Assessment of Indoor Environmental Quality and Thermal Comfort of Educational Buildings

By

TAHIR NAWAZ

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Session 2017-19

Supervision of

Dr. MUHAMMAD BILAL SAJID

A Thesis Submitted to the US–Pak Centers for Advanced Studies in Energy in partial fulfillment of the requirements for the degree of MASTER of SCIENCE in THERMAL ENERGY ENGINEERING

U.S. – Pak Centers for Advanced Studies in Energy (USPCAS-E)

National University of Sciences and Technology (NUST)

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THESIS ACCEPTANCE CERTIFICATE

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Tahir Nawaz

I dedicate this thesis to my parents.

Contents

Abstract

The indoor environment is of great health concern to the occupants as most of the poor-quality air is inhaled by the residents inside these built environments. Worldwide, indoor air pollutants cause the foremost vital indoor air quality challenges attributable to the number of people it affects, different types of pollutants involved, and the acuteness of the risks involved. Educational institutions are the second place where the students spend more time after homes which makes the students prone to indoor pollutants. This study was carried out to investigate different parameters affecting the quality of the built environment and thermal comfort along with the particulate matter of fine and coarse sizes in libraries of schools in a public university, *National University of Sciences & Technology*, *Islamabad* with a centralized and non-centralized split ventilation system. CO_2, temperature, relative humidity, were measured during the weekdays in two phases while the particulate matter in the second phase. The Extech-CO210 CO_2 data logger was used in the sampling of CO_2 and comfort parameters while Fluke 985 particle counter was used for measuring particles of different sizes. The results obtained from the study were compared against ASHRAE 55, 62.1 and, US EPA standards for the minimum required performance. It was observed that the buildings performed better when ventilation systems were switched on than switched off. Also, the centralized system regulated CO_2 in a better way than the split system. The temperatures were found to be out of the thermal comfort range defined by the ASHRAE 55 standard. The particulate matter was observed to be under the guideline value defined by US EPA for all sizes.

Keywords: CO_2 concentration, RH, Thermal Comfort, Educational Building, Indoor Air Quality, Particulate Matter, PM10, PM5

List of Figures

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List of Publications

1. “Assessment of Indoor Air Quality in Educational Building at 3rd Young Researchers National Conference on Water & Environment, USPCAS-W, MUET Jamshoro.” (1st author).
2. “Assessment of Relative Humidity, Temperature, Carbon Dioxide & Particulate Matter in Labs” at International Conference in Mechanical Engineering, UET Lahore 2020. (1st author).
3. “Gap Analysis of Municipal Solid Waste Management System in Peshawar, Pakistan” at International Conference in Mechanical Engineering, UET Lahore 2020. (co-author).
4. “Status of Solid Waste Management in Peshawar, Pakistan at 3rd Young Researchers National Conference on Water & Environment, USPCAS-W, MUET Jamshoro.” (co-author).

List of Abbreviations

Nomenclature	
IAQ	Indoor air quality
IEQ	indoor environmental quality
CO	carbon monoxide
CO_2	carbon dioxide
T	temperature
TC	thermal comfort
RH	relative humidity
ASHRAE	American Society of heating ventilation and air conditioning engineers
VOCs	Volatile organic compounds
TVOCs	total volatile organic compounds
NUST	National University of Sciences and Technology
Ppm	Parts per millions
HVAC	heating ventilation and air conditioning
WHO	world health organization
SBS	sick building syndrome
$PM_{2.5}$	particulate material of size 2.5 micron
PM_{10}	particulate material of size 10 micron
NDIR	non-dispersive infrared
TCE	trichloroethylene

Chapter 1

Introduction

1.1 Background

Increasing urban population growth has turned air pollution into a global problem. Both indoor and outdoor air pollutants can indeed be detrimental to human health depending on the time and concentration of the exposure to the pollutants [1]. In most circumstances, concentrations of indoor air contaminants are found to be significantly higher than the concentrations of open-ari pollutants [2]. Mostly, people spend their time indoor, around 90% of their daily lives in built environments like inside offices, schools, college, commercial, industrial buildings or inside their houses. This makes the built environment more concerning to ensure human health[2–5]. According to the World Health Organization, more deaths occur due to indoor pollution than outdoor pollution[6]. Previously conducted studies suggest that the pollutants present in the indoor air are far more than that of the outside atmosphere[4,5]. Besides, contamination from outdoor air defuses into the indoor built environment and affects the indoor conditions, thus we cannot deny the effects of outdoor conditions on the conditions of the built environment[1]. With all these, the behavioral trends of the occupants of the building also greatly impact the indoor air quality[7].

Moreover, indoor air quality (IAQ) and thermal comfort can also influence the productivity, concentration, performance, and well-being of an occupant[8,9]. Around the world, the IAQ is assessed by CO_2 levels as CO_2 is usually considered as a substitute for ventilation quality assessment because CO_2 levels above a certain concentration shows poor ventilation in the building which indicates the possibility of build-up of higher concentrations of other indoor pollutants which can have negative impact on human health[10,11].

Figure 1. 1 Indoor Environmental Quality[12]

1.2 Sources of IAQ pollutants

Though there are many indoor pollutants in atmospheric air, but, most prominent are nitrogen dioxide, Sulphur dioxide, carbon monoxide, carbon dioxide, total volatile organic compounds and particulate materials 2.5 & 10 micrometers. In this study, only carbon dioxide will be monitored and analyzed. The following are possible causes of CO_2 in the built environment:

- Living organisms such as animals and humans release CO_2 as a result of respiration process occurring in their lungs. If an occupied space is overcrowded with occupants without proper ventilation, CO_2 concentrations build up in that space.
- Another process which release CO_2 into the indoor space is soil capping.
- The carbon based fuels used in different activities such as cooking, heating etc. combusts and release CO_2 into the indoor along with other gases[13].

Sources of the other pollutants are shown in the figure.2.

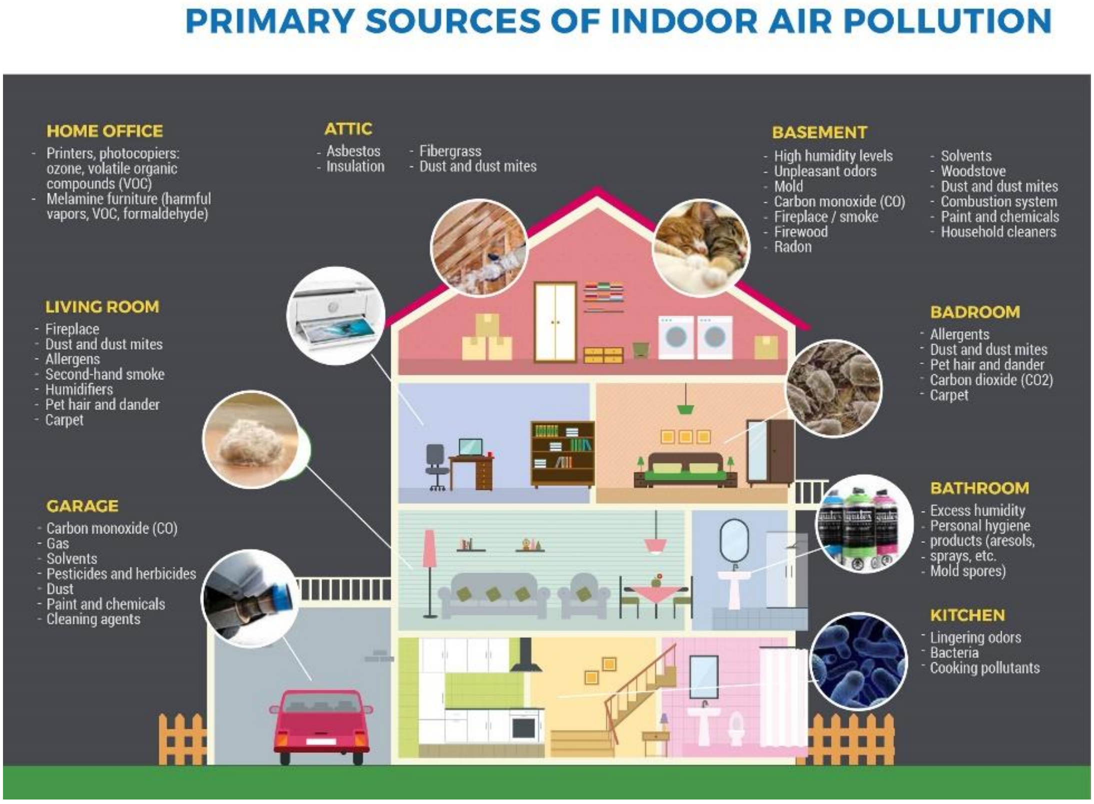

Figure 1. 2 sources of pollutants [14]

1.3 Health effects associated with CO_2

At low concentrations, carbon dioxide is harmless to living, but beyond some concentrations it can lead to various health issues like, headaches, fatigue and breathing difficulties. It can also be fatal if someone is exposed to it for long time[13].

1.4 Thermal Comfort

One of the best ways to define thermal comfort is the way Fanger (1970) describe it as “the state of mind in which a person expresses satisfaction with the thermal environment”. The physical parameters that effects the TC are T and RH of the indoors. In relation to the physical parameters that describe the flow of heat between the human body and the environment in which it is situated (thermal equilibrium), several authors subsequently argued that the satisfaction with thermal environment depends on other parameters such as social, cultural and psychological factors that explain the varying perceptions and reactions for the same sensory stimuli [15].

1.5 Scope of the study

Many researchers studied IAQ in past and investigated IAQ of different types of buildings such as museums, residential buildings, old age community centers, offices, health care centers and, academic buildings[16–20]. As students and teachers spend the majority of their time in Academic institutes after homes make them one of the most important built environment to be studied[8,9,17]. In schools & universities mostly, classrooms were studied in the past. One more very important site in the building which can affect the productivity and health of students is library.

1.6 Problem statement

This study aimed to assess the indoor concentrations of CO_2 along with indoor temperature, relative humidity in libraries of different academic building present in NUST, Islamabad. Data were gathered during the occupational hours of the schools. ASHRAE 55 and ASHRAE 62.1 standards were used to check the quality of the built environment.

1.7 Objectives

The main objectives to carry out this research work are given below:

- To study the IAQ and PM of libraries of different schools at NUST
- To assess thermal comfort of these libraries
- To compare the results with ASHRAE standard 55 & 62.1 for thermal comfort and IAQ and US EPA for PM concentration performance.

1.7 Organization of Thesis

Following pathway was adopted for carrying out this research

- Chapter 1, Introduction

  Background, Objectives, IAQ, CO_2, thermal comfort, built environment of academic buildings, Research Statement and Methodology, data logging, data analysis

- Chapter 2, Literature Review

  Indoor Air Quality, pollutants sources and impacts, thermal comfort, factors affecting occupant's comfort, standards for IAQ and thermal comfort, monitoring of IAQ, previous work.

- Chapter 3, Methodology, Instrumentation

  Instruments, types of sensors used, NDIR CO_2 sensor, humidity capacitive sensor, thermistor, methodology

- Chapter 4, Results and Discussion

  Results, SMME library, NICE library, SADA library, SCME library, SNS library, USPCAS-E library, Particulate Matter, Critical analysis with standards and literature

- Chapter 5, Conclusion & Recommendation

Summary

This chapter gives a brief introduction of indoor air quality, thermal comfort and the parameters that have an influence on IAQ and thermal comfort. Causes and effects of indoor pollutants are also discussed and represented in a pictorial form. Also, the research scope and statement are briefly explained. At the end research objectives were discussed.

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Chapter 2

Literature Review

In this chapter work of several researchers in the fields of IAQ monitoring and assessment is discussed. Moreover, literature covering different types of buildings with different types of ventilation systems are also presented here.

2.1 Indoor Air Quality

Many factors have combined to increase awareness of concerns about indoor air quality. An increasingly large number of people spent their time indoors, and in more controlled built environment, as the service industry emerged and overtake the manufacturing industry[1]. To be more precise, about 90% of the time is spent indoors by humans[2]–[5]. A rapid increase in the release of chemicals in the atmosphere served as one of the major causes of the pollutants in the air. Besides, the use of these products such as synthetic products installed in buildings utility equipment used indoors, pesticides, and fluids used in cleaning and maintenance act as a major source of pollutants in the built environment.

Good indoor air quality is as important to the occupants as the thermal comfort and acoustic comfort of the building. As the indoor air can affect greatly the productivity of individuals, and can be a cause of a loss of great fortune, designers are now considering the indoor air quality along with energy efficiency measures for the buildings[1].

According to ASHRAE (Standard 62.1, 2013) acceptable air quality is: “air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction[6].”

IAQ is now becoming a topic of concern as the pollutants both living and non-living, can cause great damage to the human health[7][8]. In previously conducted studies a detrimental impact of IAQ on the human health has been observed. The severity of the effects depends upon the duration and the concentration of the exposure to the pollutants[3], [9].

2.2 Pollutants Sources and its Impacts

Indoor air pollutants can be defined in two ways i.e. either it is a physical contaminant like particulate material, gases etc. or the effect it produces like odors, irritation etc.

The table 2.1 enlists few of the indoor pollutants that can exists.

Table 2. 1 list of different contaminants in indoor air[1], [10], [11]

Pollutants	Sources	Effects	Control Strategies
Moisture in air	Cooking, washing, respiration, perspiration etc.	Molds, bacteria Growth indoors	Dehumidification
CO_2	Respiration, combustion etc.	Stuffiness	Increase ventilation
CO	Incomplete combustion	Headaches, dizziness, higher concentration can be fatal	Better combustion devices
NO_2	High temperature combustion	Irritation	High efficiency burners with proper measures for flue gases
SO_2	High Sulphur content fuel	Irritation in eyes	High efficiency burners with proper measures for flue gases, use of alternative fuels
Poly aromatic hydrocarbons	Smoking, wood, burnt carbonaceous food	Major cause of cancer	Avoid wood burning indoor and quit smoking indoor
Ozone	Printing devices, photocopying devices	Inflammation in respiratory tract, loss of breath, asthma	Proper exhaust system

Volatile organic compounds (VOCs)	Paints, solvents, adhesives, cleaning products etc.	Irritation and burning sensation in eyes & nose, loss of breath etc.	Use of alternative materials, proper ventilation
Lead	Old paints, pipes, leaded gases	Neurotoxic	Identify and remove the sources
Pesticides	All treated areas of the dwelling	Neurotoxic, kidney problems	Identify and remove the source
Asbestos	Pre-1970 steam pipes and ducts, combustion devices	Very carcinogenic	Identify and remove the source
Mineral and glass particles	Thermal insulations, fire-resistant tiles and fabrics	Burning and itching sensation in eyes and skin respectively	
Fungus	Grow in dump places	All dieses related with fungus	Proper cleaning and removing of moisture
Bacteria	Dirty and humid places	All dieses related with bacteria	Proper cleaning
Radon	Soil	Carcinogen	Cover the floor and drains
Methane and other soil gases	Decomposing of organic waste and other toxic waste	Explosive and toxic	Proper planning during the construction to cover this problem.

