Supporting Design for Indoor Environment Quality (IEQ) & Occupant Comfort in Warm-humid Climate:

Development of an IEQ Assessment Model for naturally ventilated school classrooms

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of

Doctor of Philosophy

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CERTIFICATE

This is to certify that the work contained in this thesis, titled "*Supporting Design for Indoor Environment Quality (IEQ) & Occupant Comfort in Humid Sub-tropical Climate: Development of an IEQ Assessment Model for naturally ventilated school classrooms*", has been carried out under my guidance and supervision and is a bonafide work of Abdul Mohsin Ali. This work, submitted for the degree of Doctor of Philosophy, is original and contains no materials previously published or written by any other person for a degree or diploma at IIT Guwahati or any other institute or university. All the requirements, including mandatory coursework as per the rules and regulations mentioned in the Ph.D. ordinance for submitting the thesis for the Ph.D. degree of the Indian Institute of Technology Guwahati, have been fulfilled.

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DECLARATION

I hereby declare that the research work presented in the thesis, titled "*Supporting Design for Indoor Environment Quality (IEQ) & Occupant Comfort in Humid Sub-tropical Climate: Development of an IEQ Assessment Model for naturally ventilated school classrooms*", has been conducted by me under the guidance of my supervisor, Dr. Shakuntala Acharya. The thesis has been formatted as per the Institute's guidelines. The content of the thesis (text, illustration, data, plots, pictures, etc.) is original and is the outcome of my research work. Any relevant material taken from the open literature has been referred to and cited, as per established ethical norms and practices. All collaborations and critiques that have contributed to giving the thesis its final shape are duly acknowledged and credited. I fully understand that in case the thesis is found to be unoriginal or plagiarized, the Institute reserves the right to withdraw the thesis from its archive and revoke the associated degree conferred. Additionally, the Institute also reserves the right to apprise all concerned sections of society of the matter, for their information and necessary action (if any).

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ABSTRACT

One of the most important prerequisites to good learning is a comfortable learning environment, as occupant comfort has a profound impact on attention span, retention, and reproduction of knowledge. The Indoor Environment Quality (IEQ) of schools is of utmost priority, as young minds of the future citizens are moulded in their classrooms. Overall, the importance of IEQ has increased in recent times since people are spending more and more time indoors in urban areas, and children in their formative years spend up to 6-8 hours a day in classrooms. Presently, various passive cooling strategies, such as insulating roofs, large windows for cross-ventilation, etc., are incorporated with consideration alongside building codes and standards for sustainable design of school classrooms in India, yet overall occupant comfort and IEQ are not achieved. *Therefore, there is a need to strive to support design for Indoor Environment Quality & Occupant Comfort, with a focus on naturally-ventilated (NV) school classrooms, in India and other regions with a warm-humid climate.*

A rigorous design research methodology was followed, and a systematic literature review highlighted the lack of IEQ parameters' comfort model and weighting scheme for NV school classrooms in a warm-humid climate. These models and weights are always specific to their context: location climate, building typology, and ventilation systems, and so, it was hypothesised that the models and weights of IEQ parameters for this context would be significantly different from those recommended and existing. Empirical studies were conducted in Guwahati, a metropolitan city in North-East India. Both quantitative and qualitative data were collected on-site through instrument measurements and questionnaire surveys, respectively, for the major four IEQ parameters. A total of 45 spot measurements and 1087 questionnaire responses were correlated to derive the respective IEQ parameters contextually-appropriate models and weighting scheme. Upon comparison with Building codes and literature, significant differences were observed in the recommended and existing limits. *Overall, it was ascertained that thermal discomfort was the predominant cause for poor IEQ in NV school classrooms in a warm-humid climate.* Therefore, further building simulation studies were conducted to test the effectiveness of commonly used passive cooling strategies (PCs) in this context, to examine whether thermal comfort could indeed be achieved throughout the year or not. It was found that conventional PCs alone cannot achieve thermal comfort throughout the year, but with the appropriate combination of advanced PCs, it can be achieved. ***Thus, it was demonstrated that naturally-ventilated, sustainable school buildings can be designed for the future with good IEQ and less energy usage, by leveraging the proposed IEQ Comfort Model and Weighting scheme during design and retrofit.***

This thesis sits at the intersection of Sustainable Development Goals 4 – Quality Education, and 11 – Sustainable Cities and Communities, and presents an IEQ Assessment Model for NV school classrooms in a warm-humid climate that has been demonstrated to have the potential to support design of sustainable school buildings with improved IEQ, occupant comfort, and thus, enhanced learning.

Keywords: *IEQ; Comfort model; Weighting scheme; Passive cooling strategies; Naturally ventilated; School classroom; Effective passive cooling strategies; Humid sub-tropical climate.*

Publications

JOURNAL PAPERS

1. Ali, A. M., & Acharya, S. **(2026)** Proposed IEQ parameters weighting scheme for naturally ventilated school classrooms in warm-humid climate. ***Science and Technology for the Built Environment***. Taylor & Francis

CONFERENCE PAPERS

1. Ali, A. M., & Acharya, S. (2025). Appropriate Passive Design Strategies for achieving Thermal Comfort in School Classrooms in a humid sub-tropical climate. ***In the International Conference on Research into Design,*** Responsible and Resilient Design for Society, Volume 3, (pp. 143-154). Springer Nature Singapore.
2. Ali, A. M., & Acharya, S. (2023). Understanding Indoor Environmental Quality (IEQ) of Naturally Ventilated Educational Buildings—A Systematic Literature Review. ***In the International Conference on Research into Design,*** Design in the Era of Industry 4.0, Volume 1, (pp. 279-291). Springer Nature Singapore.
3. Ali, A. M., & Acharya, S. (2023). An Alternative Window Design Solution for a Naturally Ventilated Educational Building. ***In the International Conference on Research into Design,*** Design in the Era of Industry 4.0, Volume 1, (pp. 267-278). Springer Nature Singapore.

JOURNAL PAPERS (*under review*)

1. Ali, A. M., & Acharya, S. *(under review)* Defining indoor environment quality (IEQ) parameters comfort limits for naturally ventilated (NV) school classrooms in warm-humid climate. ***Journal of Architectural Engineering***. ASCE
2. Ali, A. M., & Acharya, S. (*under review*) Effective passive cooling strategies to achieve thermal comfort in naturally ventilated school classrooms in tropical and humid sub-tropical climate. ***Journal of Building Physics***. Sage

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List of Abbreviations

SDGs – Sustainable Development Goals

IEQ – Indoor Environment Quality

SBS – Sick Building Syndrome

HVAC – Heating, Ventilation, and Air Conditioning

ASHRAE – American Society of Heating, Refrigerating, and Air Conditioning Engineers

ISHRAE – Indian Society of Heating, Refrigerating and Air-Conditioning Engineers

NBC – National Building Code, India

EN – European Norm

LEED – Leadership in Energy and Environmental Design

WHO – World Health Organization

DRM – Design Research Methodology

TC – Thermal Comfort

VC – Visual Comfort

AC – Acoustic Comfort

AQ – Air Quality

PMV – Predicted Mean Vote

PPD – Predicted Percentage of Dissatisfied

CO_2 – Carbon dioxide

PRISMA – is an abbreviation that stands for Preferred Reporting Items for Systematic Reviews and Meta-Analysis

NV – Naturally Ventilated

KVS – Kendriya Vidyalaya School

DBS – Don Bosco School

MAS – Markaz Academy School

HIS – Hidayah International School

IITG – Indian Institute of Technology

AHP – Analytical Hierarchy Process

FCE – Fuzzy Comprehensive Evaluation

M_{TC} – Thermal Comfort Model

M_{VC} – Visual Comfort Model

M_{AC} – Acoustic Comfort Model

M_{AQ} – Air Quality Model

W_{TC} – Thermal Comfort Weight

W_{VC} – Visual Comfort Weight

W_{AC} – Acoustic Comfort Weight

W_{AQ} – Air Quality Weight

Tc – Operative temperature in the classroom

Vc – Light level in the classroom

Ac – Noise level in the classroom

AC – Air Conditioner

ACs – Active Cooling System

PCs – Passive Cooling System

NZEB – Net Zero Energy Building

AT_{max} - Maximum Air Temperature

AT_{avg} – Average Air Temperature

OT_{max} – Maximum Operative Temperature

OT_{avg} – Maximum Average Temperature

ST_{max} – Maximum Surface Temperature

ST_{avg} – Average Surface Temperature

WWR – Window Wall Ratio

PCM – Phase Change Material

EAHE – Earth Air Heat Exchanger

IEC – Indirect Evaporative Cooling

Chapter 1

Research Overview

Agenda 2030 for Sustainable Development, which outlined the vision towards a sustainable planet by the year 2030, called on all United Nations members in 2015 to commit to the holistic development of the three pillars of sustainability in achieving the 17 Sustainable Development Goals (SDGs). A decade later, as time draws close to reflect on the achieved vision, sound new knowledge and prompt actions are the need of the hour!

1.1. Importance of occupant comfort and significance of Indoor Environmental Quality (IEQ)

The built environment is integral for the attainment of the SDGs and directly falls under the purview of SDG 11 – Sustainable Cities and Communities, while also contributing towards several other SDGs. Buildings consume the highest amount of energy to fulfil various functions, out of which half of the energy is used for heating, ventilation, and air-conditioning (HVAC) systems for providing ***occupant comfort***. However, these systems adversely impact the environment, the economy, and most importantly, human health; thus, motivating scientists, engineers, and architects to find alternative sustainable solutions.

Indoor Environmental Quality (IEQ) profoundly affects occupant comfort and performance, and is a resultant of several parameters, four of the key being - Thermal Comfort, Visual Comfort, Acoustic Comfort, and Indoor Air Quality. Owing to the change towards a sedentary lifestyle and prolonged occupancy in the indoor environment, IEQ is increasingly becoming a critical factor for consideration in the sustainable design of buildings. The widely agreed-upon approach to address this pressing issue of inadequate IEQ and occupant comfort is ***sustainable or green building design,*** referring to the practice of designing and constructing buildings in a way that reduces their environmental impact, conserves resources, and promotes the health and well-being of occupants. Presently, sustainable design is almost viewed synonymously with energy-efficient strategies like natural ventilation, hybrid ventilation, Smart humidity buffers, biomimetic facades, and phase-change materials that reduce heating, ventilation, and air conditioning (HVAC) loads by 15–40%. Yet 68% of net-zero energy buildings fail to meet American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE-55) thermal comfort standards.

Reputed international organizations, such as, British Research Establishment (BRE), Representatives of European Heating and Ventilation Associations (REHVA), British Safety Council (BSC), United State Environmental Protection Agency (EPA), Whole Building Design Guide (WBDG) have emphasised the importance of building IEQ and have been proving different services, like; awards, certification, testing, research, professional and academy training, annual conferences, publications, membership, audit and consultancy, standards, net zero strategic advisory, and many more to improve the overall IEQ condition of the built environment. Green certifications now include IEQ metrics and post-occupancy evaluations in Leadership in Energy and Environmental Design (LEED). In India, the National Building Code (NBC, 2016) and the Indian Society of Heating, Refrigeration, and Air Conditioning Engineers (ISHRAE) provide threshold values or comfort limits for the major four IEQ parameters for different building typologies. The green building rating system, such as Green Rating for Integrated Habitat Assessment (GRIHA) and Indian Green Building Council (IGBC), has also integrated points for strategies that maintain good IEQ in occupied space, further underscoring the importance of IEQ in buildings.

One of the most promising approaches for improving IEQ while reducing energy consumption without compromising comfort in conditioned and free-running buildings is ***passive design strategies***, also referred to as bio-climatic or climate-responsive architecture [1], [3]. These strategies were traditionally used for achieving comfort in what is now classified as naturally ventilated buildings when there were no active means. The main intention of passive strategies is to reduce heat gain from outdoors and remove heat from indoors to natural sinks, such as air, water, earth, and sky, in hot climates, and vice versa in cold climates [2]. To incorporate passive design strategies in building design, understanding the local climate is very important, and for this reason, many architects and designers take the help of climate analysis tools [4]. However, building space and feature use, as well as occupant behaviour, are key to understand whether the recommended passive strategies improve comfort.

1.2. Research motivation and aim

Children represent the future, and ensuring their health, well-being, and access to ***'Quality Education'*** is a top priority under the Sustainable Development Goals (SDG 4) in both developing and developed countries. One-fifth of the world population is engaged in education [1], where students spend 6-8 hours in classrooms during weekdays [2]. Formal education is one of the most potent means through which the highest potential of a child can be achieved to benefit the world, the nation, the society, and the individual [3]. India has the largest young population in the world, which, if provided with quality education, can change the future of the country [4]. There are about 1.5 million schools in the country, with over 8.7 million primary and secondary teachers, and more than 260 million students [5]. *Therefore, schools are an indispensable space where students and teachers spend a significant portion of their indoor time, particularly in classrooms, and hence, must provide a comfortable indoor environment to support effective learning and teaching experiences.*

The ***IEQ of classrooms*** is one of the most important factors that can affect teaching and learning performance, which in turn can affect students' academic achievement [6], [7]. It is particularly important in schools due to the high occupant density and the fact that children are still in critical stages of physical and cognitive development [8], [9]. When occupants feel comfortable and satisfied with their indoor environment, they tend to be more focused, productive, and take fewer breaks or sick leaves [10], [11]. Research shows sufficient evidence that students' learning outcomes and short-term academic performance are influenced by the quality of their indoor environment. Classrooms with good IEQ support better concentration and sustained attention spans. Conversely, poor IEQ can lead to both short and long-term health problems, including increased stress, sleep disturbances, and reduced concentration [1], [12]. Studies also indicate that inadequate IEQ in classrooms can cause students to feel fatigued more quickly, experience sleepiness, and suffer health consequences, ultimately contributing to higher rates of absenteeism and lower academic achievement [8], [13].

Brink et al. [13] have specifically investigated '*does the IEQ of the classroom influence the quality of learning*?', and have confirmed that good IEQ of the classroom positively influences the quality of learning where students feel comfortable and pay more attention to the lecture presented, poor IEQ in classroom negatively influence the quality of learning due to discomfort and impaired health condition, which impact the academic achievements of the students. Other studies, such as Haddad et al. [14]**,** have shown that elevated temperature above the upper comfort limit can significantly affect academic performance since children are more sensitive compared to adults due to a lack of adaptive opportunities in the classrooms. Heschong et al. [15] have shown that a higher amount of daylight improves the academic performance of the students. Shield and Dockrell [16] have shown that high noise levels in the classrooms negatively impact the test scores of the students, and low noise levels favour cognitive work. And Bako-Biro et al. [17] have shown that poor air quality due to lack of ventilation can significantly reduce students' attention time and memory. Therefore, the overarching ***aim of this research (thesis) is to support design for Indoor Environment Quality (IEQ) & occupant comfort in warm-humid climate of educational buildings***, particularly for naturally ventilated (NV) school classrooms.

