman correlation test showed strong link of thermal sensation votes with indoor temperature and weak link with indoor humidity. Dominance of subject's sensations on their preferences was concluded. Strong influence of indoor and outdoor temperatures on clothing insulation values was found. Although gender differences were evident in the results of thermal sensation votes, no significant difference in indoor T_c between two genders was observed. Using linear regression method, T_c during summer were calculated as 26.4ºC and 27.8ºC for females and males respectively. For winters, calculated T_c were 22.7ºC and 22.4 ºC for females and males respectively. The mean indoor comfort operative temperatures using Griffths method, corresponding to Griffths constant of 0.5 were 26.82±1.53ºC and 27.62±1.67ºC during summer while 22.66±2.33ºC and 22.30±1.99ºC during winter season for females and males respectively.

Besides, subjects in the offices under study were found active towards changing outdoor climatic conditions with more clothing insulation (clo) levels during winter season and less during summer season. Also due to well-maintenance of indoor temperature in CS_H mode, clo levels were found lesser in comparison to N_H mode. Thermal sensation votes were found inclined towards warmer sensation. However, humidity and air movement sensation votes were more down towards humid and neutral sensation respectively. On comparing thermal comfort of natural and central mechanical ventilation system shows that the perception of majority of occupants in natural ventilation system towards thermal comfort is more towards hotter side during summer (N_{ACoff} mode as hottest mode with more subject votes on warmer side of ASHRAE scale) and towards cooler side during winter season (N_H mode was coolest during winter season with more votes on cooling side of scale). Moreover, most of the subjects preferred a cooler, drier with a bit more or much more air movement. Statistical comparison between natural and central mechanical ventilation systems showed significant difference ($p>0.05$) in indoor operative temperature and indoor relative humidity during summer while no significant difference ($p<0.05$) during winter season. However, clothing insulation levels, sensation and preference votes were significant ($p>0.05$) between natural and central mechanical ventilation system for both seasons. Using linear regression method, indoor T_c for N_{ACon}, N_{ACoff}, CS_C, N_H and CS_H modes was calculated as 27.4, 25.5, 26.6, 19.2 and 19.3ºC respectively with comfort bandwidth corresponding to TSV±1 as 25.2-29.7, 22.5-28.4, 24.1-28.99, 16.9-21.5 and 15.8-22.7ºC respectively. Mean indoor operative T_c using Griffith's method for all slopes (0.25, 0.33 and 0.5) on combined summer data was found as 25.2 (sd= ±3.9), 26.2

(sd= ±2.8) and 27.3 (sd= ±1.8) ºC respectively and on combined data of winters as 19.4 (sd= ±5.1), 19.4 (sd= ±3.8) and 19.4 (sd= ±2.6) ºC respectively.

Furthermore, T_c with given operative temperature was predicted using linear, cubic and logistic adaptive approaches. Comparatively, the logistic adaptive model performed better than the other two. However, the accuracy of all models was below 50%, which can presumably be improved if other predictor variables were considered in the analysis. Thus, the last part of Phase 1 included prediction of thermal sensation votes by using different predictor variables in logistic model. Moreover, all predictor variables were also added in the model and percentage accuracies were compared. Results showed that percentage accuracies could be improved to >60% when all predictor variables were input in logistic model. In addition, a machine learning algorithm i.e., K nearest neighbor (KNN) was also used and results were compared with logistic model. It was found that the percentage accuracies of logistic model were greater than KNN.

5.1.2. IAQ, AERS and Airborne Infection Risk Assessment

Evaluation of IAQ by two-season monitoring of indoor CO_2 in naturally ventilated classrooms of NCLS showed significant variation ($p>0.05$) in indoor CO_2 levels between two seasons during weekdays. A comparison with ASHRAE standards showed indoor CO_2 levels exceeding >50% times during occupancy hours for all classrooms. In addition, minute-by-minute AERs and VRs were calculated for occupancy hours. Average VRs were found well below ASHRAE recommended standards showing insufficient ventilation.