Though all of these are species of great concern, among them I only studied CO_2 as I had device that can only monitor CO_2 along with temperature and RH.

2.3 Thermal Comfort

A human body is a living machine which performs numerous functions. These functions require energy, this energy comes from the food human eats through the process called metabolism. The process of metabolism converts the digested food into usable energy. This energy is then used by individual cells to perform different functions. However, this energy conversion is very poor in terms of heat production. A lot of heat is lost, as body needs to regulate a close range of temperature, this heat needs to be removed from the body [1], [12], [13]. Thus, thermal comfort has been defined by many in different ways. Hensen defined thermal comfort as " a state in which there are no driving impulses to correct the environment by behavior"[14]. According to ASHRAE definition "the condition of the mind in which satisfaction is expressed with the thermal environment"[15]. Thermal comfort is mainly affected by individual's mood, cultural and social factors. From the above definitions of the thermal comfort, it is controlled by mind rather than state condition[16].

2.4 Factors Affecting Occupant's Comfort

There are many factors that affect the state of mind inside the dwellings. Major factors are discussed here.

2.4.1 Indoor Environmental Quality

IEQ can further be divided into the following areas:

2.4.1.1 Indoor Thermal Environment

In the past many researchers studied the relationship between the thermal comfort and the thermal conditions like indoor temperature, relative humidity and air speed. Many studies defined neutral temperature that best suits most of the occupants[17]. Neutral temperature is the one in which almost all the occupants neither feels cold nor heat indoors[18], [19]. Besides, air speed also plays important role in thermal comfort. Cold spots under vents can cause feeling cold to the occupants[17].

2.4.1.2 Indoor Air Quality

As discussed earlier different gaseous as well as solid particle play role in defining the quality of the indoor environment. CO_2, CO, TVOCs, NO_2, SO_2, Redon, methane and particulate materials can greatly affect the comfort the occupants in the dwelling, as these pollutants causes many discomforting situations like irritation, burning, dizziness etc.[1]–[3], [17]–[19].

2.4.1.3 Indoor Visual Conditions

Previously conducted studies suggest that the visual comfort is mainly affected by six factors, they are, glare, privacy, outside view, lighting level. Daylighting and uniformity of light[20], [21].

Some other factors which can affect the comfort and the IAQ are listed in bullet form[17], [20], [21]:

- Outdoor environment
- Surrounding infrastructure
- Building acoustics
- The occupant characteristics such as age, gender etc.
- The building characteristics such as type of building, area, orientation, level of occupancy etc.
- Clothing of the occupants

2.5 Standards for IAQ and Thermal Comfort

Table 2.2 represents list of different international bodies along with many other standards they define the IAQ standards[22]:

Table 2. 2list of international organizations for IAQ standards

Country	Organization
Australia	The national health and medical research council (NHMRC)
Belgium	Air infiltration and ventilation center (AIVC)
Canada	Health Canada
China	Administration of quality supervision, inspection and quarantine (AQSIQ)
China	State environment protection agency (SEPA)
Hong Kong	Hongkong environmental protection department (HKEPD)
Denmark	Danish society of indoor climate (DSIC)
Europe	European Commission (EC)

Finland	Finnish society of indoor air quality and climate change (FiSIAQ)
Germany	Deutsche Forschungs Gemeinschaft
Japan	Ministry of health, labor and welfare (MHLW)
Kuwait	Kuwait environmental protection agency (KuwaitEPA)
Korea	Korea environmental industry and technology institution (KEITI)
Malaysia	Depart of occupational safety and health (DOSH)
Singapore	Singapore indoor air quality guideline (SIAQG)
UK	Health and safety commission (HSC)
USA	Environmental Protection Agency (EPA)
USA	American society of heating refrigeration and air conditioning engineers (ASHRAE)
Worldwide	World health organization (WHO)

In this study I used ASHRAE 55 and 62.1 standards.

As I used ASHRAE standards, I will discuss it briefly here:

For thermal comfort ASHRAE 55 2010 standard was used. In this standard temperature, relative humidity air speed and personal factors such as clothing are explained. According to this standard, the optimum temperature indoors for thermal comfort varies during individuals but should be between 22.5-26℃. The relative humidity of the indoor air must be below 65%[6].

The other ASHRAE standard used was ASHRAE 62.1 2013. This standard explains limits and measures in ventilation rates and other factors to provide a better IAQ. According to this standard the CO_2 level inside a dwelling should not exceed 700ppm above outdoor levels[6]. The Table 2.3 represents limiting values of CO_2 by few organizations.

Table 2. 3list of limiting values of CO_2[22]

Country	Value	Organization
China/Hongkong	800ppm	AQSIQ
Japan Korea Kuwait	1000ppm	HKSAR MHLW KEITI DOSH KuwaitEPA
Singapore	1000ppm	SIAQG
Australia	5000ppm as 8 hr avg	NOHSC
Canada	3500ppm long term exposure	Health Canada
US	No more than 700ppm 800ppm	ASHRAE USEPA
Finland	700ppm	FiSIAQ
France Germany	5000ppm as 8 hr avg	MAK
Poland UK	5000ppm as 8 hr avg	HSC
Worldwide	1000ppm	WHO

2.6 Monitoring of IAQ

In order to study and observe the conditions in the built environment and to apply corrective measures to prevent the health as well as energy related issues, it is of great importance to monitor the indoor environment. IAQ is usually monitored in two ways i.e. microbial quality monitoring and ventilation quality monitoring. This work is based on ventilation quality monitoring.

2.6.1 Monitoring the Ventilation Quality

The process in which the polluted indoor air is replaced with fresh air from the outdoor is termed as ventilation. Ventilation plays an essential role in maintaining the indoor air quality up to the required standard values[23]. The type and present state of the HVAC of the building has potent effect on the amount of outdoor pollutants that can diffuse into the indoor environment thus maintaining an acceptable indoor condition[24]–[28]. In today's world there is more emphasis on the energy consumption of the buildings, which led to design of tightly built indoor spaces and therefore reduced the quality of indoor environment[29], [30]. In the previous conducted study, Kinnane et al showed that the building indoor environment is better diluted if it has an efficient ventilation system installed[30].

Worldwide, CO_2 is considered as primary indicator for the quality of indoor environment. As CO_2 will build up indoor if the ventilation system is unable to replace the polluted air with fresh air from outside. This will also develop a possibility of building up of pollutants other than CO_2 which can be harmful to human health while temperature and relative humidity is considered as comfort level indicators[2], [9], [24], [25], [27], [28], [30]. The design of the building and the in-efficiency of the ventilation system is one of the major reason for CO_2 accumulation indoor[31].

The ventilation system is of two main types i.e. mechanical ventilation and natural ventilation.

2.6.1.1 Natural Ventilation

The process of air replacement in the indoor environment without the use of any machine is termed as natural ventilation[32]. Many of the buildings that are used publicly like academic buildings has natural ventilation system. If designed in a proper way, a natural ventilation can provide very good indoor environment to the occupants with the use of minimal amount of energy[28], [32].

Though natural ventilation is good at maintaining CO_2 levels indoors, but it cannot regulate the thermal comfort parameters T and RH. Along with that, open doors and windows brings the issue of noise[27]. Besides, open doors and windows can also bring aerosols with it which can be very harmful to humans[28].

2.6.1.2 Mechanical Ventilation

The process of replacement of indoor air with fresh air using mechanical instruments is called mechanical ventilation. This mechanical system can provide both cooling and heating services along with regulation of the indoor air. It may be centralized or non-centralized[25]. This system can help maintain good IAQ. The main setback to this system is its short life, costly maintenance and high consumption of energy[33].

2.7 Previous Work

The study of built environment is very vast. A huge literature covering different aspects of the built environment is available. Here work of few is presented.

Ayesha Asif et al conducted their study in 4 schools of NUST. They measured CO_2, RH and T for 2-4 weekdays and weekends during the occupancy and non-occupancy period. They concluded that the buildings with centralized ventilation system has better indoor air quality and they maintain CO_2 at good level[25]. In another study Krystallia K. Kalimeri et al conducted study in 2 primary schools and a kindergarten in a city of Kozani in Greece. They selected 3 classrooms in each school for their study. They simultaneously sampled the air indoor and outdoor for five weekdays during school hours. The parameters they assisted during their study were HCHO, benzene, trichloroethylene, tetrachloroethylene, pinene, limonene, NO_2, O_3, radon, CO, $PM_{2.5}$, $PM_{10}/PM_{2.5}$, temperature, relative humidity and ventilation rate. They concluded from this study that the calculated AER (air exchange rate) values were indicative of inadequate ventilation inside the rooms. Seasonal differences were noted for outdoor CO and are attributed to the increased CO depletion is during summer and possible to the lignite power plants of the area. Formaldehyde and benzene were detected in all school environments; although the associated carcinogenic risk estimates were within the WHO “acceptable” limits all exposures indoors should be considered relevant. Trichloroethylene, pinene and limonene were detected only indoors, with only limonene presenting significant higher concentrations during heating period. The contribution of the building material emissions to VOC concentrations found in school microenvironments may reach up to 30%, while the contribution of other sources may be higher than 90%. Particulate matter measurements indicated the outdoor environment sources (i.e. traffic) and the dust re-suspension from pupils' activities as the main factors influencing particles levels[34].

Norhidayaha et al investigated the occurrence of SBS on the selected buildings, to investigate the parameters that define the level of IAQ and to determine the association between IAQ with symptoms of SBS. The chose three buildings and sampled the IAQ two times a day one at morning and one at evening. They concluded that the had the problem of SBS. He also compared the buildings among themselves but found no significance between them[35]. Ehsan Majid et al. conducted their study in sixteen schools in three different seasons. CO, $PM_{2.5}$ and NO_2 was monitored for all schools.

They found that mostly the levels of the pollutants exceed the WHO guideline, specially NO_2. The levels were observed to be higher in the fall and winter seasons. They found out that the concentration of the indoor pollutant is directly linked with the outdoor sources[36].

Yuefei et al. monitored the IAQ of two schools in Beijing, china. They monitored CO_2 concentration and $PM_{2.5}$ concentration in the classrooms in both scenarios with doors and windows open and closed. They found out that CO_2 concentration can increase up to 2500ppm in the class. While $PM_{2.5}$ concentration was observed to be higher when doors and windows were open. They concluded that mechanical ventilation system can best suit the job in this scenario[37]. D. Mumovic et al. investigated nine newly built secondary schools in England. During field study they investigated indoor air quality, thermal comfort and acoustic performance of the building. The outcome of this study was that most of the classrooms met the criteria for CO_2 levels, but minimum required air flow was not achieved, and, thermal comfort was mostly acceptable, but temperature was little higher. Acoustic standards can be met with natural ventilation when there is very low outdoor noise[38].

In another study conducted in France on seven newly built energy efficient homes by Mickaël Derbez et al. parameters like TVOCs, VOCs, aldehydes, CO, $PM_{2.5}$, radon, CO_2, temperature, noise and relative humidity was studied when the houses were not been occupied and after their occupation. They found that TVOCs and VOCs were higher before the occupancy than the post occupancy. $PM_{2.5}$ was on the other hand found in higher concentration post occupancy. Most VOCs related with human activity were found in higher concentration after occupancy[10].

Shelly L. Miller et al. conducted study in hundred residential homes in Commerce city Colorado. CO, CO_2 and $PM_{2.5}$ was monitored in these homes for 24 hours a day and on outside location. Dust particles were collected for studying allergens. CO and CO_2 concentrations were observed to be higher for the homes in which doors and windows are kept closed for larger amount of time. $PM_{2.5}$ was observed to increase with the increase of occupants and their activities. Cat and mouse allergens were obtained from the dust samples from approximately 70% of homes[39].

Arindam Datta et al. studied VOC, CO_2 and $PM_{2.5}$ concentration in two office buildings and one educational building present in New Delhi India. IAQ was monitored during working hours for five days a week. Among the three, the lowest level of pollutants was found to be in the educational building. Both the office buildings CO_2 concentration exceed the ASHRAE allowable limit. One office building had higher $PM_{2.5}$ concentration due to the poor condition of its air conditioning system[5].

Summary

In this chapter a preview on indoor air quality and thermal comfort is presented. Here, different types of pollutants that are present in the indoor air is introduced. Along with that, factors that can affect the presence of these pollutant along with different sources from which these pollutants originate are discussed. A list of international standards developed and adopted by different countries is also presented. In the monitoring of the indoor air and previously conducted studies in the field of air quality are discussed.

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Chapter 3

Instruments and Methodology

In this chapter, a brief introduction to the instruments used is presented. Besides, the methodology adopted to conduct this study is also explained here.

3.1 Instrument

In this study, a carbon dioxide datalogger CO210 manufactured by EXTECH instruments was used. This data logger is capable of sensing and logging CO_2, T, and RH simultaneously. The following are the main specification of this device:

- Carbon Dioxide (CO_2) concentrations sensing and data logging.
- The CO_2 sensor does not require any maintenance.
- User-programmable High/Low Visible and Audible CO_2 warning alarms.
- Displays Year, Month, Date, and Time, Max/Min CO_2 value recall function.
- Equipped with automatic Baseline Calibration or manual calibration in the fresh air.