1.3. Contextual frame of reference

Climate is an average weather pattern considered for a long duration of time in a particular geographical location. The most well-known climate classification was developed in 1884 by W. Koppen based on temperature and precipitation closely correlated to biome classification; however, for the purpose of building design, particularly in warm climates of the tropics, a more appropriate classification based on human thermal comfort was proposed by G.A. Atkinson in the 1950s.

The Indian Climate Classification, adopted from Atkinson's classification, notes four basic types of climates are defined as: hot-dry, warm-humid, temperate, and cold; and any location climate not falling under these four is termed as composite by the National Building Code of India. With respect to NBC (Table 1), the location of our conducted study is 'warm-humid climate', which seemingly corresponds to 'humid sub-tropical climate' under the Koppen Climate Classification. However, the Koppen Classification falls short as it fails to distinguish between the temperature implications experienced in South Asia and South-East Asia, and some parts of the Far East, in comparison to its European, African, and North and South American counterparts.

Table 1: Indian Climate Classification System

Indian Climate Classification	**Mean Monthly Maximum Temperature**	**Mean Monthly Relative Humidity**
Hot-dry	Above 30°C	Below 55%
Warm-humid	Above 30°C or Above 25°C	Above 55% or Above 75%
Temperate	Between 25-30°C	Below 75%
Cold	Below 25°C	All values

Note: All climates outside of the above four are classified as composite.

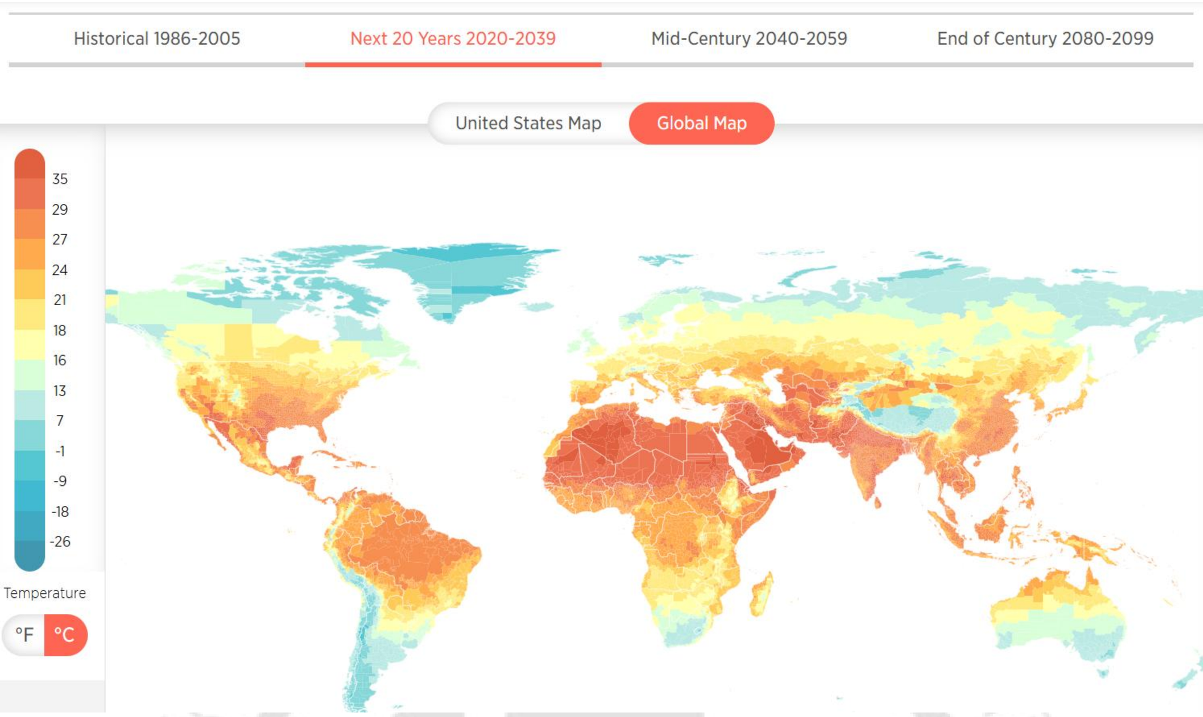

Figure 1: World map showing the Average Annual Temperature project
(courtesy: Prof. D. Silvermann and Climate Impact Lab, UC Irvine)

The '***warm-humid'*** climatic type is characterized by high average annual temperature owing to its proximity to the equator (as in Figure 1), and high humidity resulting from heavy annual precipitation for a significant part of the year and long coastal exposure, and thus, is identified as the appropriate frame of contextual reference for this study.

Therefore, ***the outcome of this research can be a reference for all the locations across South Asia and South-East Asia sharing these common characteristics*** (as shown in Figure 1). Notably, this region together comprises 30% of the world's population, has some of the fastest-growing economies of the world, such as India and Indonesia, and shares a common heritage and socio-cultural structure. Even the vernacular architecture and traditional passive cooling strategies of nocturnal cooling, verandahs, jali-walls, etc., are common in use, and natural ventilation is largely in practice.

1.4. Research methodology and Thesis structure

In this thesis, a Design Research Methodology (DRM) proposed by Blessing and Chakrabarti (2009) is adopted, and Type II research entailing a comprehensive descriptive study is conducted to develop an initial support in the form of a model. The thesis is structured as follows:

Chapter 1 – In this chapter, an *introduction* to the overall area of design research, the motivation, significance, and aim, and an overview of the structure of the dissertation are presented.

Chapter 2 - *Research Clarification:* In this chapter, the objective of the study is defined through an extensive literature review, and the research problem, questions, and hypotheses are formulated.

Chapters 3 and 4 - *Comprehensive Descriptive Study I*: In this chapter, a deeper literature review is conducted to identify key factors that must be addressed to improve the current state, followed by comprehensive empirical investigations and data analysis to highlight existing gaps and validate the hypotheses posed. The findings of one informed the next, resulting in the development of a contextually appropriate Comfort Model for Assessment of IEQ.

Chapter 5 - *Initial Prescriptive Study*: In this chapter, the effective cooling passive strategies and their combination were identified through building simulation software, since it was seen in the previous chapters that thermal comfort was the main issue in NV school classrooms in a warm-humid climate.

Chapter 6 – In this final chapter, the *conclusions*, *limitations*, and directions for future research are outlined.

1.5. Core contributions & impact

The core contributions of this thesis are:

- Proposal of a ***contextually-appropriate IEQ Assessment Model*** for NV school classrooms in warm-humid climate, through;
    - derivation of *contextually-appropriate* ***comfort limits*** of the major four IEQ parameters, and
    - derivation of *contextually-appropriate* ***weighing scheme*** of the major four IEQ
- Assessment of **effective passive strategies** based on **proposed thermal comfort limits** and recommend improvements to achieve thermal comfort throughout the year in naturally ventilated school classrooms in a warm-humid climate.

The proposed ***contextually-appropriate IEQ Assessment (Comfort) Model*** for warm-humid climate supports the design for occupant comfort and IEQ, an important facet of the sustainable design of buildings. It has the potential to assist in the practical achievement of comfortable IEQ in NV school classrooms of the developing regions of the world, having tropical climates, which also have a significant young population attending school.

Therefore, the envisioned impact of this research is to enable occupant comfort and, in turn, enhance learning of occupants, i.e., school students attending public schools, that are mostly naturally-ventilated in these regions of the world, thereby striving towards the pivotal SDGs of Quality of education (SDG 4) and Sustainable Cities and Communities (SDG 11).

Chapter 2

IEQ of Educational Buildings

2.1 Introduction

According to national and international standards, IEQ refers to the building's indoor environment that is regularly occupied and has an impact on the occupant's comfort, health, well-being, and productivity [12], [18]. A literature review of **IEQ parameters** has revealed that there are four major parameters: thermal comfort (TC), visual comfort (VC), acoustic comfort (AC), and air quality (AQ) which have a greater impact on occupant overall comfort and their productivity [19], [20], [21], [22] (as shown in Figure 2), even though there are other parameters associated with the building indoor environment such as workspace layout, indoor decoration, plantation, furnishing, cleanliness, view to outdoor, etc. [23], [24], [25], [26]. Among the major four IEQ parameters, TC is undoubtedly given the highest importance by most researchers due to its great impact on occupants' productivity and comfort [27], [28]. However, some of them have also considered AQ [20] and AC [26] to be equally important, and VC was always given the least importance [19], [29], which may be due to ease of control. Even though these parameters are independent in themselves, they are correlated to the overall IEQ comfort. TC and AQ have the greatest interdependency. TC is also correlated with light level, but AC could not be directly correlated [21], [23]. The relation between IEQ and occupants' well-being/performance is very complex [30]. The common units used for measuring TC are air temperature, relative humidity, operative temperature, Predicted Mean Vote (PMV), and Predicted Percentage of Dissatisfied (PPD); for VC are illuminance level, and daylight factor; for AC are noise level and reverberation time; for AQ are ventilation rate, and Carbon dioxide (CO_2) level [19].

The **importance of IEQ** has increased in recent times since people are spending more and more time indoors for work in urban areas [31]. It is common worldwide to work at least eight hours per day, and in many cases, it gets extended over this [32]. IEQ of the workspace has a great impact on the occupant's performance and productivity [21], [26], [33], [34]. In many cases, mental and physical illness is associated with poor IEQ, which is termed 'sick building syndrome' (SBS) [35], [36], [37]. The annual salary of the employees is far greater than the operational cost of the building. Hence, a small decrease in productivity and health can bring huge losses to the company or organisation [38]. The building sector is also blamed for 30% of all greenhouse gas emissions and 40% of total energy consumption for maintaining the IEQ of buildings [30], [39]. Therefore, optimising the building IEQ can bring benefits to both the occupants and the natural environment.

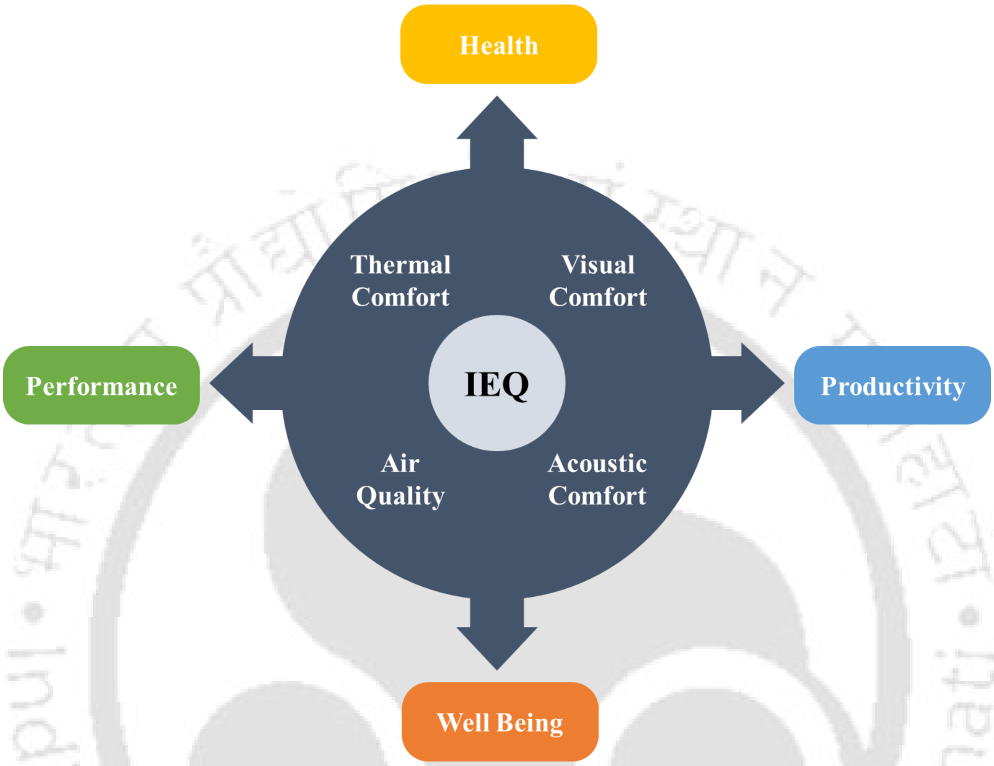

Figure 2: Major parameters of IEQ and their impact on the occupant.

2.2 Methodology for systematic literature review

For selecting relevant literature in this study, the well-known 'PRISMA' statement was adopted [28], [40]. PRISMA is an abbreviation that stands for Preferred Reporting Items for Systematic Reviews and Meta-Analyses. It provides a simple process that gives a minimum set of items to report a systematic literature review. It consists of 4 phases, namely: Identification, Screening, Eligibility, and Inclusion (as shown in Figure 3). These will be discussed in detail in the context of this study in the following sections: -

2.2.1 Identification

For identifying literature initially, the search engines used were 'SCOPUS' and 'Web of Science', which are the largest databases for research papers and the most reliable. The keywords used were ((IEQ OR "Indoor Environment Quality") AND (classroom OR school OR college OR institute OR university OR "educational building")) with a Boolean operation in this manner. Initially, the keywords were searched in the title, abstract, and keywords of all papers in the databases. But the results shown in each database were 626 and 365 documents, respectively, which were too many to even go through the abstract. Therefore, to reduce the number of search results, specific papers were identified that have focused their study on IEQ and educational buildings by searching the above keywords in the title only. Hence, the results were reduced to 125 and 73 documents, respectively. Out of these, 63 documents were identified as duplicates and were excluded. The total number of documents identified for screening was 135.