IAQ in IESE classrooms was assessed under five ventilation scenarios. Occupancy level and duration of class sessions are found driving factors for the build-up of indoor CO_2 levels in all ventilation scenarios. Besides, indoor CO_2 levels were found significantly different ($p<0.05$) between occupancy and non-occupancy hours for all classrooms. The difference in CO_2 levels among ventilation scenarios was also statistically significant. The calculated AERs and VRs showed average levels well below the ASHARE recommended limits (i.e., 8 l/sec/person) most of the time with close windows ventilation scenarios (VS3, VS4 and VS5).

Furthermore, opening of windows and ventilators could aid in lowering airborne COVID-19 transmission risk.

Besides, evaluation and comparison of IAQ in two naturally and two mechanically ventilated office buildings was also made. It was found that indoor CO_2 levels varied significantly ($p<0.05$) between seasons. Moreover, results were also significantly different ($p<0.05$) among the buildings. Comparatively lower indoor CO_2 levels in mechanically ventilated offices were evident from mean hourly profiles. Furthermore, VRs and AERs were also comparatively higher in mechanically ventilated offices.

Lastly, three types of dormitory buildings (cubical, bi-seater and tri-seater) were monitored for IAQ evaluation and assessment. Highest indoor CO_2 levels were found in tri-seater dormitories which is the only dormitory type exceeding ASHRAE standard limits frequently. Moreover, indoor CO_2 levels were significant difference ($p<0.05$) between sleep hours and non-sleep hours for all dormitories. Based on results, frequent opening and closing of windows during sleep hours is recommended in dormitories. Moreover, indoor thermal comfort parameters were found to be affected by outdoor climatic conditions, opening/c closing of windows and indoor heating system. Furthermore, comparison of calculated AERs with ASHRAE limits were concluded as all the monitored dormitories were well ventilated.

5.1.3. System Dynamics Based Modeling for Air Exchange Rates

In the Phase 3 of dissertation, a SD based model was developed to simulate minute-by-minute indoor CO_2 concentration, utilizing calculated average as well as minute-by-minute VRs in two different model runs. The model results showed lesser correlation with monitored CO2 concentration when averaged VRs were input, proving the averaging of VR for naturally ventilated spaces to be inappropriate approach. The developed ventilation model showed REHVA suggested VR (3 l/s/person) to be insufficient for keeping CO2 level below 1500 ppm. However, ASHRAE recommended VR (8 l/s/person) was sufficient to keep the CO2 levels below 1000 ppm.

In the second part of Phase 3, three methods i.e. transient mass balance, steady-state and decay method were practiced for the calculation of ventilation rates (VRs). Indoor CO_2 levels were then simulated by taking calculated VRs as an input in SD-based model and results were compared with the actual monitored data. Results of spearman correlation test and root mean square error (RMSE) between the monitored and simulated levels demonstrated transient mass balance method as more accurate approach for VRs calculation with more predictive power. In the last part, different VRs were input in the SD based ventilation model to identify the minimum VRs required to meet American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) standards (i.e. CO_2 concentration should not exceed 1100 ppm), Chartered Institute of Building Services Engineers (CIBSE) (>800 ppm) and Spanish regulations (>700 ppm) in the light of recent COVID pandemic. Modelled results showed that minimum VRs requirement to meet the regulations are 10, 16 and 20 l/sec/person respectively.

5.1.4. Association of Indoor CO_2 with Particulate Matter

Simultaneous monitoring of indoor CO_2 and two size bins of PM i.e., $PM \geq 0.5$ and $PM \geq 2.5$ was made. In addition, Dylos particle number count (PNC) was also converted into mass number (PMC) using fit curve method. Indoor to outdoor ratios of two PM size bins were less than 1 showing strong impact of outdoor PM infiltration on indoor PM levels. However, as buildup of indoor CO_2 levels was more affected by occupancy level in indoor space thus weak correlation was observed between indoor CO_2 and PM levels.

5.2. Contribution of the Study to the Body of Knowledge

IAQ and thermal comfort has been investigated by many researchers in the past with a special focus on optimizing the energy consumption by HVAC system without compromising indoor conditions. However, knowledge gaps existed and the contributions of the present study to the body of knowledge are discussed below.