Some of the specifications of the sensing ability are presented in Table 3.1

Table 3. 1 specification of the data logger[1]

Function	Range	Resolution	Accuracy
CO_2	0-9999ppm	1ppm	±5%
Temperature	-10 to 60 degree centigrade	0.1 °C	± 0.6 °C
Relative humidity	0.1 to 99.9 %	0.1 %	± 3% (0-90%) ± 5% (90>)

3.1.1 Types of Sensors Used

This instrument is equipped with an NDIR CO_2 sensor, a Capacitance RH sensor and a Thermistor for temperature sensing. They are briefly discussed below:

3.1.1.1 NDIR CO_2 Sensor

NDIR stands for non-dispersed infrared. This is the most common sensor used to calculate the level of CO_2.

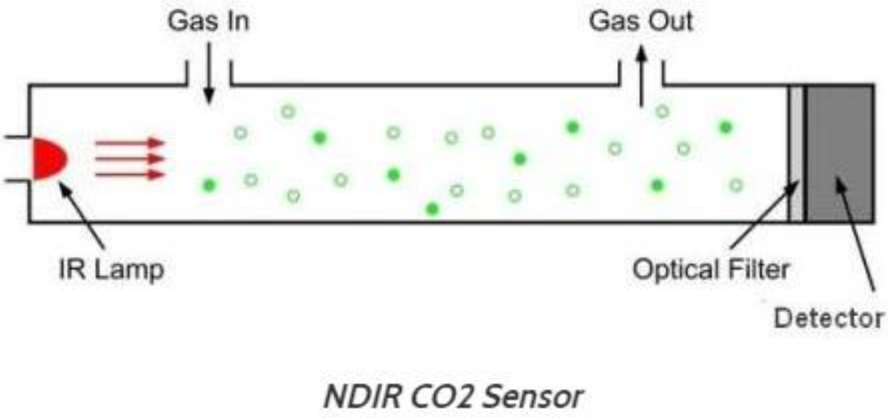

Figure 3. 1 NDIR CO_2 sensor

The working principle of this device is to emit a non-scattered beam of infrared light in a chamber containing the gas whose concentration is to be detected. The amount of light that reaches is inversely proportional to the concentration of the gas present in the chamber. This is because the greater concentration of the gas present will absorb a greater amount of light and less light will be received by the detector. The difference of the light emitted by the source and the light absorbed by the detector will give the concentration of the gas in the chamber[2,3].

3.1.1.2 Humidity Capacitive Sensor

The sensor used in this device is a tiny capacitor having a hygroscopic dielectric sandwiched between two conducting plates. Mostly, a low dielectric media is used in the majority of the capacitive sensors with a constant value of less than 15. The dielectric constant value of water vapors at room temperature lies beyond 80, thus when moisture is trapped between the conducting plates of the sensor, it increases the capacitance of the capacitor. This increase is directly related to the amount of moisture, the vapor pressure of the water vapors and the temperature[4].

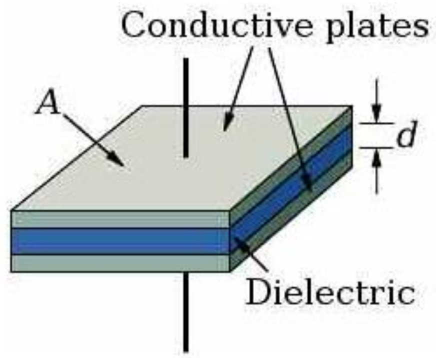

Figure 3. 2 humidity capacitive sensor

3.1.1.3 Thermistor

A thermistor or thermal resistors are semiconductors used to sense the changes in the temperature. The resistors of thermistor changes with the temperature i.e. either it increases with the temperature (positive temperature coefficient) or decrease with the increase in temperature (negative temperature coefficient). The latter is most widely used as a temperature sensor. The working of a thermistor is that resistance is temperature dependent. If the exact behavior of the resistance with temperature is known then the slight changes in the temperature can be detected by measuring the change in resistance using ohmmeter[5].

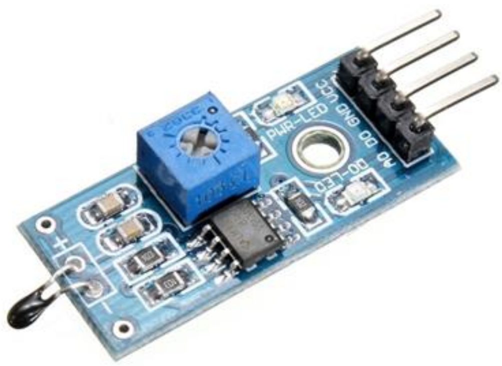

Figure 3. 3 Thermistor[6]

3.1.1.4 Fluke 985 Particle Counter

Fluke 985 particle counter was used to gather data of the airborne particulate matter. The particle counter was calibrated using a zero-count filter prior to each measurement.

This device is equipped with a class 3B laser and has 6 channels for six different size particles. Table 3.2 presents specifications of the instrument.

Table 3. 2 Fluke 985 Particle Counter

Sr.no	Specification	Range
1	Particle-Size range	0.3, 0.5, 1.0, 2.0, 5.0, 10.0) µm
2	Channels	6
3	Flow rate	2.83 liter/min
4	Data storage	10000 points
5	Light Source	775 nm to 795 nm, 90 mW class 3B laser
6	Counting Efficiency	50 % @ 0.3 µm; 100 % for particles >0.45 µm (per ISO 21501)
7	Sample Inlet	Isokinetic Probe

3.2 Methodology

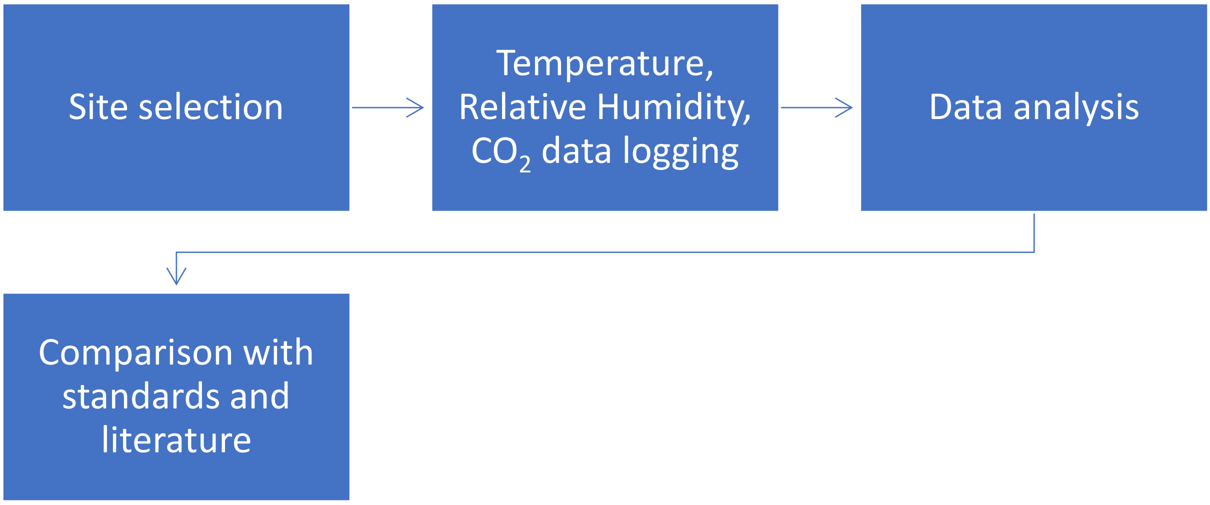

Figure 3. 4 Methodology pathway layout

3.2.1 Site Selection

This study was conducted to assess the quality of the built environment of libraries present in NUST, Islamabad, Pakistan. Islamabad has four different seasons. The duration of each season is varying in length, autumn lasts about 5 to 6 months between September to March, the winter from November to February about 4 months, summer about 3 to 4 months from late May up to September and spring lasts for a couple of months between March and May Six libraries present in different buildings of the university were selected for this study. The six selected school buildings are NUST Institute of Civil Engineering (NICE), School of Art, Design & Architecture (SADA), School of Chemical & Materials Engineering (SCME), School of Mechanical & Manufacturing Engineering (SMME), School of Natural Sciences (SNS) and U.S. Pakistan Centers for Advanced Studies in Energy (USPCASE). All libraries of each school will be mentioned in this article by the acronym of the school name All the selected sites were constructed within the last 2 decades.

The selected sites are present on different floors of the building, detail of which is given in table 1. Among all the buildings only USPCASE has a centralized HVAC system installed while all other schools have window units installed. All schools have undergraduate as well as graduate degree programs except for SADA and USPCASE which has the only undergraduate and graduate program respectively. The working hours of the libraries were from 9:00 a.m. to 5:00 p.m. Table.1 represents a brief description of the selected study sites.

3.2.2 Sampling

The study was conducted in two phases, phase 1 started at the end of September till the 1st half of October and phase 2 from 2nd half of November to 1st week of December. CO_2, RH and indoor temperature were monitored in both phases while particulate matter (PM) was monitored only during phase 2 of the study due to the unavailability of the PM measuring instrument. The sites were monitored from 10:00 a.m. to 4:30 p.m. The sample was collected with a 1-minute interval for all parameters. In phase 1 the ventilation systems were operational while in phase 2 all ventilation systems were shut down. The occupancy of the selected site was observed to be varying in nature and the number of occupants was counted every 15 minutes. Table. 1 represent an average number of occupants for all sampling period.

Table 3. 3 Brief Description of the selected buildings

Library/Building	Floor	Number of windows	Number of doors	Number of occupants (average)	Testing period	Number of test/sampling days	Ventilation system
NICE (NUST Institute of Civil Engineering)	Ground floor	8	1	20	10:00 a.m. – 4:30 p.m.	2-4	Split system
SADA (School of Art, Design & Architecture)	1st	7	2	8	10:00 a.m. – 4:30 p.m.	2-4	Split system
SCME (School of Chemical and Material Engineering)	1st	10	1	8	10:00 a.m. – 4:30 p.m.	2-4	Split system
SMME (School of Mechanical & Manufacturing Engineering)	2nd	1	1	10	10:00 a.m. – 4:30 p.m.	2-4	Split system
SNS (School of Natural Sciences)	3rd	3	2	7	10:00 a.m. – 4:30 p.m.	2-3	Split system
USPCASE (U.S Pakistan Centers for Advanced Studies in Energy)	3rd	7	1	9	10:00 a.m. – 4:30 p.m.	2-4	Centralized HVAC system

For the analysis of the data three software MS Excel, IBM SPSS and Origin Pro were used. Along with real-time graphs, mean 30-minute average graphs were also developed. In the end, the data was compared with the guidelines of the ASHRAE 55, ASHRAE 62.1 standards, and US EPA along with literature.

Summary

In this chapter, a brief introduction to the device used in this study is presented. An introduction and working of the sensors used by CO210 are also discussed in this chapter. In the end, a research methodology of this study is discussed.

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Chapter 4

Results and Discussions

This chapter presents the results of the conducted study. Graphical representation of the obtained data along with descriptive statistical analysis is discussed in this chapter.

4.1 Results

IAQ parameters and PM of six libraries of six schools of NUST was studied and recorded in two phases. The data was collected during working hours. Occupants were counted every 15 minutes of the occupancy. Besides the number of occupants in the library, the behavior of the occupants had a great influence on the quality of the built environment. In the libraries, the occupancy is mostly varying with peaks during free times in between classes and very low during breaks. The real-time graphs of all parameters on different days for all libraries are presented here. Detailed descriptive statistics is given in the Table 4.1. The IAQ results for all the libraries are presented separately while PM is discussed collectively:

4.1.1 SMME Library

This library is equipped with a conventional split air conditioning system. 2 units of the system were installed in which only one was operated during occupancy. The door and the windows were closed during the entire period of testing. The average number of occupants during entire study period was 10. Figure 4.1 shows the real-time CO_2 vs Time graph. As can be seen from the graph, the peaks were observed during those hours in which the average number of occupants was maximum. The maximum value recorded was 954 ppm and 1233 ppm in phase 1 and 2 respectively. while the minimum value of CO_2 concentration was 539 ppm and 546 ppm respectively. Figure 4.2 represents the Temperature variation with time during the occupancy period. The temperature of the SMME library showed very little variation during the testing period in each phase. The average value recorded was 26.6℃ and 19.8℃ in phase 1 and 2 of the testing period. In contrast to the temperature, the average value of RH of this study

Table 4. 1 Descriptive statistics of all parameters of each site (PM was monitored only in phase 2)