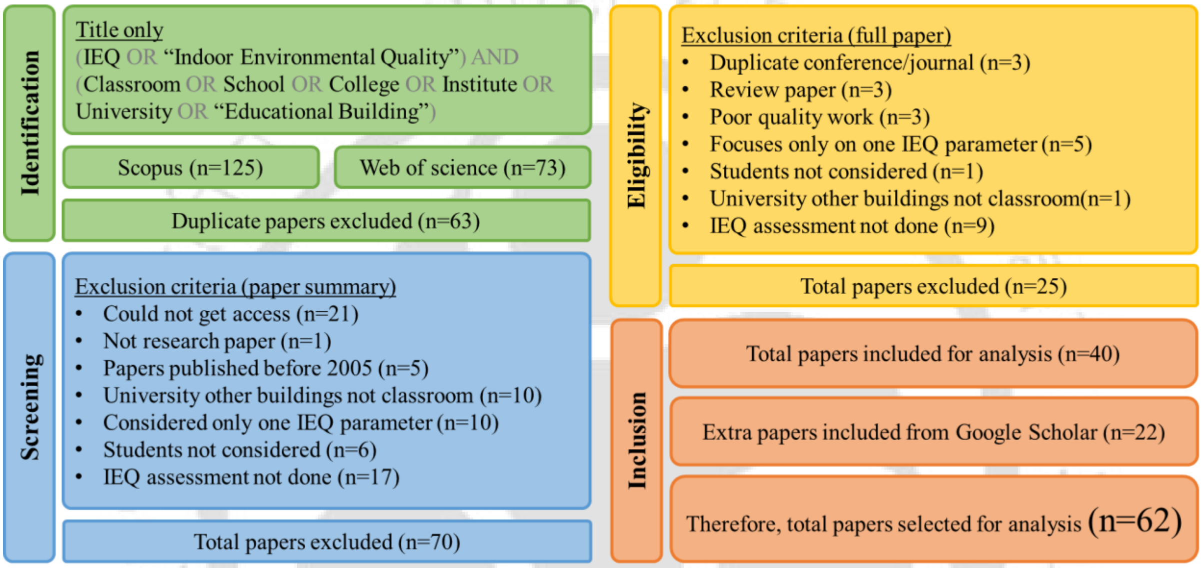

Figure 3: Literature review process

2.2.2 Screening

For screening the identified literature, the details of the documents were checked, followed by reading only the abstract for relevance. The exclusion criteria and the number of papers excluded are as follows: could not get access to 21 documents, 1 document was not a research paper, 5 papers were published before 2005 (papers below this year may be too old for consideration), 10 papers were conducted in the university building other than the classroom, 10 papers considered only one IEQ parameters, 6 papers did not consider students and 17 papers did not do IEQ assessment. Therefore, the total number of papers excluded was 70, and hence, we were left with 65 papers for eligibility.

2.2.3 Eligibility

For eligibility, the complete paper was read multiple times to check relevance. The exclusion criteria and the number of papers excluded are as follows: 5 documents were duplicates which could not be detected earlier because these are conference papers, journal papers, or book chapters with the same content, 3 papers were review papers which were considered for reading but not for analysis, 3 papers quality were very poor, 5 papers focuses only on one IEQ parameter, 1 paper did not consider students, 1 paper was conducted in university building other than classroom and 1 paper did not do IEQ assessment. Therefore, the total number of papers excluded was 25, and hence, we were left with 40 papers for inclusion.

2.2.4 Inclusion

The papers that were found to be of good quality and relevant were considered for inclusion as mentioned above. Apart from these, 22 papers were included from the 'Google Scholar' search engine through a similar systematic literature review process. Therefore, the total number of papers included for data extraction and analysis was 62. The results from these papers are discussed below.

It is important to mention that all the papers selected have done IEQ assessments of educational buildings, even though some of the studies have considered other aspects like energy, cost, etc. The outcome of only the IEQ assessment was extracted and analysed for each paper to understand the complete picture of work done on this topic and to find out possible research gaps for further studies.

2.3 Literature review

It was found from the significant contributions in the area of IEQ for educational buildings that the outcome of the papers could be categorised under two broad themes – (1) Descriptive outcomes and (2) Derivative or Prescriptive outcomes, with three sub-themes each (as shown in Figure 4);

(1a) Description of the overall IEQ condition of studied buildings - 23 papers;

(1b) Comparative study of different building IEQ conditions - 52 papers;

(1c) Correlation between different IEQ parameters - 13 papers; and

(2a) Comfort model of IEQ parameters – 6 papers,

(2b) Weighting scheme of IEQ parameters - 8 papers;

(2c) Overall IEQ prediction model - 4 papers.

It is also important to mention that many papers have presented multiple outcomes; hence, they are categorised under more than one sub-theme. The outcomes and methods from these papers are discussed in detail below.

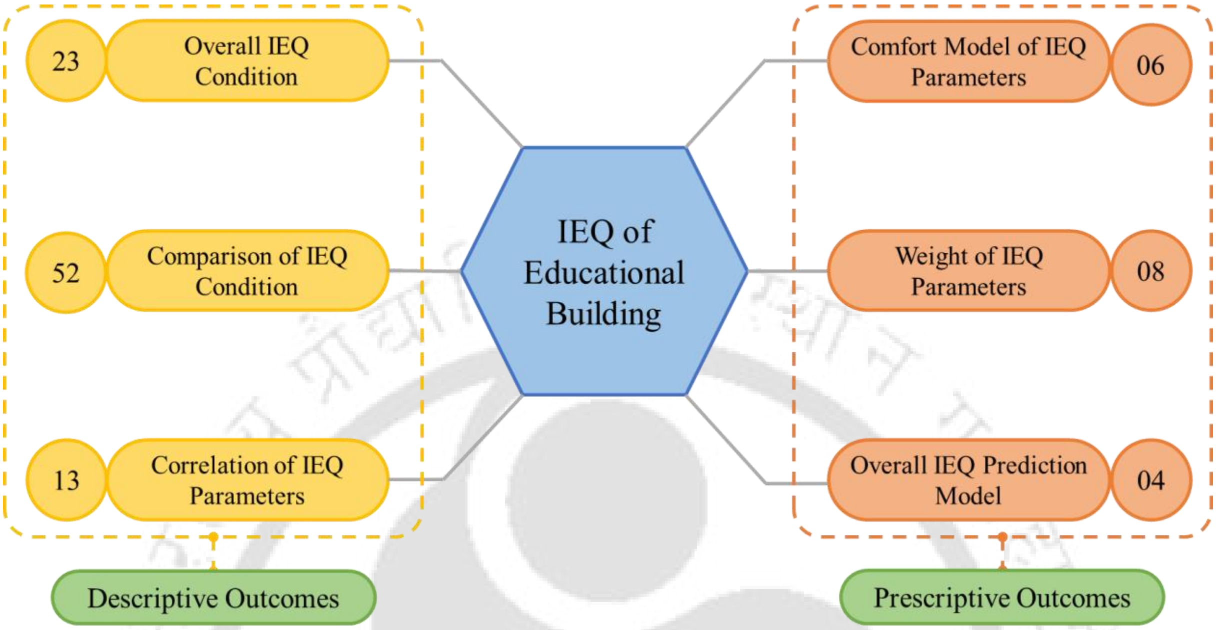

Figure 4: Thematic categories of paper outcomes

2.3.1 Overall IEQ condition of educational buildings

Many papers have tried to understand the existing IEQ condition of the studied buildings before presenting any comparison, correlation, etc. All the papers that have shown the IEQ condition of the existing educational buildings, irrespective of other outcomes, are mentioned below:

Norazman et al. [41] have presented averages of on-site measurements and questionnaire survey responses for overall IEQ and its parameters of the studied schools. Sahin et al. [42] and Nasir et al. [43] have presented the average of on-site measurements for IEQ parameters of the studied schools and the institutional buildings. Sarbu et al. [44] have presented average simulation results for PMV and PPD in a university building. Korsavi et al. [45] have presented the average on-site observation of window and door open areas for different reasons and seasons, and the frequency of the studied schools. Yang et al. [46], Aguilar [47], Dorizas [48], Korsavi et al. [49], Wang et al. [50], Turunenn et al. [51], Bluyssen et al. [52], Salleh et al. [53], Bughio et al. [54], Giuli et al. [55], Meciarova et al. [56], Jamaludin et al. [57], Yusoff et al. [58], Dascalaki et al. [59], Che-Ani et al. [60], Vilcekova et al. [61], Pistore et al. [62], and Sulaiman et al. [63] have presented average questionnaire survey responses for perception, satisfaction, performance interference, SBS symptoms, causes for discomfort, suggestion for improvement, reaction to discomfort with the IEQ parameters in their respective school and university classrooms.

2.3.2 Comparison of IEQ conditions in educational buildings

Most of the papers have compared the existing IEQ conditions between schools, institutes, universities, etc., as well as, with the standards. All the papers that have compared the IEQ conditions of the existing educational buildings, irrespective of other outcomes, are mentioned below:

Papadopoulos et al. [64] and Ekren et al. [65] have compared on-site measurements, questionnaire survey responses, and simulation results of IEQ parameters between different classrooms of the schools. Almeida et al. [66], Samad et al. [67], Pereira et al. [68], Dhalluin et al. [69], Giuli et al. [70], Gao et al. [71], Zhang et al. [72], Tahsildoost et al. [73], Dorizas [48], Kraus et al. [74], Ghita et al. [75], Ramprasad et al. [76], Catalina et al. [77], Oldham et al. [78], Ricciardi et al. [79], Giuli et al. [55], Sarbu et al. [44], and Meciarova et al. [56] have compared on-site measurements, and questionnaire survey response of IEQ parameters between different classrooms of the schools, universities, ventilation system, and also with standards. Sadick [80] has compared on-site measurements and on-site observation of IEQ parameters between different schools. Bughio et al. [54] have compared questionnaire survey responses and simulation results of IEQ parameters between different lecture halls of the institutes. Lee et al. [81], Yang et al. [46], Aguilar et al. [47], Korsavi et al. [49], Mihai et al. [82], Shum et al. [83], Fadeyi et al. [84], Al-Isawi et al. [85], Jamaludin et al. [57], Yusoff et al. [63], Dascalaki et al. [59], Che-Ani et al. [60], Vilcekova et al. [61], Sahin et al. [42], Hameen et al. [86], Toyinbo et al. [87], Akanmu et al. [88], Almeida et al. [66], Calama-Gonzalez et al. [89], Jain et al. [90], Leong et al. [91], Zhong et al. [92], Zuhaib et al. [93], and Jayakumar et al. [94] have compared only on-site measurements of IEQ parameters between different classrooms of the schools and university buildings, space of a library, location of a studio, heating and non-heating season, and also standards. Similarly, Pistore et al. [62], Asmar et al. [95], Savelieva et al. [96], and Saraiva et al. [97] have compared only questionnaire survey responses of IEQ parameters between different schools, university buildings, and age groups of students. Whereas Bernardi et al. [98] have compared only the on-site observation of IEQ parameters between different schools.

2.3.3 Correlation of IEQ parameters

Some papers have correlated the IEQ parameters to check if there exists any relation. All the papers that have shown the correlation of IEQ parameters irrespective of other outcomes are mentioned below:

Korsavi et al. [49], Ricciardi et al. [79], Korsavi et al. [99], Turunen et al. [51], Dorizas et al. [48], and Oldham et al. [78] have presented the correlation between questionnaire survey response and on-site measurement of IEQ parameters. The former three have correlated the perception/satisfaction of occupants with the instrument measurements of IEQ parameters respectively; the latter one has correlated the perception/health of occupants with the temperature and ventilation rate; and the second last one has correlated IAQ perception/SBS syndrome of occupants with the temperature and IAQ parameters, and the last one has correlated performance of occupants with the temperature. Whereas, Korsavi et al. [45] have presented the correlation between observation and on-site measurement where the window open area was correlated with the indoor/outdoor temperature and relative humidity, as well as the overall open area with the operative temperature and CO_2 level. And, Shum et al. [83], Fadeyi et al. [84], and Al-Isawi et al. [85] have presented a correlation between only on-site measurements of IEQ parameters. Where the former has correlated different IEQ parameters, the latter has correlated different AQ parameters, and the last one has correlated noise and temperature. Similarly, Bluyssen et al. [52], Salleh et al. [53], and Lee et al. [81] have presented a correlation between only questionnaire survey responses of IEQ parameters.

2.3.4 Comfort models of IEQ parameters

Very few papers have derived the comfort model of IEQ parameters, which may be due to its complexity, but it is very important since comfort limits can be calculated from such models for a specific context, and there are very few such comfort models for educational buildings in different contexts (further discussed in Chapter 3). All the papers that have derived the comfort models of IEQ parameters, irrespective of other outcomes, are mentioned below:

Lee et al. [81], Aguilar et al. [47], Kraus et al. [74], Yang et al. [46], Tahsildoost et al. [73], and Catalina et al. [100] have derived the comfort model of IEQ parameters by almost the same method. The former three have derived by relating the perception (sensation vote) of occupants with the instrument measurements of IEQ parameters; the latter two have derived by relating the satisfaction of occupants with the instrument measurements of IEQ parameters;

and the last one has derived by building simulation software considering only IEQ parameters data of different locations (occupants' perception was considered).

2.3.5 Weighting scheme of IEQ parameters

Similarly, few papers have derived the weighting scheme of IEQ parameters, but it is important since the importance of each IEQ parameter can be understood with the weight, and the overall IEQ prediction model can also be expressed with the weighting scheme for each IEQ parameter. There are very few such weighting schemes for educational buildings in different contexts (further discussed in Chapter 4). All the papers that have derived the weighting scheme of IEQ parameters, irrespective of other outcomes, are mentioned below:

Lee et al. [81], Tahsildoost et al. [73], Ramprasad et al. [76], Catalina et al. [77], Mihai et al. [82], Wang et al. [50], Yang et al. [46], and Ghita et al. [75] have derived the weight of IEQ parameters by questionnaire survey, but different question types were asked. The former three have been derived by asking for the acceptance of overall IEQ and its parameters; whereas the latter three have been derived by asking the importance (weight) of IEQ parameters; the second last one has been derived by pairwise comparison of IEQ parameters; and the last one has been derived by ranking the IEQ parameters.

2.3.6 Overall IEQ prediction model

Among the papers that have derived the comfort model and weighting scheme of IEQ parameters, few of them have combined them to form an overall IEQ prediction model. It is important to combine the comfort models with the weighting scheme to derive an overall IEQ prediction model, which can be used for IEQ assessment of existing buildings with on-site measurement and proposed buildings with simulation data (further discussed in Chapter 4). All the papers that have derived the overall IEQ prediction model, irrespective of other outcomes, are mentioned below:

Lee et al. [81], Yang et al. [46], Tahsildoost et al. [73], and Catalina et al. [100] have derived the overall IEQ prediction model using slightly different equations. The former is derived from a logistic regression equation, which is based on the derived formula (requiring coefficient and on-site measurement of IEQ parameters), and the latter three have been derived by a linear regression equation, which is based on a weighting scheme and comfort model of IEQ parameters.