Most of previous studies were focused on developed countries. Besides, due to seasonal, regional and cultural differences, adaptive thermal comfort models developed for a particular building type and climatic conditions couldn’t be used universally. In Pakistan’s context, this research area has been overlooked previously and was thus addressed. Moreover, the dissertation investigated assessment of the accuracies of widely used linear, cubic and logistic adaptive models for the prediction of thermal comfort, which up-to author’s knowledge was not assessed previously. Furthermore, research gap also existed in identifying the individual as well as combine effect of environmental and personal variables that could influence thermal comfort of an individual and was thus discussed in the current study. Therefore, the proposed modeling approach involved seven variables that could possibly influence thermal comfort and this could be utilized for all climatic conditions.

In naturally ventilated buildings, as the ventilation is managed through windows and ventilators mainly, the windows/ventilators should be incorporated in enough number/sizing to deliver the required air exchange rates under all possible occupancy scenarios. The system dynamics-based models developed in this study (Section 3.3.1) can be used for the accurate calculation of required ventilation rates (degree of windows/ventilator openings) for the possible occupancy levels of the indoor microenvironment being planned/designed. To optimize the energy use for both, the space heating and cooling, the building operator can be instructed through building operation manuals to open the windows/ventilators as per the occupancy level. Research also involved comparison of accuracies of different ventilation rate calculation methods and optimization of ventilation rates.

5.3. Practical Implications of the Research Work

In contemporary times, with increased energy costs, outbreak of COVID-19 and strict requirements of ventilation, the findings of the dissertation will provide valuable insights for the provision of good IAQ and thermal comfort conditions in buildings of the study region. The findings can be significant contributions to the global knowledge about thermal comfort, existing thermal and IAQ conditions. The calculated comfort temperature set-points suggested that the existing Pakistan’s building energy codes for designing a thermally comfortable building with minimum energy consumption, needs revisions. The proposed modeling approach involving all possible environmental and personal variables for the prediction of occupants' comfort temperature can be applied in the design and operation of HVAC system universally for all building types and climatic conditions. The findings of the dissertation emphasized on provision of more windows during the building design phase of naturally ventilated buildings to reduce risk of airborne transmission of COVID-19 and other adverse health impacts. Moreover, proposed SD-based model for IAQ simulation can facilitate in auditing existing IAQ conditions of a building.

5.4. Recommendations for Future Work

The study investigated and simulated IAQ and thermal comfort in different indoor environments. However, some limitations can be addressed by future investigations which are given as follows.

- Thermal comfort being a subjective concept can be investigated in future for other indoor environments of Pakistan e.g., hospitals, hotels, shopping malls etc.
- Impact of variables like skin temperature, wall thickness, building and windows orientation and over all building envelop etc. on thermal perception of occupants can be explored.
- IAQ and airborne infection risk can be estimated under controlled occupancy and ventilation conditions in future.
- Assumption of a constant outdoor CO_2 levels for simulation of IAQ might not be true every time e.g., the buildings closer to busy roadsides and industries might have higher outdoor levels and thus need to be monitored along with indoor CO_2 levels in futuristic studies.
- Machine learning algorithms can be developed by new researchers for the prediction and simulation of indoor CO_2 levels.
- Optimizing the energy consumption while maintaining the thermal comfort and IAQ within acceptable limits can be further emphasized by monitoring

energy consumption under various ventilation modes for naturally ventilated buildings.

5.5. Summary

With climate change and more frequent extreme weather events, the thermal safety and health of occupants in buildings become a growing concern in Pakistan. On one hand, the higher living standards and economic development justifiy a more comfortable and healthier indoor environment, while on the other hand, more energy use and associated GHG emissions from HVAC systems in buildings need mitigation strategies to meet Pakistan's building decarbonization and overall energy and climate goals. Understanding the current conditions of thermal comfort and indoor air quality in diverse building types and for diverse populations across seasons is essential to guiding the development of effective strategies to addressing the problem. To contribute to the fundamental understanding and solving of this problem, this thesis proposes novel research in four phases.