Site/Building	Parameter	No. of readings (Phase 1/Phase 2)	Mean (Phase 1/Phase 2)	Minimum (Phase 1/Phase 2)	Maximum (Phase 1/Phase 2)	Std. Deviation (Phase 1/Phase 2)
NICE (NUST Institute of Civil Engineering) Library	CO_2 (ppm)	780/780	1199.9/1230.2	602/693	1824/1729	372.3/297.2
	Temperature (℃)	780/780	27.34/20.97	26.70/20.10	28.20/21.60	.38/.30
	Relative Humidity (%)	780/780	45.27/54.79	40.90/52.80	54.50/56.30	3.47/.64
	PM 10µm (µg/m^3)	780	30.54	9.86	99.18	12.90
	PM 5µm (µg/m^3)	780	21.07	10.24	49.78	6.34
	PM 2µm (µg/m^3)	780	1.68	0.82	3.82	0.48
	PM 1µm (µg/m^3)	780	3.93	3.05	5.44	0.45
	PM 0.5µm (µg/m^3)	780	3.150	2.54	4.22	0.41
	PM 0.3µm (µg/m^3)	780	10.52	9.2058	12.07	0.53
SADA (School of Art, Design & Architecture) library	CO_2 (ppm)	780/780	748.90/790.90	554/521	888/1087	69.70/140.40
	Temperature (℃)	780/780	26.80/19.70	26.20/19.10	27.40/19.70	0.30/0.17
	Relative Humidity (%)	780/780	47.50/52.50	44.80/50.30	50.30/52.50	0.81/1.82
	PM 10µm (µg/m^3)	780	12.51	2.46	105.65	9.41
	PM 5µm (µg/m^3)	780	9.26	3.85	57.33	6.10
	PM 2µm (µg/m^3)	780	0.74	0.33	4.48	0.47
	PM 1µm (µg/m^3)	780	2.55	1.86	4.90	0.47
	PM 0.5µm (µg/m^3)	780	3.77	2.91	4.71	0.50
	PM 0.3µm (µg/m^3)	780	12.63	10.19	14.84	1.51
SCME (School of Chemical & Material Engineering) library	CO_2 (ppm)	780/780	581.10/530	444/384	752/766	83.40/92.80
	Temperature (℃)	780/780	28.90/20.10	27.10/18.10	32.20/21.80	1.14/0.94
	Relative Humidity (%)	780/780	44.70/31.80	37.50/24.10	50.80/44.60	3.52/6.57
	PM 10µm (µg/m^3)	780	34.66	9.24	169.71	18.76
	PM 5µm (µg/m^3)	780	25.97	11.51	123.78	15.95
	PM 2µm (µg/m^3)	780	2.03	0.87	9.40	1.27
	PM 1µm (µg/m^3)	780	4.48	1.53	15.91	3.41
	PM 0.5µm (µg/m^3)	780	4.41	1.53	13.75	3.30
	PM 0.3µm (µg/m^3)	780	10.25	5.23	18.39	4.35
SMME (School of Mechanical & Manufacturing Engineering) library	CO_2 (ppm)	780/780	730.90/781.40	539/546	954/1233	83.04/153.03
	Temperature (℃)	780/780	26.60/19.80	25.60/19.20	27.40/20.40	0.52/0.28
	Relative Humidity (%)	780/780	63/52.40	54.20/48.80	68.60/57.40	2.30/2.10
	PM 10µm (µg/m^3)	780	24.92	8.01	85.93	8.29
	PM 5µm (µg/m^3)	780	17.44	7.31	52.05	6.23
	PM 2µm (µg/m^3)	780	1.38	0.61	4.04	0.49
	PM 1µm (µg/m^3)	780	3.60	1.51	7.01	1.42
	PM 0.5µm (µg/m^3)	780	3.28	1.08	6.47	1.55
	PM 0.3µm (µg/m^3)	780	9.40	3.71	15.90	3.61
SNS (School of Natural Sciences) library	CO_2 (ppm)	390/780	868.60/1048.60	585/634	1027/1288	109.70/153.60
	Temperature (℃)	390/780	27.47/19.72	27.10/18.90	27.90/21.20	0.14/0.53
	Relative Humidity (%)	390/780	52.38/53.51	51.50/48.40	53.20/56.30	0.40/1.79
	PM 10µm (µg/m^3)	780	19.60	4.62	63.14	7.14
	PM 5µm (µg/m^3)	780	12.09	6.24	22.83	2.26
	PM 2µm (µg/m^3)	780	0.96	0.52	1.72	0.16
	PM 1µm (µg/m^3)	780	3.06	1.55	4.30	0.46
	PM 0.5µm (µg/m^3)	780	3.30	1.99	4.43	0.71
	PM 0.3µm (µg/m^3)	780	11.07	8.34	13.48	1.83
USPCAS-E (U.S. Pakistan Centers for Advanced Studies in Energy) library	CO_2 (ppm)	780/780	515.70/850.90	397/495	680/1136	71.86/178.05
	Temperature (℃)	780/780	27.20/20.90	24.50/18.90	29.80/22.20	1.30/0.84
	Relative Humidity (%)	780/780	48.57/37.1	41.80/31.30	62.70/40.00	5.18/2.47
	PM 10µm (µg/m^3)	780	39.25	8.32	153.39	18.43
	PM 5µm (µg/m^3)	780	35.16	12.82	84.01	11.48
	PM 2µm (µg/m^3)	780	2.82	1.13	6.58	0.88
	PM 1µm (µg/m^3)	780	6.16	4.20	9.13	1.05
	PM 0.5µm (µg/m^3)	780	5.43	3.23	7.48	1.30
	PM 0.3µm (µg/m^3)	780	13.09	9.53	15.64	2.13

area remained close to the maximum allowable limit of 65% by ASHRAE 55 standard for thermal comfort in phase 1 and was below 55% in phase 2 as shown in Figure 4.3.

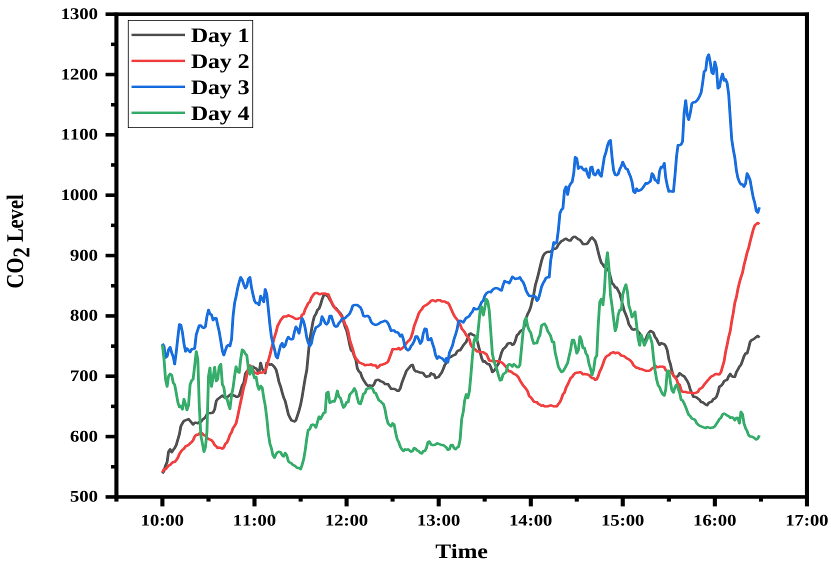

Figure. 4. 1 Real-Time CO2 vs Time graph

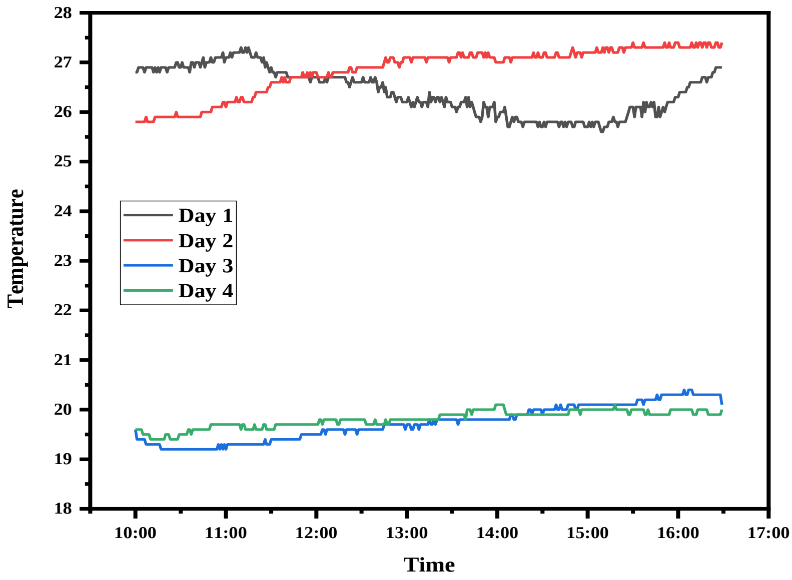

Figure. 4. 2 Real-Time Temperature vs Time graph

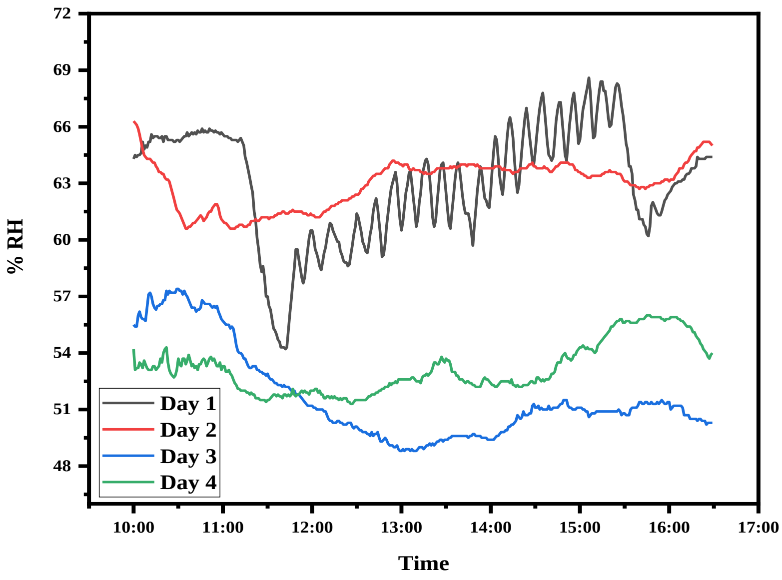

Figure. 4. 3 Real-Time RH vs Time graph

4.1.2 NICE Library

This was the largest library I have studied. It has a complete ground floor and a partial first floor which has space for students to study beside the ground floor. This library has 3 split system units running to condition the indoor air. As compared to any other library higher number of occupants were observed during the occupancy period. The average number of occupants observed was around 20. The door was closed on both days while on the second day the windows were opened by students during the latter half of the day during phase 1. The CO_2 level recorded here was the highest among all the studied area as shown in Figure 4.4. The highest value observed was 1824 ppm in phase 1 and 1729 ppm in phase 2 of testing period.

The temperature of this library stayed at an average of 27.34℃ and 20.97℃ in each phase of testing. The highest temperature was observed on day 1 which was 28.2℃. Figure 4.5 presents

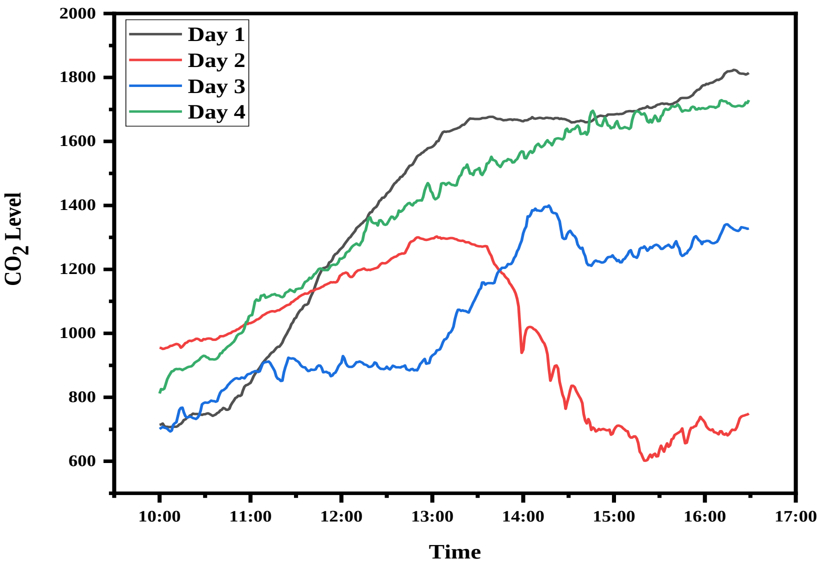

Figure. 4. 4 Real-Time CO_2 vs Time graph

the Temperature vs Time graph for the occupancy period. The relative humidity of this test site was observed to be within the allowable limits of the ASHRAE standard. the average value of RH was 45.27% and 54.79 % in phase 1 and 2 respectively. Figure 4.6 shows the RH vs Time graph of the NICE library.

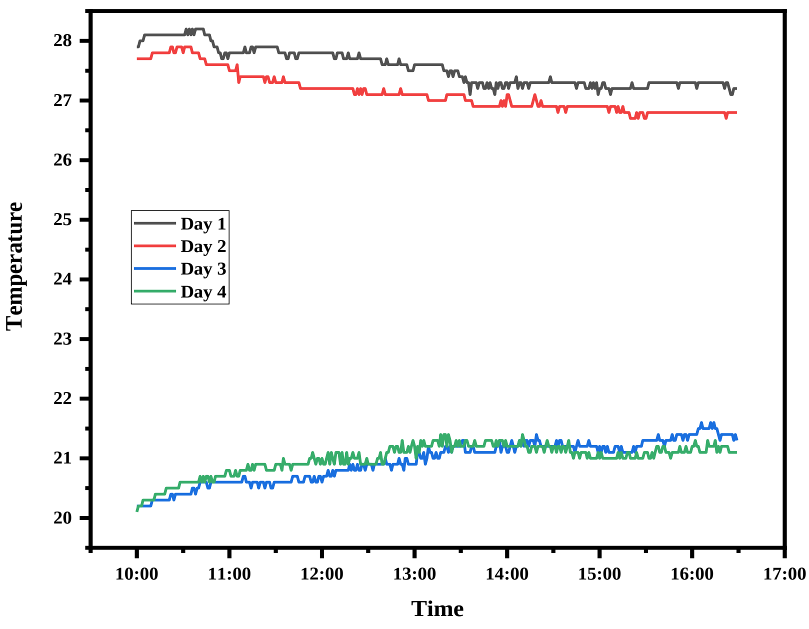

Figure. 4. 5 Real-Time Temperature vs Time graph

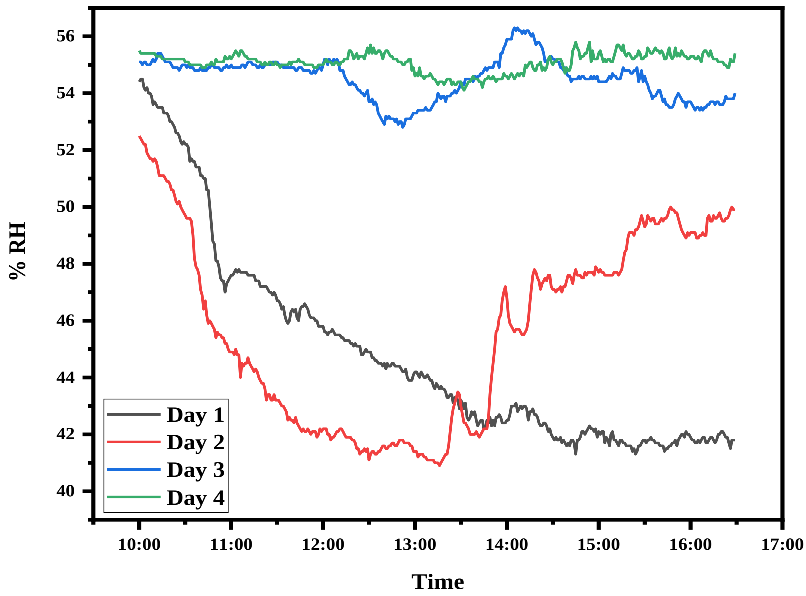

Figure. 4. 6 Real-Time RH vs Time graph

4.1.3 SADA Library

The schools of Art, Design, and Architecture (SADA) library was among those with low occupancy during the entire occupancy period. The library also had infiltrations in many places which can affect the IAQ. The air conditioning system (conventional) was completely shut off in 2nd phase and thus it completely dependent on the natural way of ventilation. The average number of occupants during the working hours were 8. The level of CO_2 as shown in Figure