Table 2: Building typology, climate, and operation of selected papers

Author and Year	**Building typology**	**Ventilation system**	**Location**	***Indian Climate Classification***
Ramprasad & Subbaiyan, 2017 [76]	University (classrooms)	Naturally ventilated and Air-conditioned	Tamil Nadu, India	Warm-humid
Wang, et al. [50]	Offices, Residential, University (classrooms)	Air-conditioned	Sydney, Australia	Cold
Lee, et al., 2012 [81]	University (classrooms)	Air-conditioned	Hong Kong, China	Warm-humid
Yang & Mak, 2020 [46]	University (classrooms)	Air-conditioned	Hong Kong, China	Warm-humid
Mihai & Iordache, 2016 [82]	University (classrooms and offices)	Air-conditioned	Bucharest, Romania	Cold
Tahsildoost & Zomorodian, 2018 [73]	University (classrooms)	Mix-mode	Tehran, India	Cold
Aguilar, et al., 2022 [47]	University (classrooms)	Mix-mode	Granada, Spain	Cold
Kraus & NovaKova [74]	University (classrooms)	Mix-mode	Bohumin, Czechia	Cold
Catalina, et al., 2022 [77]	School (classrooms)	Mix-mode	Bucharest, Romania	Cold
Ghita & Catalina, 2015 [75]	School (classrooms)	Mix-mode	Valcea, Romania	Cold
Catalina & Iordache, 2012 [100]	School (classrooms)	Mix-mode	Bucharest, Romania	Cold

Note: Mix-mode ventilation system means both naturally ventilated and air-conditioned, based on the weather.

2.3.7 Discussions and research gap

Some of the key learnings from the literature, discussed more in more detail in subsequent sections 3.2 and 4.2, are as follows:

- Research on IEQ and occupant comfort *aims to* either ;
    - *Support understanding* through descriptive studies; on existing the IEQ conditions and comparisons to offer a richer description of the contextual behaviour of one or more IEQ parameters, and to arrive at a deeper understanding of their (correlational) relationships.

- *Support practical implications for IEQ assessment of buildings* through derivative or prescriptive studies by deriving comfort models and weighing schemes of IEQ parameters by arriving at 'comfort limits', i.e., the limit within which occupants find comfort, and further, propose IEQ prediction models.

- *Context* plays a significant role in IEQ behaviour as these (comfort models and weighting schemes) are specific to the building typologies, the type of ventilation system, and the geo-climatic location of the building [74, 75]. While school classrooms and University classrooms are classified under the same typology 'educational buildings', it is important to note that school classrooms are primarily used by

- Four *dominant data-collection strategies* have been adopted to understand and model IEQ, i.e., (i) on-site measurements, (ii) on-site observations, (iii) simulation results, and (iv) questionnaire survey responses for perception, satisfaction, and causes for discomfort. However, no one strategy provides a holistic picture of IEQ conditions, and hence, more than one is often employed to converge to a richer description and a contextually-appropriate model of IEQ.

- *Overall IEQ prediction models* of a specific context are used for ***IEQ assessment*** of existing and proposed buildings, and are of *great practical value* as it helps identify the lacunae in existing design and passive or active strategies employed.

However, very few studies in the context of our interest, namely, 'naturally-ventilated', 'school classrooms', and in 'Warm-humid climate', are found. It was observed that, based on building typologies (as shown in Table 2), only 3 studies have been conducted in school classrooms (*note: all the three papers are of the same group of schools*) that too in 'cold climate' with 'mix-mode ventilation system', where the classrooms are heated during the winter months due to severe cold weather, and are naturally-ventilated during the summer months when the weather is pleasant. Whereas, with respect to ventilation system-type and climatic condition, only 1 study is found pertinent, but is of a university classroom which has a different user demographic (young adults above 17years) and use or access time through the day (generally, from morning to late evening or even open all night), in contrast to, school classrooms which have restricted time of access (morning to afternoon or early evening). Further, there were no papers that connected the IEQ assessment results to informing the most effective passive strategies to directly support design for occupant comfort.

Hence, ***there is an evident research gap*** *as no studies have been conducted* ***to support IEQ assessment of NV school classrooms in a warm-humid climate****, where summer months are severely hot, winter months are mildly cool, and a significant population of the world's school-going children attain their formative education, and in turn,* ***support design for occupant comfort towards enhanced quality of learning.***

2.4 Research Questions and Hypotheses

Therefore, this thesis intends to investigate the IEQ condition of NV school classrooms in a warm humid climate and empirically derive the individual model and weight (importance) for each IEQ parameter ***to propose a contextually-appropriate IEQ Assessment Model****, and based on it, identify the major challenges associated with existing passive design strategies employed for IEQ of school classrooms* ***to recommend improvements for occupant comfort****.*

RQ1: What is the existing IEQ condition (students' perception & satisfaction), and their comfort limit in NV school classrooms in a warm-humid climate?

H1: The **comfort limits of IEQ parameters** of NV school classrooms in a warm-humid climate **are significantly different** from those recommended by national and international standards, and existing literature in different contexts.

RQ2: What is the relative weight and cause for the discomfort of each IEQ parameter in NV school classrooms in a warm-humid climate?

H2: The **IEQ parameters weighting scheme** of NV school classrooms in warm-humid climates **is significantly different** from existing literature in different contexts.

RQ3: With respect to the derived overall IEQ Assessment Model for our context, are building passive strategies alone sufficient (assess effectiveness) to achieve good IEQ in NV school classrooms in a warm-humid climate?

H3: Building **passive strategies (**conventional and advanced**) alone is sufficient** for achieving good IEQ in NV school classrooms in a warm-humid climate

Chapter 3

Comfort Model and Limits of IEQ parameters

3.1 Introduction

Even though many national and international standards specify the comfort limit of the IEQ parameters for different building typologies, several studies have found that despite IEQ standards being met according to the national and international codes, students were not satisfied with the indoor environment of the classroom, and in some cases, vice versa [70], [73]. Due to this, many studies in different contexts have come up with their comfort models for each IEQ parameter, through which the comfort limits are defined.

3.2 Literature review

The studies (mentioned in section 2.3.7) were further assessed, and a few more papers, identified through backward (references) and forward (citations) search, were identified. Finally, only six papers were selected that have derived the comfort models and/or comfort limits for IEQ parameters in educational buildings and were found to be comparable with each other. It is worth mentioning that the proposed models of IEQ parameters cannot be compared directly with each other, and hence, comfort limits from each were calculated for comparison (as shown in Table 3). For the TC limit, a range is provided, whereas for VC, AC, and AQ limits, only the minimum and maximum values were considered due to their importance shown in national and international standards. For a richer understanding, each IEQ parameter is discussed in-depth, as follows:

3.2.1 Thermal Comfort (TC) limits

A single ‘India Model for Adaptive Comfort’ – IMAC, based on the field surveys administered in a specific building typology, i.e., office buildings, located in cities representative of five Indian climate zones, across all seasons, for all ventilation systems (i.e., naturally-ventilated, mixed mode and air-conditioned) was proposed by Manu, et al., (2016) This model has been adopted by NBC-2016 and states - "*neutral temperature in naturally ventilated buildings varies from 19.6 to 28.5 °C for 30-day outdoor running mean air temperatures ranging from 12.5 to 31 °C*". It further noted that Indian (office) occupants were more adaptive than those predicted by ASHRAE-55 and EN15251 models, and that occupants in NV offices were most adaptive. They further noted that fan and window operation, and clothing are significant measures towards occupant comfort.

For TC upper and lower limits, a significant difference was seen between the studies conducted in mix-mode ventilated classrooms in cold climates and air-conditioned classrooms in warm-humid climates. The TC range of the former was much greater than that of the latter. Specifically, Aguilar et al. [47] conducted a study in the University of Granada, Spain (cold climate), where ten classrooms in three buildings, all of which are ventilated mix-mode. It was found that the TC limit for this case was between 16°C and 29.1°C indoor air temperature (T_i). Similarly, Cao et al. [101] conducted a study in two classrooms, two offices, and a library in both Beijing and Shanghai (cold climate), where the spaces were mainly ventilated mix-mode and a few were air-conditioned. It was found that the TC limits for this case were between 15.5°C and 30.0°C operative temperature (T_O). And, Catalina and Iordache [100] conducted a study in a school in Bucharest, Romania (cold climate), where all the classrooms are ventilated mix-mode. It was found that the TC limits for this case were between 18.0°C and 28.0°C (T_O). Whereas, Yang et al. [46] conducted a study in the Polytechnic University of Hong Kong, China (warm-humid climate), where eight classrooms in eight different buildings were studied, all of them air-conditioned through an HVAC system. It was found that the TC limits for this case were between 23.3°C and 27.8°C (T_O). And, Lee et al. [81] also conducted a study in the Polytechnic University of Hong Kong, China, where eight classrooms in the same department were studied, all of them air-conditioned through an HVAC system. It was found that the TC limits for this case were between 19.8°C and 25.0°C (T_O).

3.2.2 Visual Comfort (VC) limits

For VC limits, a considerable difference was observed between mix-mode ventilated classrooms in a cold climate and air-conditioned classrooms in a warm-humid climate. Where the VC lower limit for the former was much lower than the latter. Specifically, Tahsildoost and Zomorodian [73] conducted a study in the Shahid Behesti University, Iran (cold climate), where nine classrooms located in three buildings were studied. It was found that the average light level recorded was between 321 and 480 lux in the classrooms, and the VC lower limit derived was 254 lux. Cao et al. [101] found that the light level in the studied spaces ranged between 140 and 2150 lux, and the VC lower limit derived was 110 lux. And, Catalina and Iordache [100] found that the simulated light level in the studied classrooms ranged between 267 and 655 lux, and the VC lower limit derived was 100 lux. Whereas, Yang et al. [46] found that the light level in the studied classrooms ranged between 239 and 919 lux, and the VC lower limit derived was 330 lux. And, Lee et al. [81] found that the light level in the studied classrooms ranged between 207 and 545 lux, and the VC lower limit derived was 218 lux.

3.2.3 Acoustic Comfort (AC) limits

Similarly, for AC limits, a considerable difference was observed between mix-mode ventilated classrooms in a cold climate and air-conditioned classrooms in a warm-humid climate. Where the AC upper limit for the former was slightly lower than that of the latter. Specifically, Tahsildoost and Zomorodian [73] found that the noise level in the studied classrooms ranged between 33 and 67 dBA, and the AC upper limit derived was 50 dBA. Aguilar et al. [47] found that the noise level in the studied classrooms ranged between 50 and 64 dBA, and the AC upper limit derived was 59 dBA. Cao et al. [101] found that the noise level in the studied spaces ranged between 39 and 56 dBA, and the AC upper limit derived was 60 dBA. And, Catalina and Iordache [100] found that the calculated noise level in the studied classrooms was 48 dBA, and the AC upper limit derived was 60 dBA. Whereas, Yang et al. [46] found that the noise level in the studied classrooms ranged between 47 and 60 dBA, and the AC upper limit derived was 62 dBA. And, Lee et al. [81] found that the noise level in the studied classrooms ranged between 57 and 67 dBA, and the AC upper limit derived was 66 dBA.

3.2.4 Indoor Air Quality (AQ) limits

Similarly, for AQ limits, a considerable difference was observed between mix-mode ventilated classrooms in a cold climate and air-conditioned classrooms in a warm-humid climate. Where the AQ upper limit for the former was slightly lower than the latter. Specifically, Tahsildoost and Zomorodian [73] found that the CO_2 level in the studied classrooms ranged between 417 and 2052 ppm, and the AQ upper limit derived was 1000 ppm. And, Cao et al. [101] found that the CO_2 level in the studied spaces ranged between 275 and 2360 ppm, and the AQ upper limit derived was 1200 ppm. Whereas, Yang et al. [46] found that the CO_2 level in the studied classrooms ranged between 449 and 1641 ppm, and the AQ upper limit derived was 1100 ppm. And Lee et al. found that the CO_2 level in the studied classrooms ranged between 492 and 1627 ppm, and the AQ upper limit derived was 1665 ppm.

Table 3: Models of comfort limit of IEQ parameters – A comparison of literature

Author and Year	Building typology	Atkinson Climate	Building operation	IEQ parameters	Comfort limits
Catalina & Iordache, 2012 [100]	School (classroom)	Cold	Mix-Mode	TC	Between 18 and 28 °C (operative temperature)
				VC	Minimum 100 Lux (light level)
				AC	Maximum 60 dBA(noise level)
				AQ	N/A
Tahsildoost & Zomorodian, 2018 [73]	University (classroom)	Cold	Mix mode	TC	Between 0 and 0.3 (PMV value)
				VC	Minimum 254 lux (light level)
				AC	Maximum 50 dBA (noise level)
				AQ	Maximum 1000 ppm (CO_2 level)
Aguilar, et al., 2022 [47]	University (classroom)	Cold	Mix mode	TC	Between 16 and 29.1 °C (air temperature)
				VC	negative value (cannot be considered)
				AC	Maximum 59 dBA (noise level)
				AQ	N/A
Cao, et al, 2012 [101]	University (classroom, office, and library)	Cold	Mix mode, and Air-conditioned	TC	Between 15.5 to 30.0 °C (operative temperature)
				VC	Minimum 110 lux (light level)
				AC	Maximum 60 dBA (noise level)
				AQ	Maximum 1200 ppm (CO_2 level)
Yang & Mak, 2020 [46]	University (classroom)	Warm-humid	Air-conditioned	TC	Between 23.3 and 27.8 °C (operative temperature)
				VC	Minimum 330 lux (light level)
				AC	Maximum 62 dBA (noise level)
				AQ	Maximum 1100 ppm (CO_2 level)
Lee, et al., 2012 [81]	University (Classroom)	Warm-humid	Air-conditioned	TC	Between 19.8 and 25.0 °C (operative temperature)
				VC	Minimum 218 Lux (light level)
				AC	Maximum 66 dB (noise level)
				AQ	Maximum 1665 ppm (CO_2 level)

3.2.1 Need and relevance of the study

Out of all the studies conducted in educational buildings, none were for NV school classrooms in warm-humid climates prevailing in developing countries, like India. Also, a considerable difference between the characteristics of classrooms studied in the literature and those of the school classrooms of our context was observed. In India, most of the school classrooms are NV throughout the year, and are smaller in size, higher in occupant density, and primarily dependent on natural daylight with few tube lights and ceiling fans.