Phase 1 of the dissertation involved assessment of indoor thermal comfort in dormitory and office buildings through field surveys followed by calculation of comfort temperature (T_c). Afterwards, a comparative analysis of three T_c prediction adaptive models (linear, cubic and logistic) was conducted. Seasonal as well as gender differences were considered during dormitories data analysis and the data from offices have been categorized into three summer (natural ventilation system with AC, natural ventilation system without AC and central ventilation system during cooling season) and two winter (natural ventilation system during heating season and central ventilation system during heating season) ventilation modes for the analysis. Results showed that although thermal sensation votes of both genders in dormitories were statistically different, no statistical difference in indoor T_c between two genders were observed. Following Griffth's method T_c in dormitories were calculated as 26.8±1.5 ºC and 27.6±1.7 ºC during summer and 22.7±2.3 ºC and 22.3±2.0 ºC during winter for female and male occupants respectively. Furthermore, in offices comparison of natural and central HVAC system showed significance ($p>0.05$) in sensation and preference votes. Mean T_c for offices under all five modes were 27.66, 27.18, 26.89, 19.15 and 19.73 ºC. Comparative analysis of three adaptive thermal comfort models for the prediction of T_c showed better performance of logistic regression. In the last part of Phase 1, multiple variables were input in logistic and a machine-learning algorithm for prediction of thermal sensation. Results indicated that percentage accuracies of models were improved when all variables were input in the model. The results of this phase can aid in improvising Pakistan's building design guidelines for designing a healthier and thermally comfortable building. Findings will facilitate in managing an acceptable indoor thermal environment in offices and dormitories of Pakistan with less energy consumption by adjusting the thermostat of their heating and cooling devices to the recommended levels. Besides, designers of buildings and HVAC system can use the proposed modeling approach for the prediction of thermal comfort in any building type or climatic condition.

IAQ and ventilation conditions assessment considering building designs of Pakistan has not been debated extensively in the past. Thus, in Phase 2 of the dissertation, IAQ and ventilation conditions in four indoor environments i.e., primary school classrooms (variation across two seasons in NUST creative learning school (summer and winter)), offices (between ventilation systems (naturally and mechanically ventilated)), university classrooms (ventilation under different airtightness scenarios) and dormitories (ventilation conditions across varying occupancy levels) were assessed. Results showed significant variation ($p<0.05$) of indoor CO_2 between occupancy and non-occupancy hours (in primary school classrooms, university classrooms, offices), among all ventilation modes (in offices), between buildings (offices and dormitories) and seasons (primary school classrooms and offices). Moreover, it was found that opening of windows and ventilators have significant positive impact on VRs and AERs. Besides, airborne transmission risk of COVID-19 was also calculated for all ventilation scenarios in university classrooms. Results indicated less airborne transmission risk of COVID-19 when the ventilation was increased by opening of windows and ventilators.

Phase 3 of dissertation included development of a system dynamics (SD) based model which was used to estimate indoor CO_2 concentrations utilizing calculated VRs (minute-by-minute and averaged) using VENSIM software. VRs were calculated adopting three methods i.e., transient mass balance, steady-state and decay method, and were then input in SD model for finding best method for calculation of VRs. Acknowledging the fact that provision of good IAQ and thermal comfort conditions along with optimum energy consumption is a challenge for HVAC designers, last part of this phase included optimization of VRs to keep indoor CO_2 levels within recommended limits (>1000 ppm) without consuming excessive energy. Developed SD model results showed high correlation (>0.98 for all classrooms, using minute-by-minute VRs) with monitored CO_2 concentration and low root mean square error. Similarly, minute-by-minute VRs input to models showed more accurate simulation as compared to VRs averaged for a session (Correlation coefficient <70). Transient mass balance method was found to be more accurate approach for VRs estimation. It was noticed that to limit indoor CO_2 levels below 1100, 800 and 700 ppm, minimum VRs should be maintained as 10, 16 and 20 l/sec/person respectively. Currently, the international standards and guidelines are in practice by HVAC and building designers in Pakistan. Thus, the findings could help in the development of national ventilation standards of Pakistan.

In the last phase of dissertation, simultaneous monitoring of indoor CO_2 and particulate matter (PM) was performed. Besides, fit curve method was employed for the conversion of dylos particle number count (PNC) to particle mass count (PMC). Results showed weak correlation of indoor CO_2 with PM. However, indoor PM levels were strongly correlated with outdoor PM levels. Furthermore, indoor CO_2 levels were strongly correlated with occupancy and indoor activities.

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