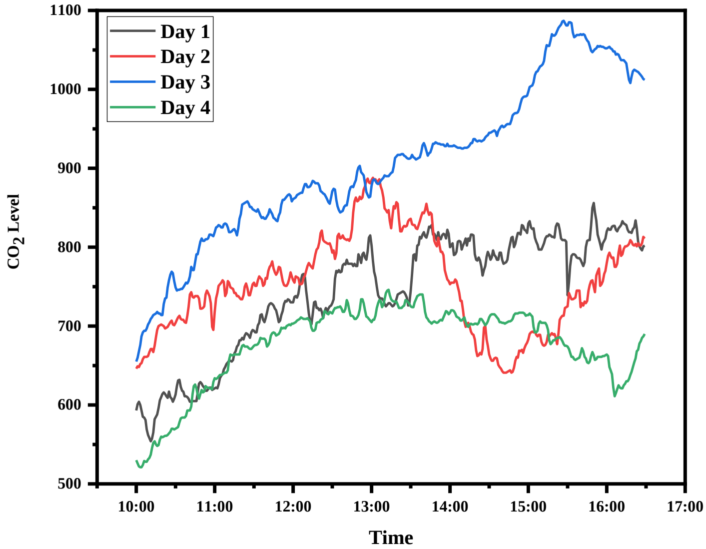

Figure. 4. 7 Real time CO_2 vs time graph

4.7 were observed to be under 1000 ppm during the occupancy period in 1st phase. The highest value recorded was 1087 ppm in phase 2 of testing.

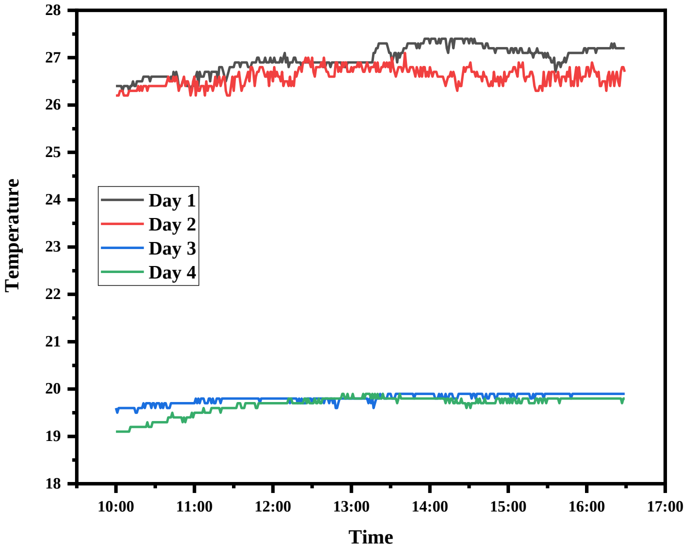

Figure. 4. 8 Real-Time Temperature vs Time graph

The temperature profile across the day is presented in Figure 4.8. the average temperature was 26.8℃ and 19.7℃ in 1st and 2nd phase respectively, while the highest value recorded was 27.4℃ on day 1. The relative humidity remains at an average value of 47 % and 52.5 % during the two phases of testing period. Figure 4.9 shows the variation of RH with time over the occupancy period.

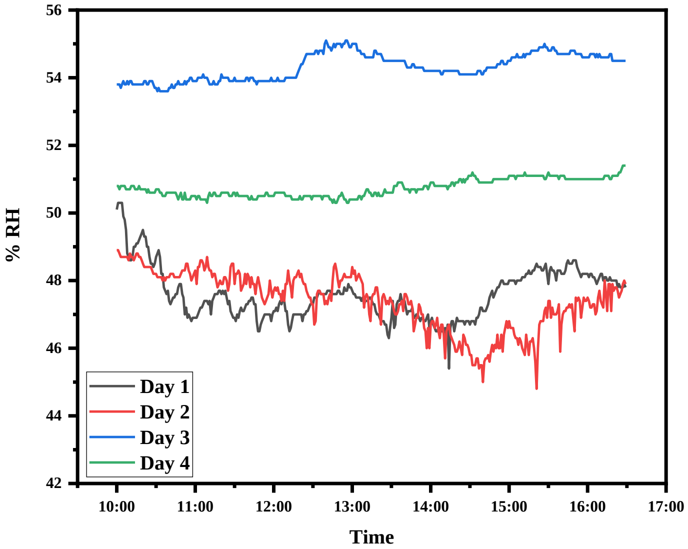

Figure. 4. 9 Real-Time RH vs Time graph

4.1.4 SCME Library

This library had the least number of occupants during the testing period. The air conditioning system was conventional split system. The 2-3 windows were observed to be open for some time during occupancy. The average number of occupants were 8 during the study period. The

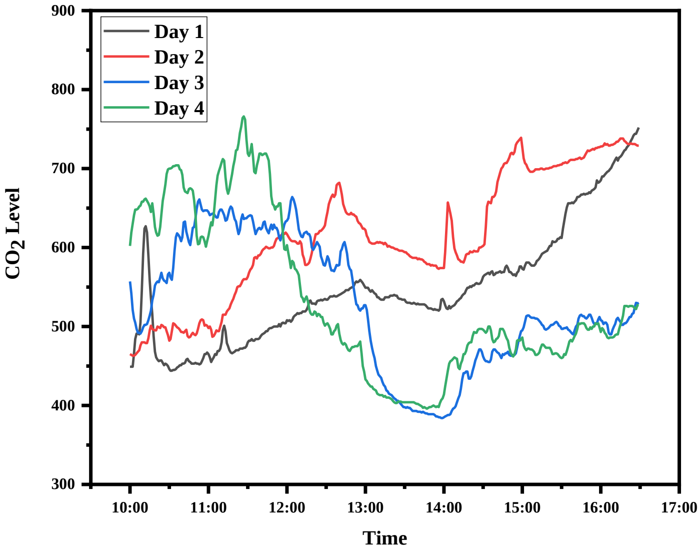

Figure. 4. 10 Real-Time CO_2 vs time graph

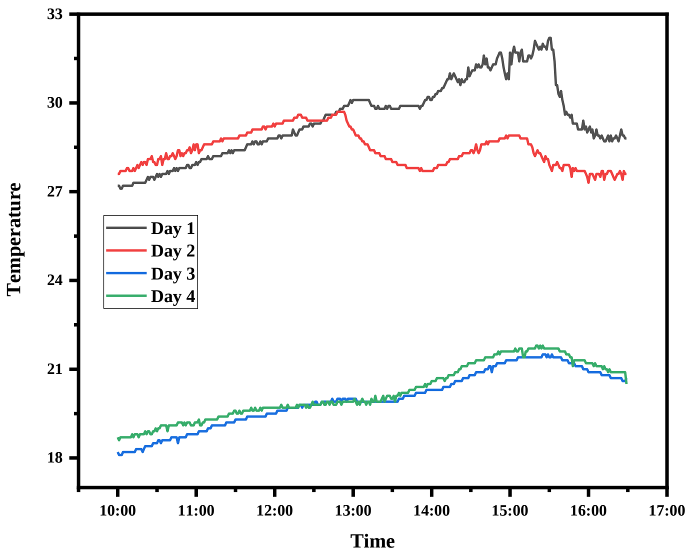

Figure. 4. 11 Real time Temperature vs Time graph

CO_2 level in this building remained below 1000 ppm in both phases of study Figure 4.10, 4.11 and 4.12 represents the real-time CO_2 vs Time, Temperature vs Time and RH vs time graphs of this library. The values of 32.2℃ and 21.8℃ was the highest recorded values during the occupancy period in each phase. The relative humidity was 44.7% and 31.8% average for the 2 phases of study.

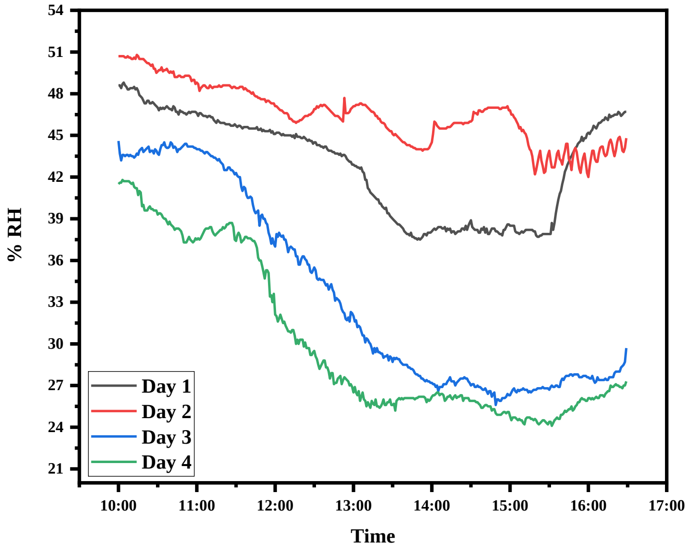

Figure. 4. 12 Real-Time RH vs Time graph

4.1.5 SNS Library

This was the smallest library among the studied libraries. It had a decent occupancy relative to

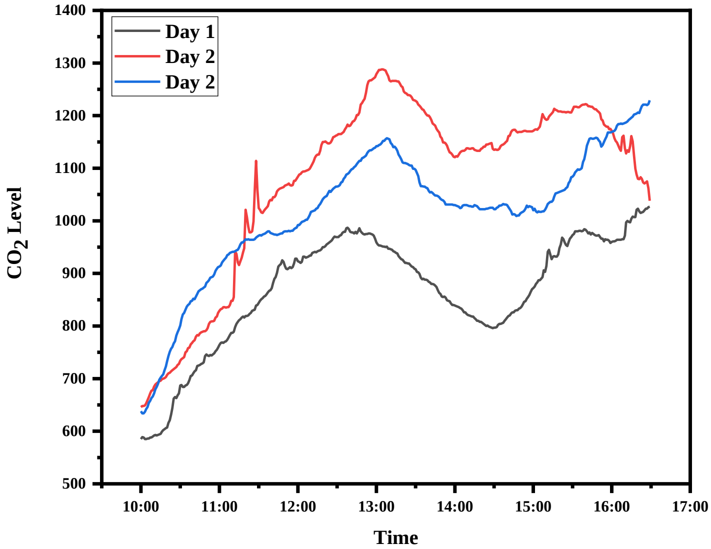

Figure. 4. 13 Real time CO_2 vs time graph

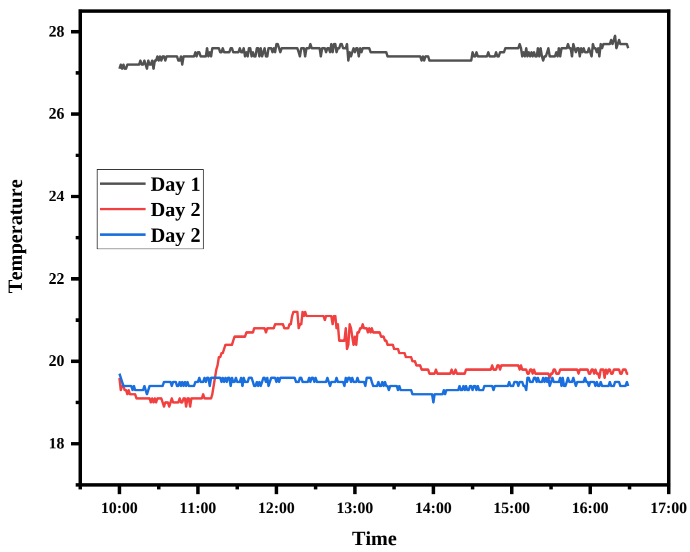

Figure. 4. 14 Real-Time Temperature vs Time graph

its size and had about 7 occupants on average during the occupancy with all doors and windows closed. The highest value recorded for CO_2 was 1288 ppm. The behavior of the CO_2, Temperature, and RH with time is represented in Figure 4.13-15. the average temperature during the occupancy was 27.47℃ and 19.72℃, and average relative humidity was 52.38% 53.51.