Thus, it is hypothesised that the comfort models and hence, the comfort limits, for each IEQ parameter would be significantly different. Therefore, the *objective of this study* (in line with RQ1) is ***to empirically derive the contextually-appropriate comfort limits of each IEQ parameter*** for NV school classrooms in a warm-humid climate.

3.3 Methodology for deriving comfort models

A two-step verification-validation approach was undertaken; first with a pilot study to verify the data collection modalities, followed by the validation study (referred to as 'main' study) to collect real-world data from four selected schools, to cover a range of representative types of school buildings within the warm-humid context.

Data Collection modalities:

(i) ***Questionnaire survey*** of the occupants of the 14 selected classrooms with respect to perception and satisfaction, with respect to the major four parameters of IEQ (thermal, visual, acoustic environment, and air quality) was conducted. Qualitative data were collected at the site.

(ii) ***Instrument measurements*** of the major four parameters of IEQ (thermal, visual, acoustic environment, and air quality) for all 14 selected classrooms were taken in summer and winter between April 2023 and Jan 2024. Quantitative data were collected at the site.

Data Analysis:

(i) Instrument measurements and over 1000+ Questionnaire survey responses were overlayed to *reveal correlations, and a linear regression model was derived* from the students' perception and instrument measurement to arrive at the individual comfort models of each IEQ parameter and their pertaining upper and lower comfort limits.

(ii) Further, *comparison of these results and hypothesis testing* was performed with respect to the comfort limits proposed in literature and those set by International and National Standards as codes, to ascertain significance.

Area of Study :

The study was conducted in Guwahati, a metropolitan city in the North-East of India, as a representative of the warm-humid climate. The hottest month is August with monthly average temperature at 28.6°C (average high 32.0°C and average low 26.1°C) and relative humidity 85% (average high 96% and average low 71%); while the coldest month is January, with the monthly average temperature as 17.0°C (average high 23.3°C and average low 12.2°C) and relative humidity 80% (max 97% and min 56%), derived from the latest weather file [102].

3.3.1 Pilot study

For the pilot study, a senior secondary school, coded as 'KVS', located within the campus of a higher education institute in Guwahati, was studied. 124 Students from the 9^{th} standard (ages 13-15 years) and 12^{th} standard (ages 16-18 years) participated in this study, of which approximately 60% were boys and 40% were girls. The study was conducted in April for two consecutive days (one day for each classroom), where data was collected once in the morning and once in the afternoon. The study was intended mainly to test the reliability of the questionnaire. After conducting the study, the questionnaire data for the four IEQ parameters were analysed separately with Cronbach's alpha test to derive their internal consistency value. It was found that for the TC questions, it was 0.70, for the VC questions, it was 0.64, for the AC questions, it was 0.72, and for the AQ questions, it was 0.76.

Note: the acceptable range is 0.70 and above; hence, all the questions are acceptable except for VC questions, which is slightly low, but the questions were kept as-it-is not to disturb the overall structure of the questionnaire.

3.3.2 Sample: Subjects and studied buildings

For the main study, four 'English medium' schools with different building characteristics were selected, coded as: KVS, DBS, MAS, and HIS (as shown in Figure 5, respectively) and only the students of Class 9 -12 were considered as sample subjects (purposive sampling) due to their ability to comprehend the language and their basic awareness of science. DBS, MAS, and HIS are located within the metropolitan city, whereas KVS is on the outskirts within the campus of a higher education institute. DBS and KVS are larger in terms of area and infrastructure (approx. 2000 students' capacity), whereas MAS and HIS are smaller (approx. 500 students' capacity) comparatively. All the schools are located in quiet areas where noise from the surroundings is minimal. All schools selected are RCC structures where the roof is a lightweight structure (tin shade with false ceiling). All the classrooms are NV throughout the year, and the only active means for achieving IEQ comfort are tube lights and ceiling fans. The size of the classroom ranged from 18.7 m2 to 46.2 m2, where the Window Floor Ratio (WFR) ranged from 0.11 to 0.29. Most of the classrooms had four ceiling fans and four tube lights each (as shown in **Error! Reference source not found.**).


KVS School Building *KVS School Classroom*


DBS School Building *DBS School Classroom*


MAS School Building *MAS School Classroom*


HIS School Building *HIS School Classroom*

Figure 5: Physical characteristics of the studied schools and classrooms, respectively.

Table 4: Physical characteristics of the studied classrooms

School and Class	Full capacity	Classroom area (m2)	Window area (m2)	Ventilator area (m2)	WFR	Number of lights	Number of fans
KVS-9A	48	46.2	5.8	2.2	0.17	4	4
KVS-12A	48	46.2	5.8	2.2	0.17	4	4
KVS-9B	48	46.2	5.8	2.2	0.17	4	4
KVS-11B	48	46.2	5.8	2.2	0.17	4	4
KVS-11A	48	46.2	5.8	2.2	0.17	4	4
KVS-12C	48	46.2	5.8	2.2	0.17	4	4
DBS-9A	50	36.0	8.9	1.6	0.29	2	4
DBS-12E	50	36.0	8.9	1.6	0.29	2	4
DBS-12D	50	36.0	8.9	1.6	0.29	2	4
DBS-11C	50	36.0	4.0	---	0.11	2	4
MAS-8A	32	54.6	8.7	2.8	0.21	1	3
MAS-9A	32	54.6	8.7	2.8	0.21	1	3
MAS-10A	24	54.6	4.4	1.4	0.11	1	3
HIS-9A	16	22.8	3.9	0.9	0.21	1	3
HIS-10A	12	18.7	2.0	0.5	0.13	1	2
HIS-SH	30	43.9	4.0	2.2	0.14	2	6

Note: GF, FF, SF, and TF are ground, first, second, and top floors, respectively.

3.3.3 Data Collection

The main study was conducted to understand the IEQ condition of the classrooms in NV schools in this context, though qualitative and quantitative data were collected on-site via questionnaire surveys and instrument measurements, respectively, for the major four parameters of IEQ (TC, VC, AC, and AQ).

The Questionnaire Survey sought to capture the ***perception and satisfaction of the occupants, i.e., the students***, based on the IEQ of the classroom at the moment, on a 7-point Likert scale (+3 to −3) for all four IEQ parameters (an exemplar is shown in Figure 6 and the complete questionnaire is available in Annexure 1, developed in conformance with ICMR

Guidelines for Research Involving Human Subjects), where **1087 questionnaires** were filled out by the students throughout the year.

It was preferred that each student participate only once to avoid getting bored, but in a few schools, due to the limited number of students in classes 9 to 12, the students' responses were taken more than once in different seasons.

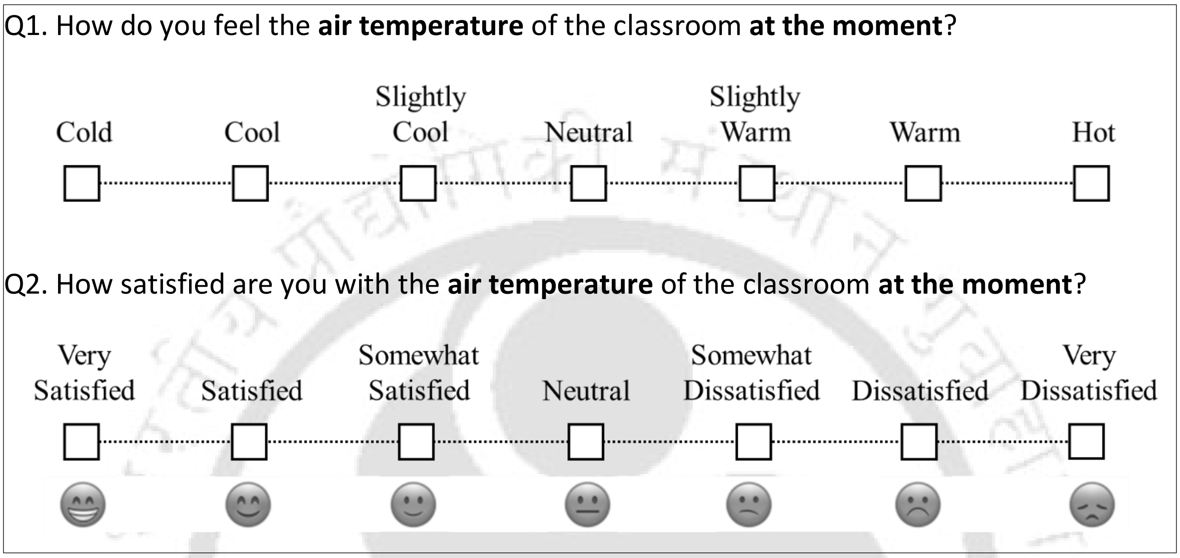

Figure 6: Example of the questions asked for perception and satisfaction of each IEQ parameter.

Questions asked for perception were:

How do you feel the air temperature of the classroom at the moment?

Responses: (cold, cool, slightly cool, neutral, slightly warm, warm, hot).

How do you feel the light level of the classroom at the moment?

Responses: (very bright, bright, slightly bright, neutral, slightly dark, dark, very dark).

How do you feel the noise level of the classroom at the moment?

Responses: (very silent, silent, slightly silent, neutral, slightly noisy, noisy, very noisy).

How do you feel the freshness of the classroom at the moment?

Responses: (very fresh, fresh, slightly fresh, neutral, slightly stale, stale, very stale).

Questions asked for satisfaction were:

How satisfied are you with the air temperature of the classroom at the moment?

How satisfied are you with the light level of the classroom at the moment?

How satisfied are you with the noise level of the classroom at the moment? and

How satisfied are you with the freshness of the classroom at the moment?

Responses: (very satisfied, satisfied, somewhat satisfied, neutral, somewhat dissatisfied, dissatisfied, very dissatisfied)

The ***instruments for measurement*** were EXTECH (EN300) 5-in-1 Environment meter, a globe thermometer, and a CO_2 meter, which were used (as shown in Figure 7) with their specification mentioned in Table 5.

Figure 7: Extech-5 in 1 Environment Meter along with globe thermometer and CO_2 meter

Table 5: Specification of the instrument used

Parameters	Unit	Range	Resolution	Accuracy
Thermal				
Air temperature	°C (°F)	0 to 50 (32 to 122)	0.1	±1.2 (2.5)
Globe temperature	°C (°F)	-100 to 1300 (-148 to 2372)	0.1	±1 (2)
Relative humidity	%	10 to 95	0.1	±4
Air velocity	m/s (ft/min)	0.4 to 30 (80 to 5910)	0.1 (1)	±3%
Visual				
Light level	Lux	0 to 20,000	1	±5%
Acoustic				
Sound level	dB	35 to 130	0.1	±1.4
Air Quality				
CO_2 level	ppm	0 to 9999	2	±75 (±5%)

The instruments were newly bought specifically for this study, and calibration was done by the company before delivery. A total of ***45 spot measurements*** were taken on-site, twice a day in each classroom, once in the morning and again in the afternoon during class hours, for both the summer and winter periods from April 2023 to January 2024.

Before taking the reading in each classroom, the instruments were left on for about 30 minutes, while the questionnaire was being explained, so that they would adjust to the present classroom indoor environment. The instruments were placed on a desk at a height of about 0.8 m in the centre of the classroom for all readings. Instrument measurements were taken of air temperature (°C), relative humidity (%), wind speed (m/s), globe temperature (°C), light level (lux), noise level (dB), and CO_2 level (ppm). For TC, the operative temperature (environment temperature) in °C was calculated based on the standard formula by Szokolay [103], while values of VC, AC, and AQ were taken as direct values of light level (lux), noise level (dB), and CO_2 level (ppm), respectively, as is practiced in previous studies and standards.

3.3.4 Data Analysis

All qualitative values were converted to quantitative values before conducting any kind of statistical analysis. Then the data was analysed to identify missing values and outliers. The outliers were identified for each observation through the mean deviation method and removed, and finally, the values of the remaining responses were averaged for each question to gain insight and correlation with the instrument measurements.

It is worth mentioning that students could answer the perception-related questions better than the satisfaction-related questions, as observed when the responses were correlated with instrument measurements, the ***R^2 value*** was greater for the former compared to the latter. Hence, the linear regression model was derived from the student’s perception and instrument measurements, to ***equate the Comfort models of each IEQ parameter***.

3.4 Results

It was found that for *perception*, the TC question had 1 missing value and 17 outliers (1.6%); the VC question had 1 missing value and 30 outliers (2.8%); the AC question had 0 missing values and 53 outliers (4.9%); and the AQ question had 0 missing values and 80 outliers (7.4%). Similarly, for *satisfaction*, the TC questions had 2 missing values and 47 outliers (4.5%); the VC question had 2 missing values and 62 outliers (5.9%); the AC question had 0 missing values and 91 outliers (8.4%); and the AQ question had 1 missing value and 85 outliers (7.9%).

For all the question types, as the percentage of missing values/outliers was lower than 10%, the reliability of the question is not questionable. Upon removing all the outliers, 1000+ responses remained for each question. In the following section, the perception and satisfaction of each IEQ parameter, during both the summer and winter months, are discussed in detail.

3.4.1 Thermal environment of the classrooms & TC model

It was observed from instrument measurements that the average operative temperature in the classroom was 28.1°C with a large standard deviation of about 4.6°C. During the summer months, the *highest temperature* recorded was 35.9°C in HIS classroom 9A (2nd floor) during the afternoon class hours, and the lowest temperature recorded was 26.7°C during the morning class hours, incidentally also in the same classroom 9A in HIS. Whereas, in the winter months, the *lowest temperature* recorded was 19.5°C in KVS classroom 9B (top floor) during the morning class hours, and the highest temperature recorded was 24.8°C in MAS classroom 9A (Ground Floor) during the afternoon class hours.

It was observed from the questionnaire survey that the *average perception of students* during the summer months was between slightly hot and hot (-1.6), with the interquartile range between -1.2 and -2.2, and during the winter months, between neutral and slightly cool (+0.7), with the interquartile range between 0.0 and +1.2.

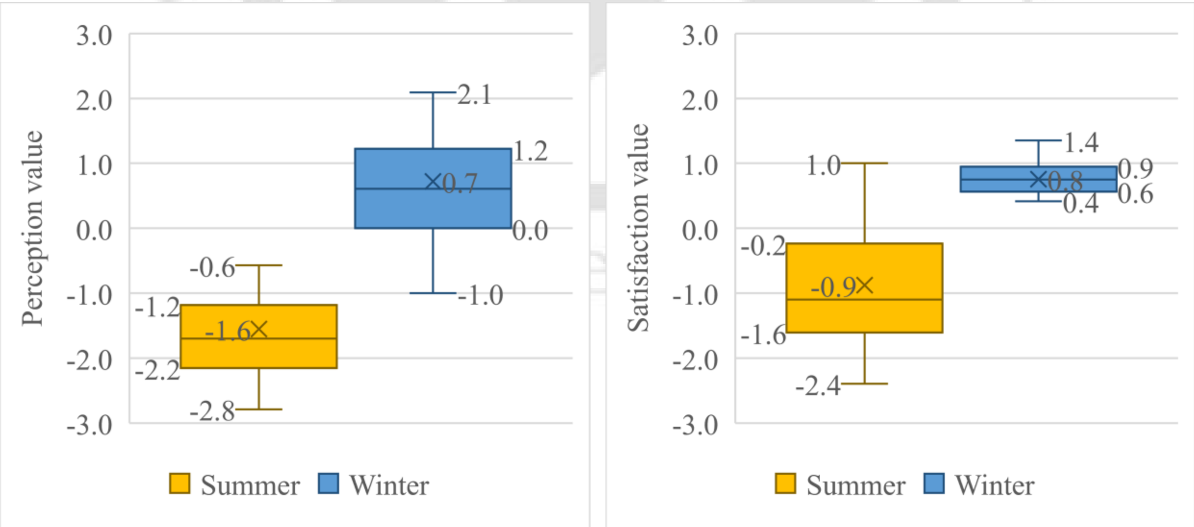

Figure 8: Perception and satisfaction of students during the summer and winter seasons for the thermal environment.

The *average satisfaction of students* during the summer months was close to ‘somewhat dissatisfied’ (-0.9), with the interquartile range between -0.2 and -1.6, and during the winter months was close to ‘somewhat satisfied’ (+0.8), with the interquartile range between +0.6 and +0.9 (as shown in Figure 8).

From the *linear regression model* derived for the thermal environment, it was found that the neutral temperature was 25.6°C, the upper limit at which it is perceived as ‘slightly warm’ was 29.1°C, and the lower limit at which it is perceived as ‘slightly cool’ was 22.1°C (as shown in Figure 9).

Therefore, the **Thermal Comfort Model (M_{TC}) = -0.2877×TC + 7.3536**
R^2 = 0.79 and p-value <0.05, which suggests that the *model is highly reliable* and valid.

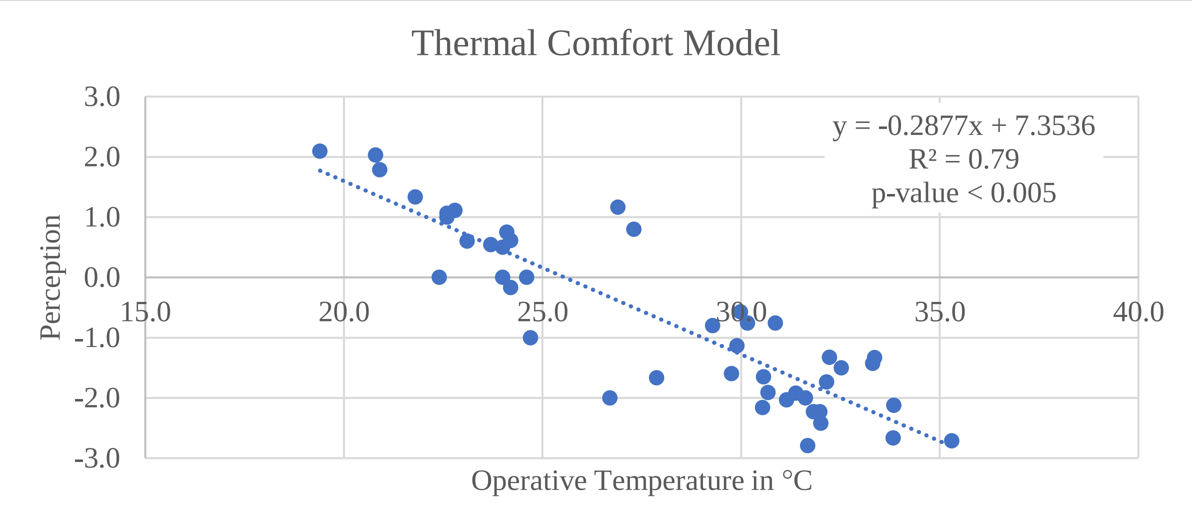

Figure 9: Relation between the perception of students and the operative temperature for TC.

3.4.2 *Visual environment of the classrooms & VC model*

It was observed from instrument measurements that the *average light level* in the classroom was 140 lux with a large standard deviation of about 66 lux. During the summer months, the highest light level recorded was 258 lux in DBS classroom 12E (top floor) during the morning class hours, and the lowest light level recorded was 26 lux in HIS classroom 10A (1^{st} floor) during the afternoon class hours. Whereas, during the winter months, the lowest light level recorded was 27 lux in HIS seminar hall (Ground floor) during the evening class hours, and the highest light level recorded was 285 lux in MAS classroom 8A (Ground floor) during the morning class hours. It was observed from the questionnaire survey that the *average perception of students* during the summer and winter months was almost the same between ‘neutral’ and ‘slightly bright’ (+0.4), with the interquartile range between -0.1 and +0.8.

Similarly, the *average satisfaction of students* during the summer and winter months was also the same between 'neutral' and 'somewhat satisfied' (+0.8), with the interquartile range between +0.4 and +1.2 (as shown in Figure 10).

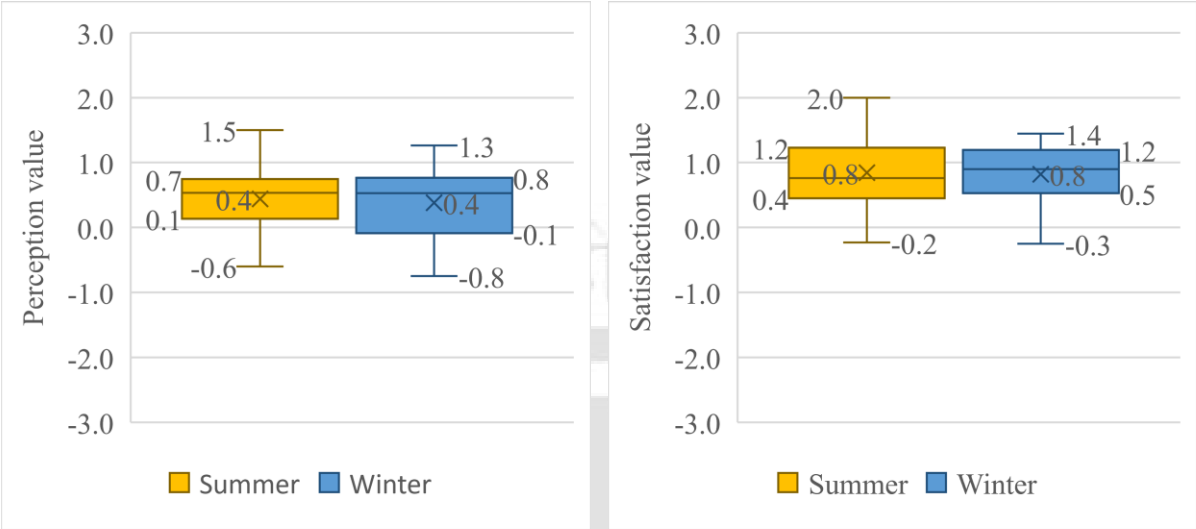

Figure 10: Perception and satisfaction of students during the summer and winter seasons for the visual environment.

From the *linear regression model* derived for the visual environment, it was found that the neutral light level was 48 lux, and the upper limit at which it is perceived as 'slightly bright' was 266 lux, whereas the lower limit at which it is perceived as 'slightly dark' could not be derived (negative value) (as shown in Figure 11).

Therefore, the **Visual Comfort Model (M_{VC}) = - 0.0046×VC - 0.2231**

R^2 = 0.28 and p-value <0.05, which suggests that the model is *less reliable but valid*.

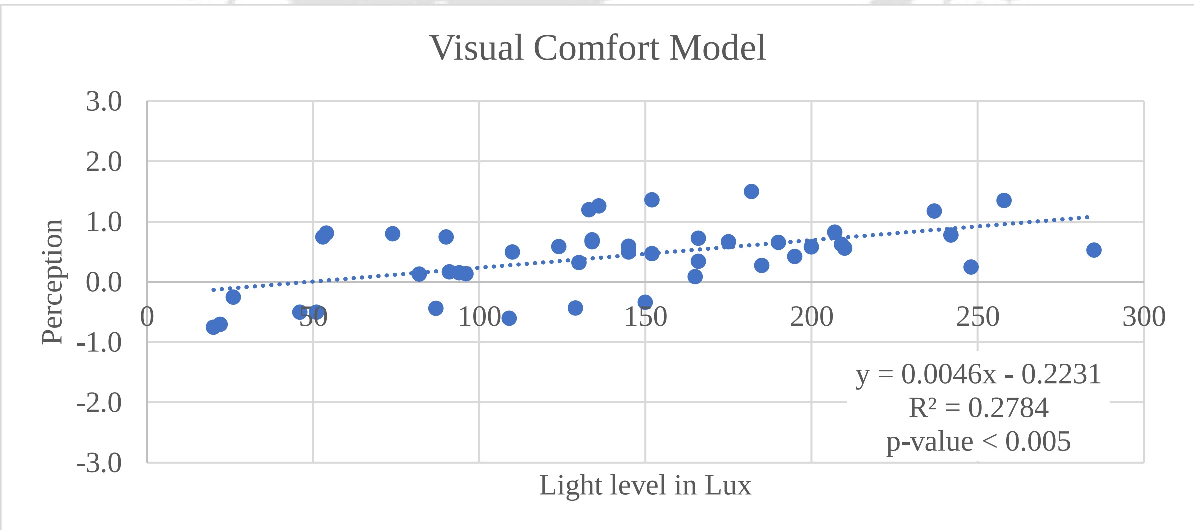

Figure 11: Relation between the perception of students and the light level for VC.

3.4.3 Acoustic environment of the classrooms & AC model

It was observed that the *average noise level* in the classroom was 64 dB with a small standard deviation of about 6 dB. During the summer months, the highest noise level recorded was 74 dB in DBS classroom 11C (top floor) during the afternoon class hours, and the lowest noise level recorded was 61 dB in HIS classroom 10A (1st floor) during the afternoon class hours. Whereas, during the winter months, the lowest noise level recorded was 47 dB in KVS classroom 12B (Ground floor) during the morning class hours, and the highest noise level recorded was 73 dB in KVS classroom 9B (top floor) during the afternoon class hours.

It was observed from the questionnaire survey that the *average perception* of students during the summer and winter months was almost the same, close to 'slightly noisy' (-1.1), with the interquartile range between -0.6 and -1.4. Similarly, the *average satisfaction* of students during the summer and winter months was also close to 'neutral' (-0.2), with the interquartile range between +0.2 and - 0.8 (as shown in Figure 12).

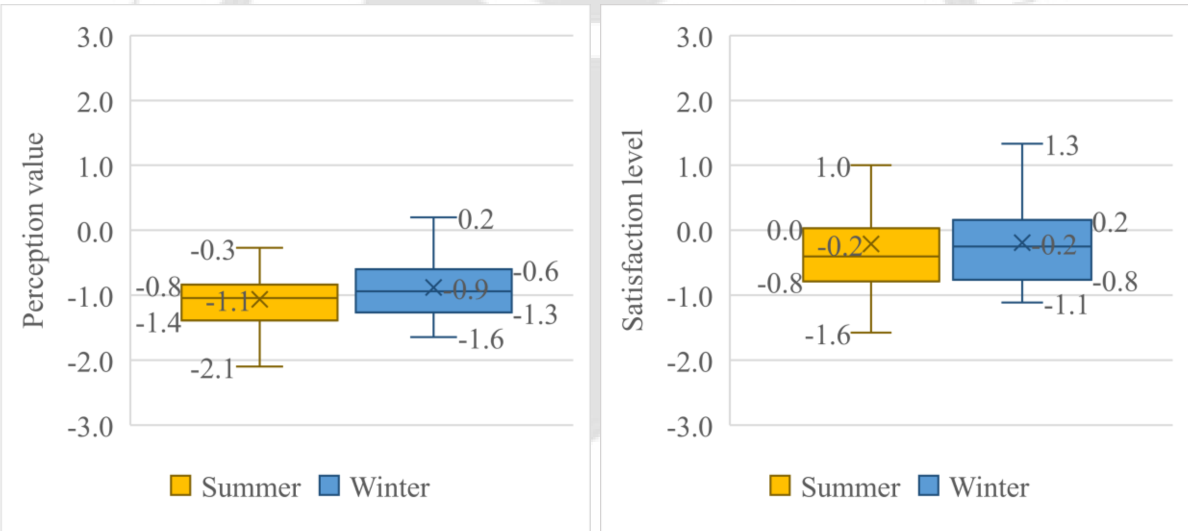

Figure 12: Perception and satisfaction of students during the summer and winter seasons for the acoustic environment.

From the *linear regression model* derived for the acoustic environment, it was found that the neutral noise level was 39 dB, and the upper limit at which it was perceived as 'slightly noisy' was 64 dB, whereas the lower limit derived was 'extremely low' at 14 dB (as shown in Figure 13).

Therefore, the **Acoustic Comfort Model (M_{AC}) = -0.0401×AC + 1.5626**

R^2 = 0.23 and p-value <0.05, which suggests that the *model is less reliable* but valid.