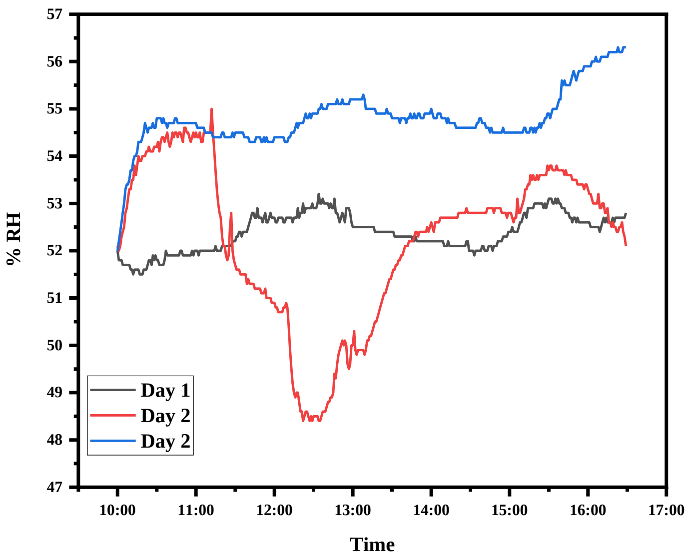

Figure. 4. 15 Real-Time RH vs Time graph

4.1.6 USPCASE Library

This was the only library building where the centralized HVAC system is installed. The average number of occupants during the testing period was 9. The highest value of CO_2 recorded was 680 ppm and 1136 ppm in phase 1 and 2 respectively. Figure 4.16-18 represents the behavior

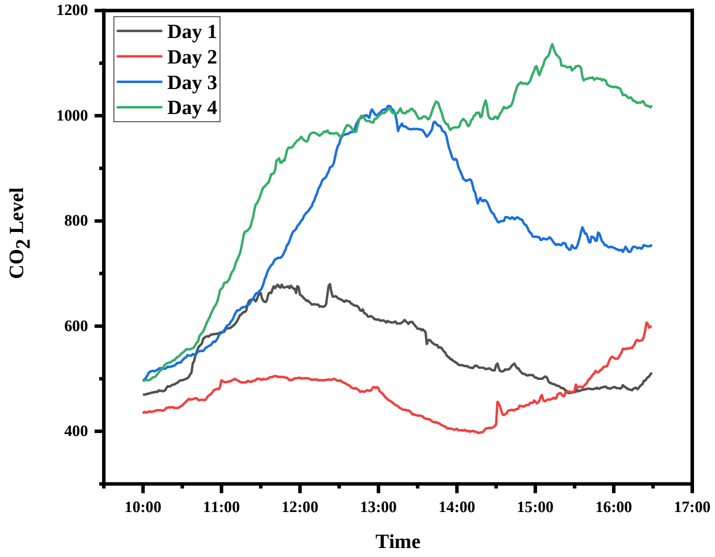

Figure. 4. 16 Real-Time CO_2 vs time graph

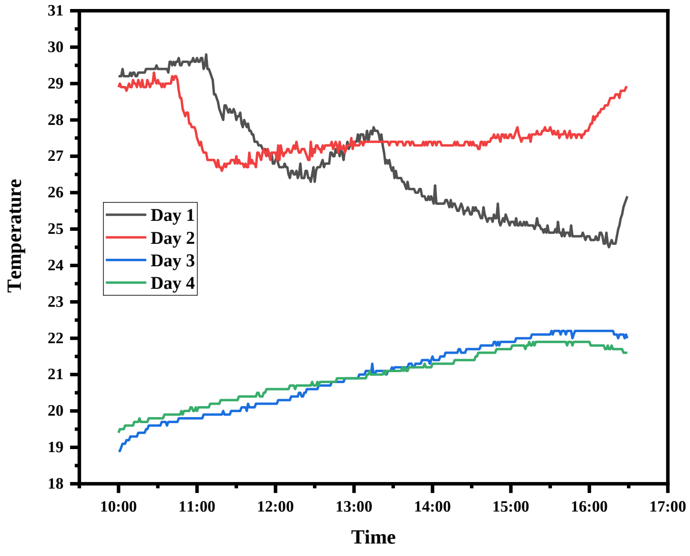

Figure. 4. 17 Real time Temperature vs Time graph

of the three parameters with time during the occupancy period. The temperature was averaged around 27.2℃ and 20.9℃ during the occupancy period in both phases. The relative humidity was around 49% and 37% averaged for both days.

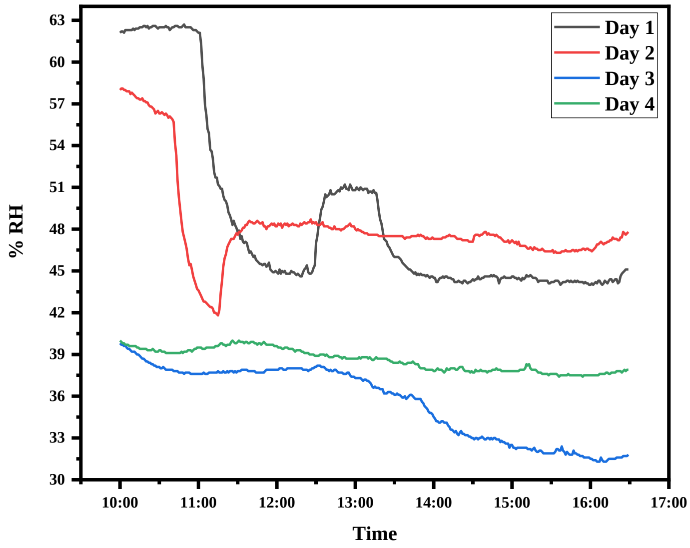

Figure. 4. 18 Real time %RH vs Time graph

4.1.7 Particulate matter of all studied site

Suspended airborne solid particles of six different sizes were monitored in all libraries. In Figure 4.19 each graph shows a comparison of distribution of the mass concentrations in (µg/m^3) of the same particle size in different buildings. In SCME, the highest concentrations of all six size particles were observed than any other library. The reason behind this might be, SCME was nearest among all studied places to one of the busiest roads of the city and 2 of the windows were open most of the time during the study period. The highest value recorded for PM10 µm, PM5 µm, PM2 µm, PM1 µm, PM0.5 µm, and PM0.3 µm was 169.71µg/m^3, 123.78 µg/m^3, 9.40 µg/m^3, 15.91 µg/m^3, 13.75 µg/m^3 and18.39 µg/m^3 respectively all in SCME. The least value recorded for PM10 µm, PM5 µm, and PM2 µm was 2.4 µg/m^3, 3.85 µg/m^3 and 0.33 µg/m^3 respectively in SADA and PM1 µm, PM0.5 µm and PM0.3 µm was 1.51 µg/m^3, 1.08 µg/m^3 and 3.71 µg/m^3 respectively in SMME.

4.2 Critical Analysis with Standards and literature

Six built spaces of the most important as classrooms were studied and data were collected for thermal comfort parameters, CO_2 and 6 different sizes of suspended particles of fine and coarse diameters. The CO_2 according to ASHRAE 62.1 standard should be 700 ppm above the atmospheric concentration or in other words, should be below 1000 ppm [1]. In the 1st phase of the study when ventilation systems were switched on in all the buildings, the CO_2 concentrations stayed within the limits defined by ASHRAE 62.1 standard except NICE. NICE had the poor regulation of the CO_2 among the studied buildings and mostly stayed above the 1000 ppm limit. SNS was another building where the 1000 ppm limit was crossed but for a very limited duration. The highest values recorded during this phase were 1824 ppm, 888 ppm, 752 ppm, 954 ppm, 1027 ppm and 680 ppm in NICE, SADA, SCME, SMME, SNS, and USPCASE, respectively. The reason that NICE performed very poorly in CO_2 regulation was that it had very few numbers of split air conditioning systems installed compared to the number of occupants and size it has. In the 2nd phase of the study, when ventilation systems were switched off, all the libraries crossed the 1000 ppm mark except SCME because SCME had 2 windows opened during the testing period. Despite values above 1000 ppm at a certain point, 4 buildings SADA, SCME, SMME, and USPCASE performed good and maintained the values of CO_2 closed to 1000 ppm. The other two study sites were unable to regulate the CO_2 values without the ventilation system operating. The highest values recorded during the 2nd phase was 1729 ppm, 1087 ppm, 766 ppm, 1233 ppm, 1288 ppm and 1136 ppm in NICE, SADA, SCME, SMME, SNS, and USPCASE, respectively. The CO_2 profile for both phases is shown in Figure 1. Among the buildings studied, NICE performed the worst and was unable to maintain the CO_2 level below 1000 ppm in both phases but performed good compared to studies reported previously e.g. studies from Korea [2], Portugal [2], and Pakistan [2] reported values of 2363 ppm, 3111 ppm, and 6294 ppm in schools. A school study in Chennai and an office study in Denmark has batter reported values of CO_2 than the present study. Other reported values in the literature are compared with the present study in Table 6.

The temperature and RH limits are defined by the ASHRAE 55 standard for thermal comfort, according to which, the temperature range should be between 22.5℃ and 25.5℃ and, RH should be maintained below 65% for the built environment to be thermally comfortable for the tenants [3]. The RH monitored was found to be under 65% all the time in each building in both phases for most of the study period. In phase 1 the RH of all studied sites remained between 45% and 55% most of the time except for SMME where RH value just below 65% was observed with the highest value of 68.1% was recorded. The temperature was the parameter that was found to be the most poorly regulated in all buildings in both phases of the study. In the 1st phase when the outdoor temperature was above 35℃, the mean temperature across the study period was between 26℃ and 32℃ for all buildings thus clearly exceeds the upper limit defined by ASHRAE 55 standard for thermal comfort. The SADA and SMME had temperatures closer to 26℃ than the other libraries. The temperature in the 1st phase for SCME was observed to be the highest among all study spaces. The highest temperatures measured during this phase for NICE, SADA, SCME, SMME, SNS, and USPCASE were 28.2℃, 27.4℃, 32.2℃, 27.4℃,27.9℃ and, 29.8℃, respectively while the lowest temperatures were 26.7℃, 26.2℃, 27.1℃, 25.6℃, 27.1℃, and 24.5℃, respectively. In the 2nd phase of the study, the outdoor temperatures averaged around 18℃, the indoor temperatures were observed between 18℃ and 22℃ thus lag the thermal comfort limit of 22.5℃. The highest values recorded in the 2nd phase for NICE, SADA, SCME, SMME, SNS and USPCASE were 21.6℃, 19.7℃, 21.8℃, 20.4℃, 21.2℃ and 22.2℃, respectively. The temperature during the entire study was found to be either lagging or exceeding the ASHRAE 55 standard. Around the globe, many standards have been developed by many countries for regulation of solid suspended particles in the indoor air. Some of these standards are US EPA, ASHRAE, OSHA, NAAQS, WHO, NHMRC, Health Canada, etc. for PM2.5 µm and PM 10 µm mentioned by Sabah Ahmed Abdul–Wahab et.al [4]. This study will compare the concentrations with US EPA's defined standard. For a particle size of fine category i.e. 2.5 µm or lesser, according to US EPA, the exposure should not exceed the limit of 65 µg/m^3 for 24-hr average. This study has 4 particles among the six i.e. 0.3 µm, 0.5 µm, 1 µm, and 2µm that fall in the fine category. The particles mass concentration for 0.3 µm, 0.5 µm, 1 µm, and 2 µm were found to be within limits defined by US EPA. Highest values of 0.3 µm, 0.5 µm, 1 µm, and 2 µm recorded was 18.39 µg/m^3, 13.75 µg/m^3, 15.91 µg/m^3 and 9.40 µg/m^3 all in SCME. All the buildings performed well in this category and maintained values under US EPA defined value of 65 µg/m^3 and some of reported values in the literature. Studies conducted in Europe [5], Portugal [5], Spain [5], Korea [5], and India [5] reported values of 32 µg/m^3, (44.42 &35.47) µg/m^3, 7.87 µg/m^3, and 60.7 µg/m^3 respectively, which were all below the US EPA defined limit. Values of 1169 µg/m^3 and 244 µg/m^3 in Pakistan[5] and Portugal[5] are reported. The other 2 particles of size 5 µm and 10µm lie in the coarse particle category. According to US EPA, the exposure to particle size 10 µm or lesser should not exceed the limits of 150 µg/m^3 for a 24-hr average. In the studied buildings, the mass concentrations of the PM5 µm and PM10 µm were observed to lie under 100 µg/m^3 during the sampling period with few values higher than 150 µg/m^3. The highest values measured were 169.71 µg/m^3 and 123.78 µg/m^3 for PM10 µm and PM5 µm both in SCME. Overall the mass concentration of all particles, despite few higher values at a certain time because of dusting, remained within the limits defined by US EPA. Higher values of 1234.7 µg/m^3, 226 µg/m^3, and 1581 µg/m^3 in Portugal[5], Korea[5], and Pakistan[5] were reported. The SCME and USPCASE comparatively had higher concentrations of the particulate matter than the other four buildings. The reason might be that they are nearer to the highway than the other buildings. Also, there was construction in progress near these buildings. The reported values of different sized particulate matter in previous literature are compared with this study in Table 5. The observed mass concentration in the present study was much lower than the studies conducted in different parts of the world.

Table 4. 2 Previous conducted studies on Indoor CO_2 in different purpose buildings

Country	**Sampling duration**	**Number and type of buildings**	**Season**	**Reported values**	**Present Study**
				CO_2 (ppm) (max/min)	CO_2 (ppm) (max/min)
Korea [2]	6hrs	34 schools	19 winter 15 in spring	2363/709	**1824ppm/384**
Portugal [6]	5-days during classes, 1-minute interval	20 schools	Winter	3111/829	
Korea [7]	Jan-Mar 5-minute interval	3 schools	cold	2290/344	
India, Delhi [8]	5 days 9:30-5:30 5-minute interval	2 offices 1 educational	Pre-monsoon	mean up to 1513	
India, Chennai [9]	60 days in 2 phases	1 school	Winter and summer	w (571/341), s (435/249)	
Denmark [10]	1 day, 9 am-4pm	9 offices	October	555/405 (HVAC) 1000/425(natural)	
Pakistan [11]	2-5 days 24hrs, 1minute interval	4 university's schools	March to June	6294/364	

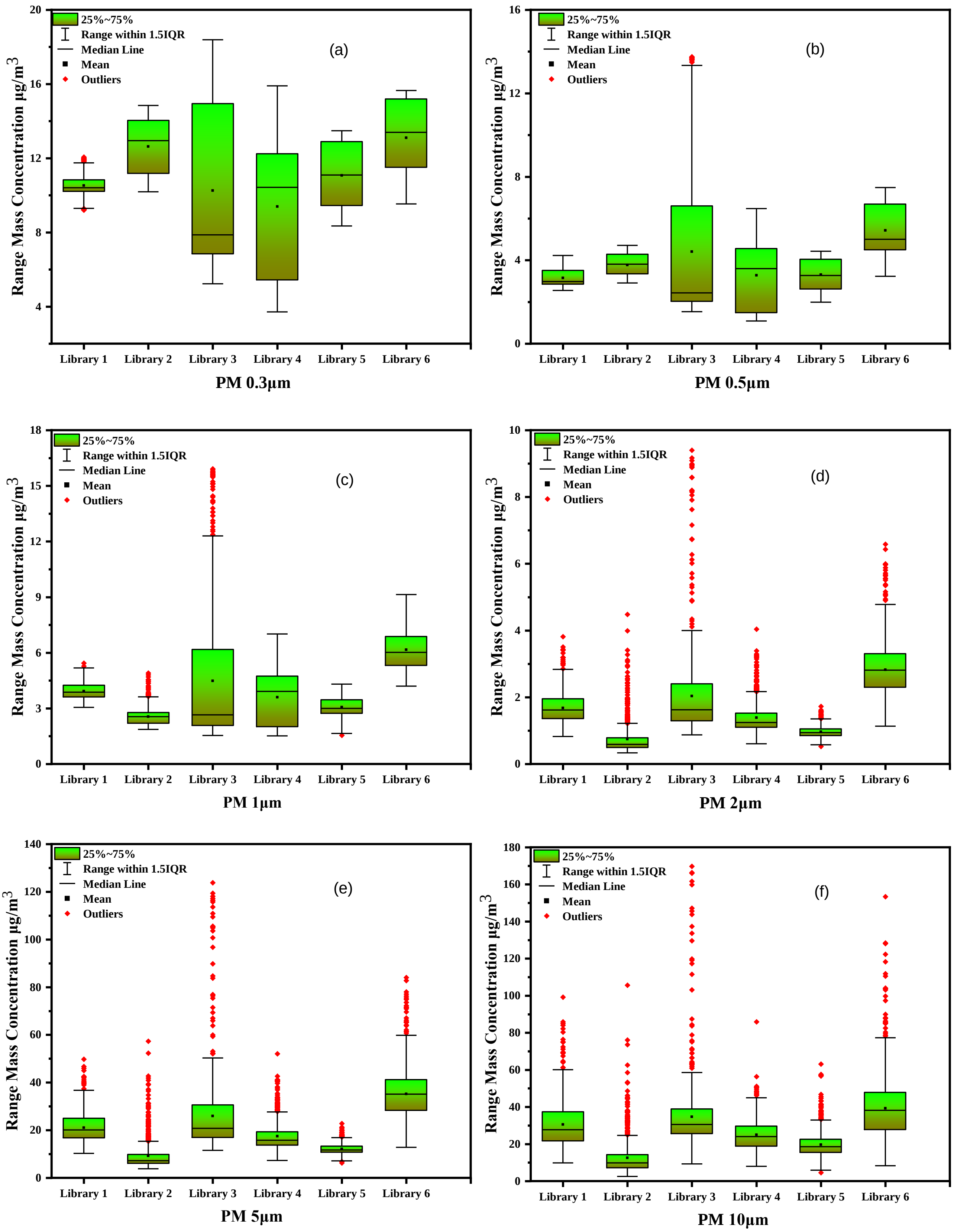

Figure 4.19 Mass concentrations of (a) PM0.3 µm, (b)PM0.5 µm, (c) PM1 µm, (d) PM2 µm, (e) PM5 µm & (f)PM10 µm

Table 4. 3 Previous conducted studies on Indoor Particulate Matter in different purpose buildings

Country	Sampling duration	Number and type of buildings	Season	Reported values			Present study			
				PM10 (max/min)	PM2.5(max/min)	PM1(max/min)	PM10 (max/min)	PM5(max/min)	PM2(max/min)	PM1(max/min)
Europe [5]	5-days, 24hrs	37-office buildings	Winter and summer		(17s & 32w)/ (2.7s & 3.4w)[1]		**169.7/ 2.4641**	**123.7/ 3.8501**	**9.4/ 0.3327**	**15.9/ 1.5111**
Portugal [12]	10-min interval 2-phase study	1-library building	Oct-Dec	1st visit (1234.77/19.01) 2nd visit (856.98/6.70)	1st visit (44.42/3.64) 2nd visit (35.47/1.34)					
Spain [13]	4-days continuous	12 classrooms	Warm and cold	avg 12.08	avg 7.87					
Korea [2]	6hrs	34 schools	19 winter 15 in spring	226/9.5	60.7/2.6					
Lahore, Pakistan [14]	Oct-Feb	3 residential sites	Cold	avg 1581 (rural site kitchen) avg 953 (rural living room) avg 533(living room urban)	avg 1169(rural site kitchen), avg 603(rural living room), avg 402(living room urban)	avg 913(rural site kitchen), avg 548(rural living room) avg 362(living room urban)				
Ecuador [15]	7-days 24-hrs	3 schools 4 houses	All year round	78.5/2.4 schools 181.5/5.6 homes	72.1/0.4 in schools 149/3.1 in homes					
Portugal [6]	5 days during classes, 1-minute interval	20 schools	Winter	320/56	244/39					
Korea [7]	Jan-Mar 5-minute interval	3 schools	cold		99.03/0.01					
India, Delhi [8]	5 days 9:30-5:30 5-minute interval	2 offices 1educational	Pre-monsoon		Range 3.8-46.7					
India, Chennai [9]	60 days in 2 phases	1 school	Winter and summer	w (938.99/40.59), s (746.1/50)	w (225.46/16.72), s (107.2/17.8)	w (146.78/9.41), s (58.5/10.8)				

[1] "s" represents summer, "w" represents winter

Summary

In this chapter of the thesis detail results of the conducted studied are discussed. Graphical representation of the parameters is presented here. The results are compared with standards and literature. Tabled statistical information of the data set is also presented in this chapter.

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Chapter 5

Conclusions and Recommendations

Six buildings of the same purpose and different ventilation systems were tested for the quality of the built environment by sampling temperature, relative humidity, carbon dioxide, and particulate matter. It was found that the thermal comfort parameters and CO_2 regulation were poor when the ventilation system was switched off as compared to when it was operating. The centralized HVAC system performed better in maintaining good indoor air for the occupants. The number of occupants and their behavior besides the ventilation system had a great influence on the indoor air quality parameters. The orientation of the building has influenced especially on the indoor temperature. The temperature was found to be higher than the ASHRAE standard in phase 1 and lower than the ASHRAE standard in phase 2 thus shows the very poor performance of all buildings in regulating temperature. In the case of particulate matter, it was observed that the buildings near to roads with heavy traffic and construction site have higher concentrations of the solid suspended particles. The particulates matter was found to be in accordance with the US EPA regulation for 24-hr average.

Recommendations:

The following are recommended future studies:

- 24-hrs continuous study should be carried out to know the behavior of the buildings in non-occupancy period.
- Extended length yearlong study can be carried out to understand the behavior of the buildings in all climatic conditions.
- The number of parameters can be increased in the future studies.
- Source tracing of the pollutants in the buildings can be done in a separate study.
- Beside libraries, laboratory conditions should be studied along with offices.

Assessment of Relative Humidity, Temperature, Carbon Dioxide & Particulate Materials in Labs

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Abstract: Commonly, individuals spend their time inside dwellings, this makes the indoor environment of great health concern to the occupants because most of the poor-quality air is inhaled inside dwellings. Worldwide, indoor air pollutants cause the foremost vital indoor air quality challenges attributable to the number of people it affects, different types of pollutants involved, and the acuteness of the risks involved. Besides, in educational buildings especially in laboratories, the indoor environment can be much different than any other area of the institute because different processes are going on there. This study was carried out to investigate different parameters affecting the quality of the built environment and thermal comfort along with particulate materials in three laboratories of an educational building with a centralized ventilation system and split system. CO_2, temperature, relative humidity, and particulate materials were measured during the weekdays. The Extech-CO210 CO_2 data logger was used in the sampling of CO_2 and comfort parameters while Fluke 985 particle counter was used for measuring particles of different sizes. Also, measurements were compared against ASHRAE 55, 62.1 and US EPA standards for the minimum required performance. All parameters were observed to be within the limits of required standards except for the temperature in all studied spaces and particle mass concentrations for size less than 10μm.

Keywords: CO_2 concentration, RH, Thermal Comfort, Educational Building, Indoor Air Quality, PM10, PM2.5

Introduction:

Mostly, people spend their time indoor, around 90% of their daily lives in built environments like inside offices, schools, college, commercial, industrial buildings or inside their houses. Previously conducted studies suggest that the pollutants present in the indoor air are far more than that of the outside atmosphere [1]-[2]. Also, IAQ is strongly controlled by both outdoor and indoor contamination sources which need to be properly controlled [3]. According to the World Health Organization, more deaths occur due to indoor pollution than outdoor pollution [4]. Moreover, indoor air quality (IAQ) and thermal comfort can also influence the productivity, concentration, performance, and well-being of an occupant [3], [5].

Around the world, the IAQ is assessed by CO_2 levels as CO_2 is usually considered as a substitute for ventilation quality assessment because CO_2 levels above a certain concentration shows poor ventilation in the building which indicates the possibility of build-up of higher concentrations of other indoor pollutants which can have negative impact on human health[6]-[7]. Besides CO_2, temperature and relative humidity, solid suspended particles are also of great health risk in the built environment[8]. Particulate materials are one of the causes of asthma, rhinitis, allergic disease[9] and can be carcinogenic in nature. PMs are suspended solid particles in the air, mainly sourced by construction, industrial processes, combustion processes in engines and other utility instruments like stoves, etc. and dust produced by vehicles[10].
Many researchers studied IAQ in past and investigated IAQ of different types of buildings such as museums, residential buildings, old age community centers, offices, health care centers and, academic buildings[11]–[15]. As students and teachers spend the majority of their time in Academic institutes after homes make them one of the most important built environment to be studied[3], [5], [12].

This study aimed to assess the indoor concentrations of CO_2 along with indoor temperature, relative humidity and particulate materials (PM) in three labs of an academic building present in Islamabad. Data were gathered during the occupational hours of the labs. ASHRAE 55, ASHRAE 62.1 and US EPA standards were used to check the quality of the built environment.

Methodology:

Measurement location:

This study was carried out to assess the quality of the built environment by measuring CO_2, temperature, relative humidity and particulate materials of different sizes of a newly built building of USPCAS-E. Three labs were selected and labeled as SL, FL & CL. A prior survey to the site was conducted to know about the activities and different factors that can affect the parameters being monitored.

All three were different purpose labs. Among them, one lab CL was centralized HVAC, while the other 2 were equipped with a split system. SL was on the first floor, FL on the second floor and CL was on the third floor.

Instruments and sampling:

Indoor concentrations of CO_2 along with indoor temperature and relative humidity were monitored during the month of June 2019. Extech CO210 data logger was used during this study Fluke 985 particle counter was used to study the airborne particle concentrations in the built environment. Specification of these instruments is given in table 1 and 2.

Continuous measurements were taken for 2 to 3 days for CO_2 and thermal comfort parameters while airborne particles were sampled for 90 minutes during weekdays. The sampling data was logged for a period of 1 minute for all parameters. The sampling period was during the official working hrs. Mean 15-minutes average values of the comfort parameters and CO_2 are presented for comparison.

Results and Discussions:

The set of data collected for all three labs is presented in a mean graphical form to show its behavior for each lab as well as to compare the parameters. The mass concentrations of all six sizes for 3 labs are presented on box charts for comparison.

Table 1 Specification of Extech CO 210

Sr.no	Specification	Range
1	CO_2	0-9999 PPM
2	Resolution	1 PPM
3	Temperature	-10 to 60 °C
4	Resolution	0.1°C
5	Humidity	0.1 to 99.9%
6	Resolution	0.1%
7	Datalogging	Up to 5333 points for each parameter

Table 2 Specification fluke 985 particle counter

Sr.no	Specification	Range
1	Particle-Size range	0.3, 0.5, 1.0, 2.0, 5.0, 10.0) µm
2	Channels	6
3	Flow rate	2.83 liter/min
4	Data storage	10000 points

Variation of Carbon Dioxide:

Figure .1 shows the CO_2 distribution of the labs with time during the sampling period. Among the three labs, the fossil fuel lab was found to be having higher CO_2 levels as compared to the computer and solar lab. Though the CO_2 concentrations were measured different in all three labs, still CO_2 was found to be within the limits defined by ASHRAE 62.1 standard, which is below 1000ppm. The maximum and minimum

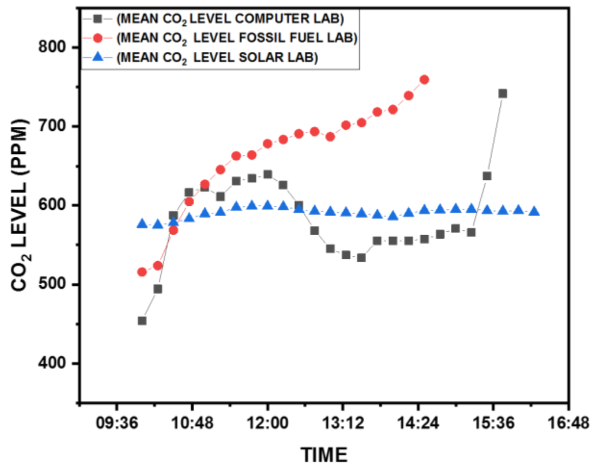

Figure 1 CO_2 profile of all three labs

values of carbon dioxide recorded were 814, 932 & 645 ppm max and 382, 405 & 530 ppm min for the computer lab, fossil fuel lab and solar lab respectively.

Relative Humidity:

Figures 2 represents the relative humidity behavior of the monitored laboratories with time. The relative humidity of solar and computer fuel lab was observed in the range of 40-45 % for most of the monitoring duration while fossil fuel had relative humidity a little higher than the other two labs. This may be because of the processes involving water in the laboratory. The maximum values recorded was 64.9%, 63% & 49% respectively in computer lab, fossil fuel lab & solar lab. While the lowest reading measured in the computer lab was 37.3% and 35% for the other labs.

Temperature:

Figure 3 shows a mean 15-minute average graph of the temperature of the monitored laboratories. The temperature profile computer lab is significantly higher than the other two tested locations. The main reason for this behavior was found to be the

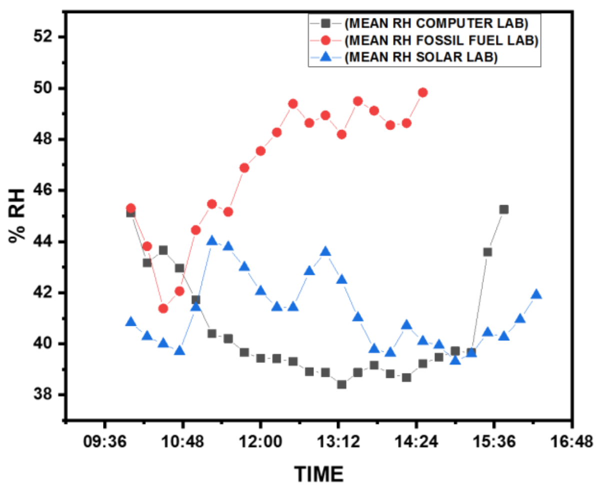

Figure 2 %RH profile of all three labs

presence of high-performance computers which were performing continuous simulation and were releasing heat into the built space, The maximum values recorded were 32.6°C, 31.9°C & 30°C for computer lab, fossil fuel lab and solar lab respectively while, lower temperature recorded was 26.1°C, 24.9°C & 25°C respectively for computer, fossil fuel, and solar lab.