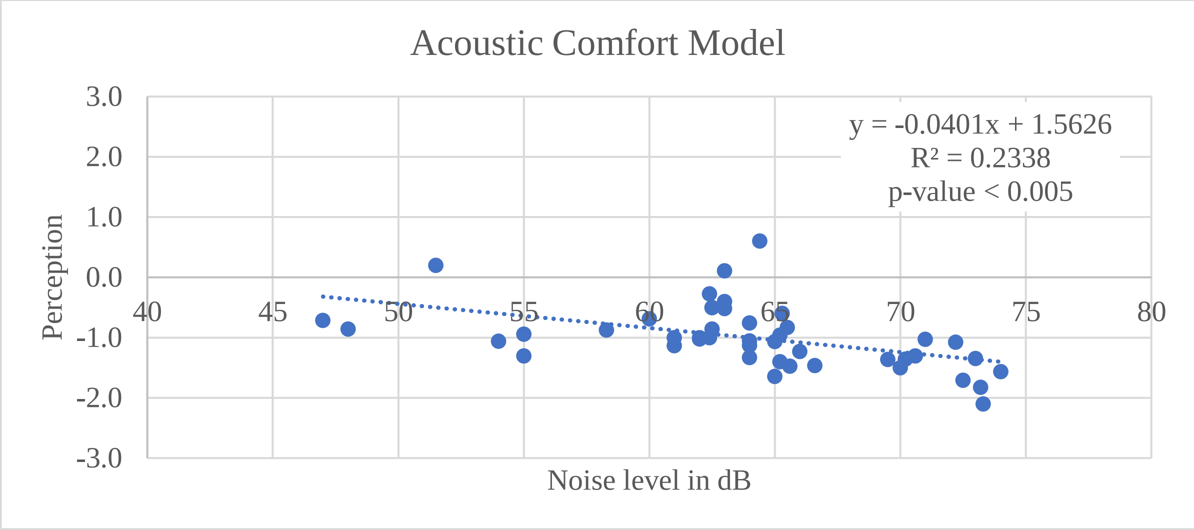

Figure 13: Relation between the perception of the students and the noise level for AC.

3.4.4 *Indoor Air Quality of the classrooms & AQ model*

It was observed from instrument measurements that the *average CO_2 level* in the classroom was 612 ppm with a large standard deviation of about 178 ppm. During the summer months, the highest CO_2 level recorded was 795 ppm in KVS classroom 9A (top floor) with 39 students during the morning class hours, and the lowest CO_2 level recorded was 412 ppm in HIS classroom 9A (2nd floor) with 8 students during the afternoon class hours.

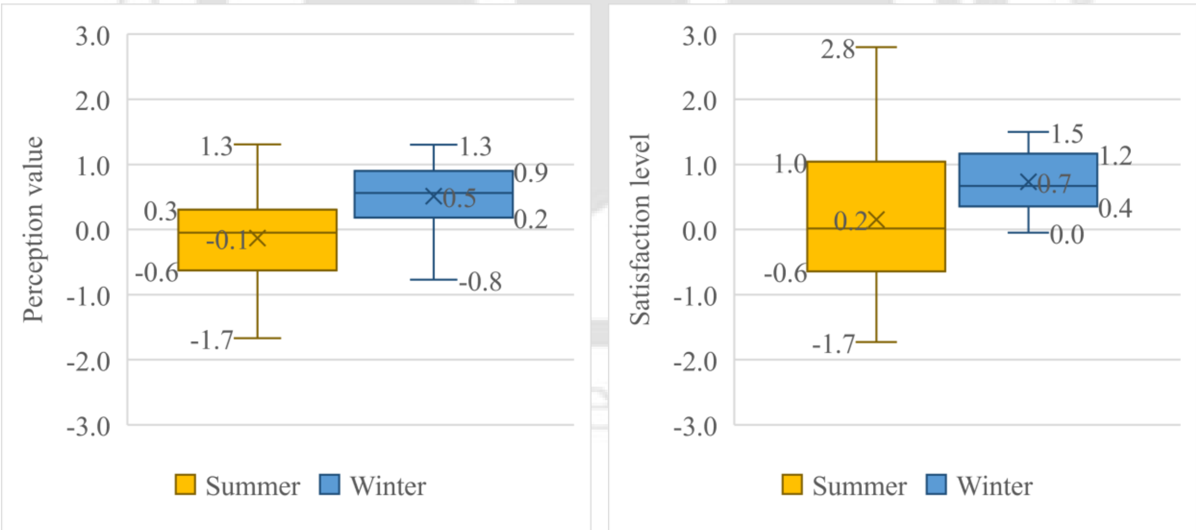

Figure 14: Perception and satisfaction of students during the summer and winter seasons for AQ.

Whereas, during the winter months, the highest CO_2 level recorded was 1364 ppm in DBS classroom 11B (top floor) with 40 students during the morning class hours, and the lowest CO_2 level recorded was 443 ppm in MAS classroom 8A (Ground floor) with 9 students during the afternoon class hours.

It was observed from the questionnaire survey that the *average perception* of students during the summer months was close to 'neutral' (-0.1) with the interquartile range between +0.3 and -0.6, and during the winter months was between 'neutral' and 'slightly fresh' (+0.5) with the interquartile range between +0.2 and +0.9. The *average satisfaction* of students during the summer months was close to 'neutral' (0.2) with the interquartile range between 1.0 and -0.6, and during the winter months was between 'neutral' and 'somewhat satisfied' (+0.7) with the interquartile range between +0.4 and +1.2 (as shown in Figure 14).

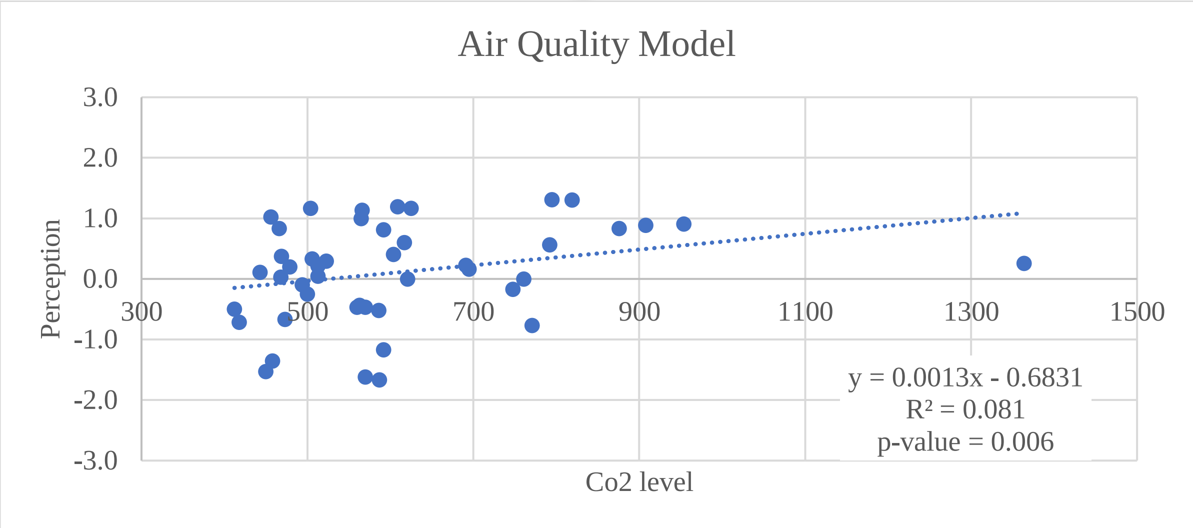

Figure 15: Relation between the perception of AQ and the CO_2 level.

From the *linear regression model* derived for AQ, it was found that the neutral CO_2 level was 525 ppm, the lower limit at which it is perceived as 'slightly fresh' was 1295 ppm (opposite direction), and the upper limit at which it is perceived as 'slightly stale' was (negative value) (as shown in Figure 15).

Therefore, the **Indoor Air Quality Comfort Model (M_{AQ}) = 0.0013xAQ - 0.6831** R^2 = 0.08 and p-value >0.05, which suggests that the *model is not reliable* and valid.

3.4.5 Contextually-appropriate comfort limits

Thus, the derived Comfort Limits for the context are as follows:

- **Thermal Comfort Limit** *(refer to Figure 9)* - It was found that the average operative temperature during the summer months was 31.2°C with a standard deviation of 2.3°C. The *perception* of the students during this period was between 'slightly hot' and 'hot', and they were 'somewhat dissatisfied' with it. Whereas, during the winter months, the operative temperature was 22.9°C with a standard deviation of 1.5°C. The *perception* of the students during this period was between 'neutral' and 'slightly cool', and they were 'somewhat satisfied' with it. The correlation between operative temperature and the perception of the students revealed that the *neutral operative temperature was 25.6°C*, with an **upper limit of 29.1°C and a lower limit of 22.1°C**, which is *within the range derived/recommended* by existing literature and the standards, respectively. But the *lower limit was significantly different* from both, which could be due to the strict school dress code and activities.

- **Visual Comfort Limit** *(refer to Figure 11)* - It was found that the average light level was 140 lux with a standard deviation of 66 lux. The *perception* of the students was between 'neutral' and 'slightly bright', and they were 'somewhat satisfied' with it. The correlation between light level and the perception of the students revealed that **the *neutral light level was 48 lux,* with an upper limit of 266 lux,** which is *significantly different* from the existing literature and the standards. It could be due to the fact that school classrooms are completely dependent on natural daylight for most part of the year.
- **Acoustic Comfort Limit** *(refer to Figure 13)* - It was found that the average noise level was 64 dBA with a standard deviation of 6 dBA. The average *perception* of the students was 'slightly noisy', but their satisfaction level was 'neutral'. The correlation between noise level and the perception of the students revealed that **the *neutral noise level was 39 dBA,* with an upper limit of 64 dBA,** which is *significantly different* from the standards but not from the existing literature. It could be due to school classrooms being highly dependent on ceiling fans for most part of the year.
- **Indoor Air Quality Comfort Limit** *(refer to Figure 15)* - It was found that the average CO_2 level was 612ppm with a standard deviation of 178ppm. The average *perception* of the students was 'neutral', and their satisfaction level was also 'neutral'. The correlation between CO_2 levels and the perception of the students revealed that no clear relation exists. Hence, **no comfort limit could be defined for AQ**.

3.5 Discussions

3.5.1 IEQ condition of the context

The IEQ conditions of NV school classrooms in a warm-humid climate were empirically found to be different from the classrooms studied in the existing literature.

For the **thermal environment**, the highest temperature recorded was 35.9°C in HIS classroom 9A, even though the classroom was on the second floor, and with very few students. In sharp contrast, the lowest temperature recorded was 19.5°C in KVS classroom 9B, even though the classroom was on the top floor and not on the ground floor. These can be classified as 'extremely hot' and 'cold' thermal environments with respect to national and international standards, where comfort limits for NV buildings in warm climates are 30°C maximum and 20°C minimum (IMAC, NBC 2016). The main reason behind such extremely hot temperatures could be due to cross-ventilation of the classrooms during the class hours (predominant wind direction East-West), supported by the orientation of the building (HIS is oriented East-West). On average, the students perceived the summer months to be 'hot,' and they were 'somewhat dissatisfied' with it. Whereas, winter months were perceived as 'slightly cool', but they were 'satisfied' with it.

For the **visual environment**, the highest light level recorded was 285 lux in MAS classroom 8A, which is surprisingly below the minimum level of 300 lux set by the national and international standards. What is even more surprising is that the average light level recorded throughout the year was 140 lux, and yet the students perceived it as 'neutral' to 'slightly bright', and they were 'somewhat satisfied' with it. Similarly, for the **acoustic environment**, the highest noise level recorded was 74 dB in DBS classroom 10A during summer, with ceiling fans running, while the lowest noise level recorded was 61 dB. The maximum level of 40 dB set by the national and international standards can only be achieved if the ceiling fans are off, as seen in the winter months, with one instance of the lowest noise level recorded at 47 dB, which is still higher than the standard. However, the noise from ceiling fans was not the cause of acoustic discomfort. It was rather students themselves who were the cause, due to which the *average perception* of students was 'slightly noisy' in both the summer and winter months, and the *satisfaction level* in winter was lower than in summer.

Lastly, **for AQ**, the highest CO_2 level recorded was 1364 ppm, which was recorded only once in DBS classroom 11B, where all windows and doors were closed due to cold weather. Otherwise, for most of the year, the average CO_2 level was 612 ppm. However, the CO_2 level could not be directly perceived at such a range between 300 and 1000 ppm. Therefore, in winter it was perceived as better than summer, and the students were more 'satisfied' in winter than in summer, even though the CO_2 level in winter was higher than in summer, comparatively.

3.5.2 Comparison of IEQ comfort limits

It was hypothesised that ***the proposed comfort limits of IEQ parameters for NV school classrooms in warm-humid climate would be significantly different compared to studies conducted in educational building for other contexts*** in the literature, and also the national (NBC 2016 [104], and ISHRAE [12]) and international (EN-15252 [11], ASHRAE [105], IES-US [106], and ANSI [107]) standards due to general specification for educational buildings.

To test if this is true, a hypothesis test was conducted for each IEQ parameter and each case. According to a two-tailed Z-test (parametric test) for variance at 5% level of significance (calculation in Annexure 3a).

It was found that the **TC upper limit was not significantly different** from either the existing studies or standards. But the lower limit was significantly different for all (as shown in Figure 16). Even though it was expected that in NV classrooms the TC range would be larger than MM classrooms due to adaptation, it was found that this is not true for school students, maybe due to strict restrictions on dress code and their activity.

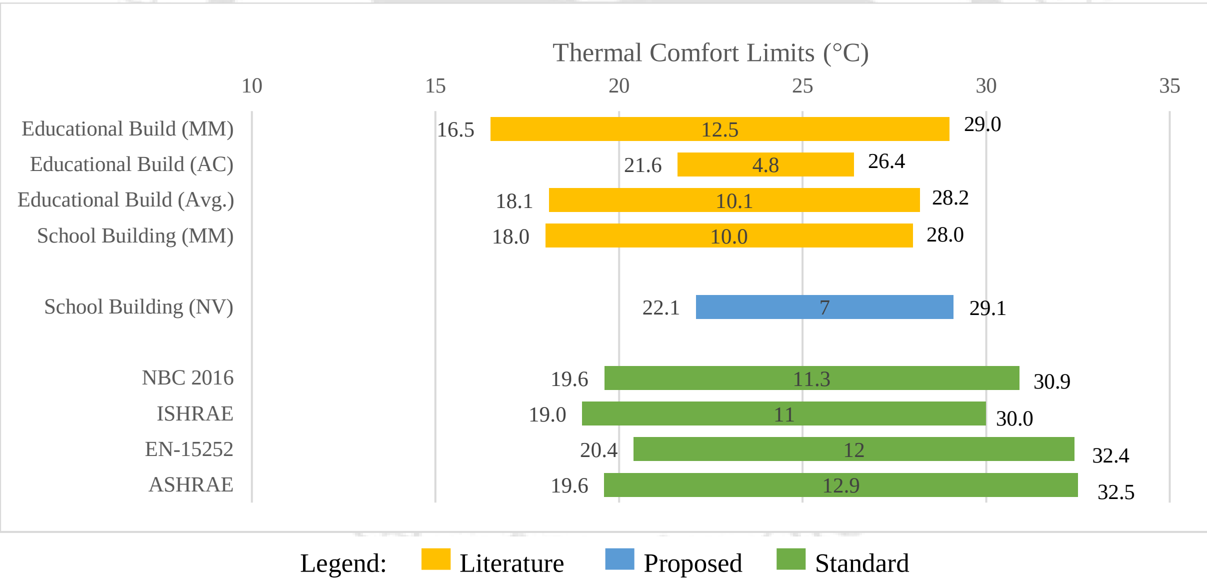

Figure 16: Comparison of thermal comfort limits between existing and proposed.