As compared to the computer lab, the fossil fuel and solar lab had temperatures at the lower level but were still above the ASHRAE 55 standard guideline for thermal comfort. The fossil and solar lab's temperature lies between 25°C-28°C for most of the time during measurement. the mean temperature for all tested areas was above the standard value of 25°C. This is mainly because of our university's rule or setting the thermostat of the air-conditioning devices at 26°C.

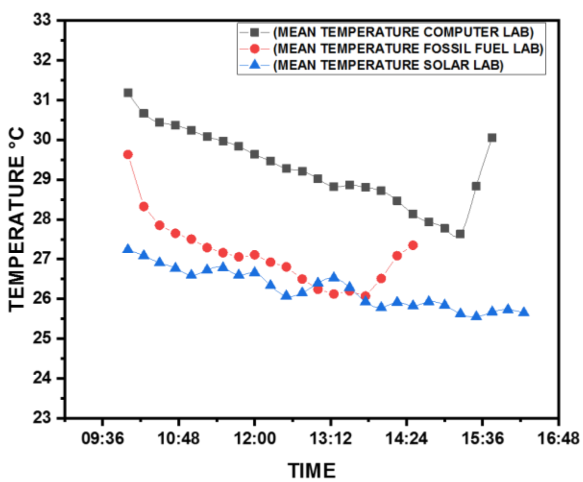

Figure 3 Temperature profile of labs

Particulates matter:

Six different sizes of solid suspended particles were measured in the selected built environment for the study. Figure 4 to 9, each chart shows the distribution of the mass concentration of the particles of the same size in different studied areas.

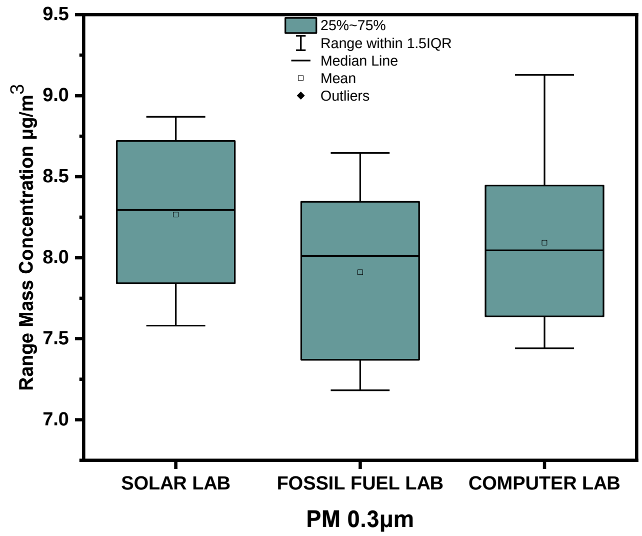

Figure 4 PM 0.3µm distribution in labs

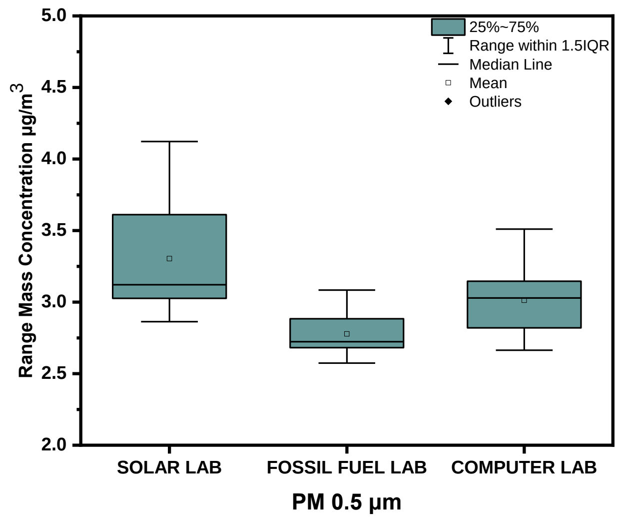

Figure 5 PM 0.5µm distribution in labs

The highest mass concentration of 0.3µm and 0.5µm particles were observed in a solar lab where for most of the time, a mass concentration between 7.5 µg/m^3 and 9 µg/m^3 for 0.3µm and between 3 µg/m^3 and 4 µg/m^3 for 0.5µm were observed. While mass concentration in the other two was just below for the other 2 studied areas for 0.3µm and was lowest for in fossil lab for 0.5µm.

The PM 1µm and 2µm mass concentrations were also the highest in the solar lab as compared to the other two studied labs. The mass concentration of all the labs for 1µm and 2µm
were below 10 µg/m^3 for all three labs.

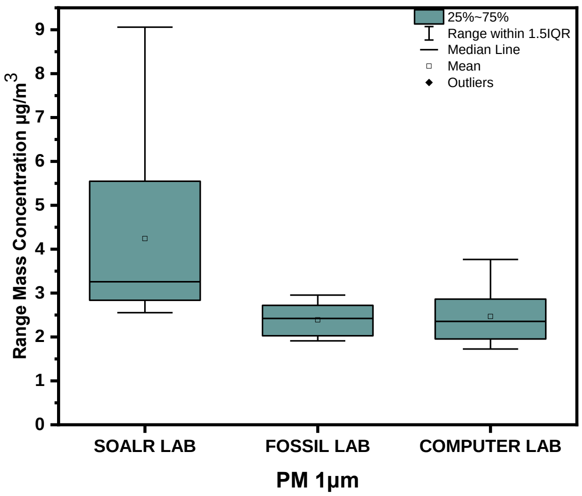

Figure 6 PM 1µm distribution in labs

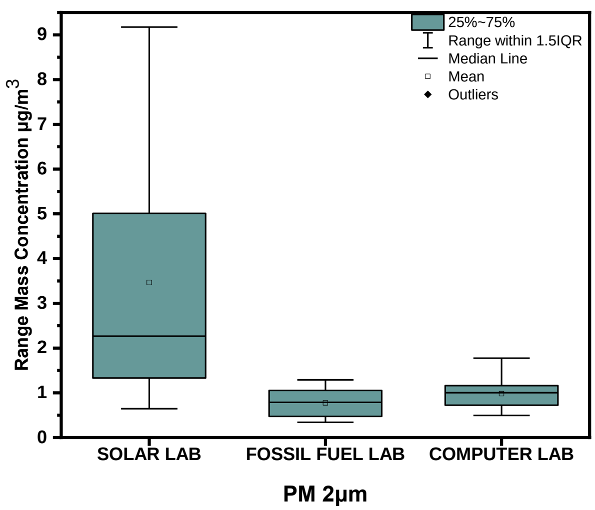

Figure 7 PM 2µm distribution in labs

The mass concentration of 5µm and 10µm was the highest among all other particle sizes. Solar lab with PM10 as high as 335 µg/m^3 was recorded. The PM5 was also recorded with as high as 169 µg/m^3. The mass concentration in the computer lab and fossil lab was below 50 µg/m^3. Table.3 shows mean, minimum, maximum and std. deviation of the recorded mass concentrations of six sizes.

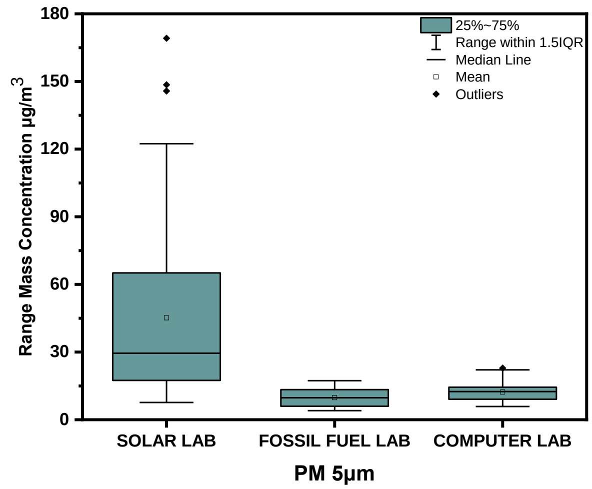

Figure 8 PM 5µm distribution in labs

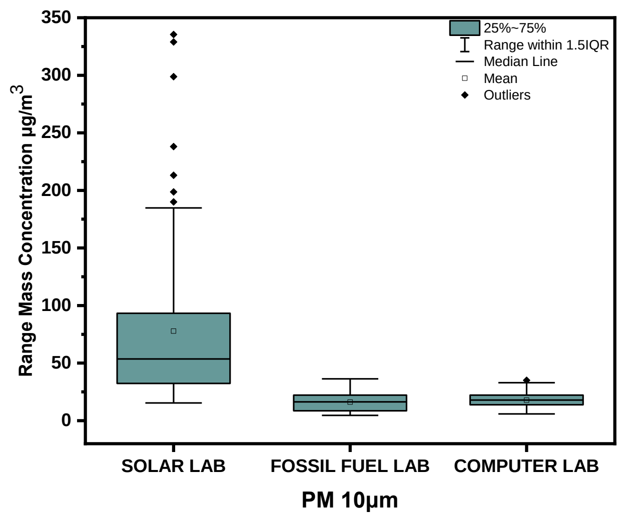

Figure 9 PM 10µm distribution in labs

Safety Measures:

Till now, many mitigation techniques have been developed to counter the problems posed by indoor air pollutants. These techniques may require the involvement of the building management and staff along with educating the occupants on the causes of the indoor air pollutants.

Many problems can attribute to the poor indoor air quality, some examples of problems and solution are presented here:

Low air ventilation rate, poor distribution of ventilation, outdoor diffusion of pollutants, problems in HVAC, the lab equipment are the source of the contaminations, building material, and combustion processes in the occupied space.

According to US EPA, to counter such problems, for example, 1) source control by relocating contaminant producing equipment near to air exhaust, choose products with better safety, proper storage of contaminants producing materials, cleaning and disinfecting for micro-organism removal, 2) through measures related to ventilation by increasing the air supply and improving air distribution, avoid recirculation of the air, and maintain pressure differential to block the path of contaminant diffusion, 3) through air cleaning by particulate filtration, electrostatic precipitation, gas sorption, 4) exposure control by scheduling the contaminant producing activities to non-occupant hrs, etc. are few of the remedies to maintain good IAQ[16].

Conclusion:

Indoor air quality and thermal comfort were assessed by measuring CO_2, temperature & relative humidity in 3 different laboratories with different ventilation systems. The results show that the IAQ not only depends on the number of occupants and outdoor conditions but also affected by different processes going on inside the occupied space. The overall CO_2 level was found to be under 1000ppm which is considered very good according to ASHRAE 62.1 standard. It may be attributed to very low occupancy in FL & SL labs usually less than 10. The relative humidity was also found to be within the limits of ASHRAE 62.1 standard and valued under 65% all the time. The in and out of occupants, as well as the running equipment and water taps, contributed to the variation in RH. The temperature, on the other hand, was slightly higher for the lab CL than the other 2 labs. The main contributors to these higher values of temperature in CL were around 40 computers in which approximately half are simulation hardware and run 24/7. The other 2 labs also had a temperature higher than the allowed ASHRAE 55 standard, because there are also different machines running at relatively higher temperatures. The common factor which affected the temperature collectively is the university's policy of not allowing to set the thermostat below 26°C. In a bigger picture, the IAQ of the labs was found very good, of course, except for temperature. The particulate materials of size less than 2.5µm were found to be within limits of most of the standards like ASHRAE, US EPA and NAAQS, etc. which stats that mass concentration of particles of size less than 2.5µm should be below 65 $\mu g/m^3$ for 24 hrs average. On the other hand, PM10 particles' mass concentration was observed to be higher than the guidelines specified by the ASHRAE and US EPA, etc. which defines PM10 to be less than 150 $\mu g/m^3$ for a 24hr average. The solar lab on few occasions exceeds this limit for both PM10 and PM5 particles. The reason solar lab having higher mass concentrations than the other labs could be explained by the fact that some pieces of equipment were under installation.

Table 3 descriptive statistics of PM

PM 10µm					
Lab	Number of samples	Min ($\mu g/m^3$)	Max ($\mu g/m^3$)	Mean ($\mu g/m^3$)	Std. Deviation
Solar Lab	90	4.6201	335.4223	72.967432	69.4197259
Fossil Fuel Lab		4.6201	36.3451	16.126005	7.8789266
Computer Lab		5.8522	35.1131	17.844012	6.6542657
PM 5µm					
Solar Lab	90	7.6232	169.1357	45.187549	36.4236699
Fossil Fuel Lab		5.8522	22.8697	12.284443	4.3366270
Computer Lab		4.0041	17.3255	9.804539	3.9124451
PM 2µm					
Solar Lab	90	.6456	12.5619	3.464435	2.7134587
Fossil Fuel Lab		.4953	1.7741	.980565	.3384511
Computer Lab		.3425	1.2912	.773145	.2952540
PM 1µm					
Solar Lab	90	2.5543	9.0592	4.243247	1.7043706
Fossil Fuel Lab		1.9115	2.9547	2.388535	.3309090
Computer Lab		1.7261	3.7660	2.467173	.5975701
PM 0.5µm					
Solar Lab	90	2.8631	4.1225	3.304141	.3514111
Fossil Fuel Lab		2.5742	3.0838	2.777282	.1279075
Computer Lab		2.6636	3.5099	3.012501	.2224972
PM 0.3µm					
Solar Lab	90	7.5809	8.8700	8.265608	.4531830
Fossil Fuel Lab		7.1818	8.6463	7.910159	.5046534
Computer Lab		7.4406	9.1280	8.092198	.5039062

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