The **VC lower limit was significantly different** from both the existing studies and standards (as shown in Figure 17). This could be due to school classrooms in this context being completely dependent on natural daylight throughout the year, and students are adapted to it.

However, the **AC upper limit was not significantly different** from the existing studies, but significantly different from the standards (as shown in Figure 18). This could be due to school classrooms in this context mainly depend on ceiling fans for most part of the year, which creates a lot of background noise, and students are adapted to it. And for the AQ limit, it could not be compared, since the model was not valid, and the upper limit could not be derived.

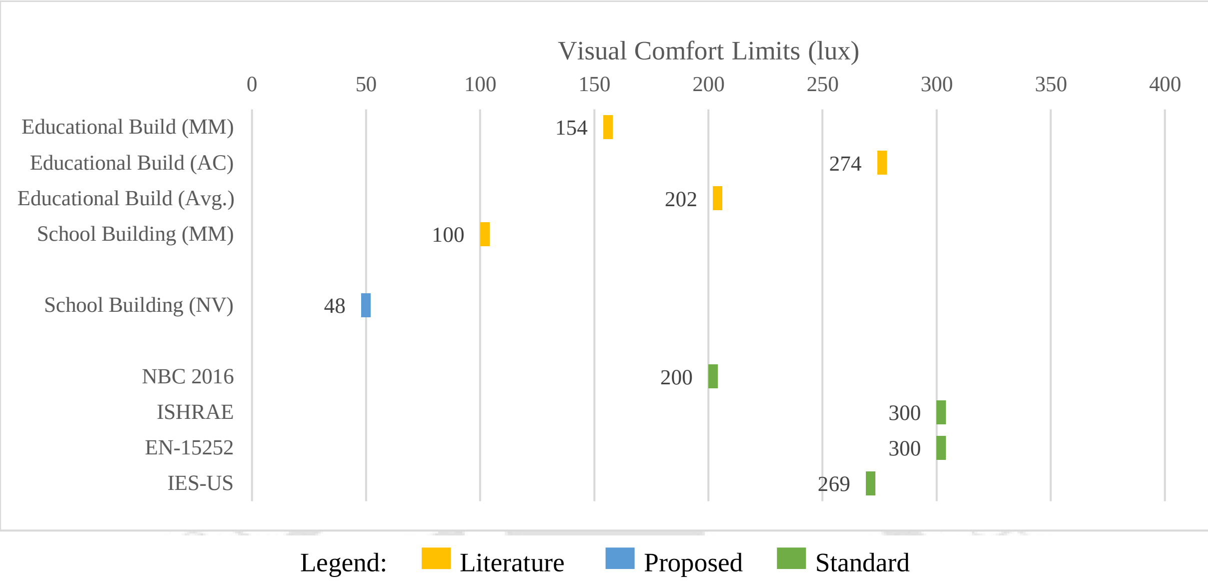

Figure 17: Comparison of visual comfort limits between existing and proposed.

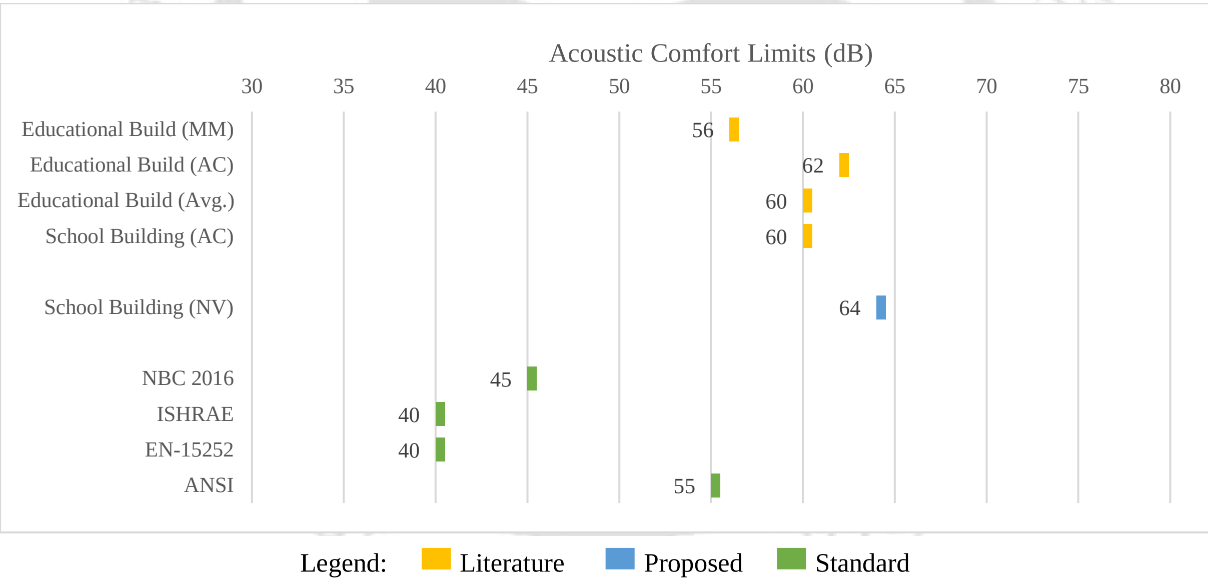

Figure 18: Comparison of acoustic comfort limits between existing and proposed.

Therefore, **H1:** The IEQ parameters comfort limits of NV school classrooms in warm-humid climates ***are significantly different*** from those recommended by national and international standards, and existing literature in different contexts is **partially true for TC, but completely true for VC and AC,** and could not be tested for AQ.

3.6 Chapter summary and conclusions

NV school classrooms in a warm-humid climate were, thus, found to be thermally not comfortable, visually comfortable, acoustically neutral, and the air quality could not be perceived by the occupants. Therefore, it is ***empirically corroborated that, as hypothesised, the comfort limits for NV school classrooms in warm-humid climates are distinct*** from broader recommendations available, and deriving the comfort limits of the IEQ parameters for this context is a valuable research contribution, as there is a lacuna in the literature on the same. Additionally, it may be concluded that a case-by-case study is required for specific socio-economic and climatic contexts, and particular building typologies and ventilation systems, to determine the appropriate comfort limits of IEQ.

Deriving and defining **IEQ comfort limits** for NV school classrooms in a warm-humid climate will surely provide a better understanding of occupant comfort of students, which plays a key role in their performance and productivity. Imbibing these re-defined values may also bring about positive changes in the design of the building and its characteristics, such as reduced size or alternate window design. Such changes may also have the potential to decrease the cost of construction and embodied energy of the building, thereby reducing the negative environmental impact, making school buildings more sustainable and resilient.

Chapter 4

Weighting Scheme and Overall IEQ Assessment Model

4.1 Introduction

To develop an overall IEQ assessment (comfort) model, both individual comfort models and a weighting scheme of the IEQ parameters are required, as only then a holistic picture of IEQ can be understood and addressed. The importance, i.e., the weightage of an IEQ parameter, profoundly impacts the overall comfort model of a context, and hence, many researchers have tried to arrive at the importance/weight of the IEQ parameters. In general, it was seen in literature that TC was given the highest weight and VC the lowest [19], [20], [27], [108], while the weight of the other two parameters is ambiguous [109]. However, the weighting scheme of IEQ parameters can vary depending on context, as the weight given by occupants to the parameters depends on the level of discomfort that it causes in that specific context [20], [27].

4.2 Literature review

The weighting scheme derived by a few studies (mentioned in section 2.3.7) was not appropriate and hence removed. A few more papers were identified through backward (references) and forward (citations) search. Finally, only ten papers were selected that have derived the weighting scheme for the IEQ parameters in educational buildings and can be compared with each other. It is worth mentioning that for the papers that have derived the weighting scheme for the major four IEQ parameters, or more, the weights of the four IEQ parameters were normalized, whereas for others who have derived the weighting scheme for only the three major IEQ parameters, the weights of these parameters were normalized so that the sum is equal to 3/4. The weighting scheme for different contexts derived with different methods is shown in Table 6 and discussed in detail below.

Table 6: Summary of the context, method, and weight of IEQ parameters for educational buildings.

	Context			Method			Weight			
Author and year	**Building Typology**	**Indian Climate**	**Ventilation System**	**Types of questions**	**Scale**	**Analytical method**	**Thermal comfort weight**	**Visual comfort weight**	**Acoustic comfort weight**	**Air Quality weight**
Astolfi & Pellerey, 2008	School (classrooms)	Cold	MM	Satisfaction of four IEQ parameters and the overall IEQ	5-point Likert scale	Pearson's correlation	0.33	0.19	0.26	0.22
Ghita & Catalina, 2015	School (classrooms)	Cold	MM	Ranking of IEQ parameters	1 to 4	not mentioned.	0.27	0.24	0.19	0.30
Leccese et al., 2021	University (classrooms)	Cold	AC	1) Acceptance of overall IEQ and its parameters; 2) Ranking of IEQ parameters; 3) Pairwise comparison of IEQ parameters	1) 5-point Likert scale; 2) 1 to 4; 3) 9-point rating scale	1) Multilinear regression; 2) and 3) AHP;	0.42	0.22	0.19	0.17
Buratti et al. 2018	University (classrooms)	Cold	AC	Weight of IEQ parameters in percentage	0 to 100	Mean percentage	0.26	0.22	0.27	---
Mihai & Iordache, 2016	University (classrooms and offices)	Cold	AC	Importance of each IEQ parameter	0 to 100	Mean score	0.25	0.25	0.24	0.26
Tahsildoost & Zomorodian, 2018	University (classrooms)	Cold	MM	Satisfaction with IEQ parameters and the overall IEQ	5-point Likert scale	Pearson's correlation	0.34	0.31	0.26	0.09
Cao et al. 2012	University (classrooms, offices, library)	Cold	MM and AC	Satisfaction of four IEQ parameters and the overall IEQ	graphical scale from -1 to +1 (no neutral value).	Multi-linear Regression	0.38	0.21	0.27	0.14
Lee et al., 2012	University (classrooms)	Warm-humid	AC	Acceptance of each IEQ parameter and the overall IEQ	dichotomous scale	Multi-linear Regression	0.22	0.21	0.39	0.18
Yang & Mak, 2020	University (classrooms)	Warm-humid	AC	Pairwise comparison of IEQ parameters	9-point rating scale	Combined fuzzy comprehensive evaluation (FCE) and AHP	0.32	0.24	0.28	0.16
Ramprasad & Subbaiyan, 2017	University (classrooms)	Warm-humid	NV and AC	Satisfaction with IEQ parameters and the overall IEQ	5-point Likert scale	Multi-linear Regression	0.20	0.28	0.26	0.26

Note: The building ventilation system is written in short form, where AC = Air-conditioned, NV = Naturally ventilated, and MM = Mix-mode (both AC and NV).

Astolfi & Pellerey [110] and Ghita & Catalina [75] have conducted studies in the same context (school classrooms, cold climate, and MM ventilation), but the weighting scheme was derived with slightly different methods. The former found that TC was given the highest weight, followed by AC, AQ, and VC, the lowest. Whereas the latter found that AQ was given the highest weight, followed by TC, VC, and AC, the lowest.

Similarly, Leccese et al. [108], Buratti et al. [111], and Mihai & Iordache [82] have conducted studies in the same context (university classrooms, cold climate, and AC ventilation), but the weighting scheme was derived with different methods. The first found that TC was given the highest weight, followed by VC, AC, and AQ the lowest. The second found that AC was given the highest weight, followed by TC, and VC the lowest, where AQ weight was not derived. Whereas the third found that AQ was given the highest weight, followed by TC, VC, and AC the lowest.

Similarly, Lee et al. [81], and Yang & Mak [46] have conducted studies in the same context (university classrooms, warm-humid climate, and AC ventilation), but the weighting scheme was derived with different methods. The former found that AC was given the highest weight, followed by TC, VC, and AQ the lowest. Whereas the latter found that TC was given the highest weight, followed by AC, VC, and AQ the lowest.

However, Tahsildoost & Zomorodian [73] and Cao et al. [101] have conducted studies in almost the same context (university classrooms, cold climate, and mainly MM ventilation), and the weighting scheme was also derived with a similar method. Both of them found that TC was given the highest weight, and AQ the lowest; for VC and AC, the results were different. The former found that VC was given more weight than AC, whereas the latter found the reverse.

Ramprasad & Subbaiyan [76] have conducted a study mainly in NV university classrooms in a warm-humid climate. The method used was similar to previous studies. Surprisingly, it is the only study that found that VC was given the highest weight, followed by AC, AQ, and TC the lowest. This could be because the data was collected only in the winter and spring seasons.

4.2.1 Need and relevance of the study

From the literature review, it is observed that the weighting scheme of IEQ parameters within a context can vary due to different methods employed to conduct the studies. Therefore, to arrive at a consolidated position, many studies are required for a specific context [27], [108], [112]. However, it can be seen (in Table 6) that most of the studies were conducted in university classrooms, very few in school classrooms, only one in NV classrooms, and none in NV school classrooms in the warm-humid climate.

Thus, the *objective of this study* (in line with RQ2) is to support the development of an overall IEQ Assessment model by ***deriving a contextually-appropriate IEQ weighting scheme for NV school classrooms in a warm-humid climate,*** prevalent in the developing regions of the world. There is a need for this study as the learning experience of the huge student population pursuing primary and secondary education is severely hampered due to the harshness of the climate and the lack of air-conditioning, thereby overall impacting the quality of education, and there is negligible research to address this pressing need.

4.3 Methodology for deriving weighting scheme

Since there was a lot of variation in the methods used for deriving the weighting scheme in the literature (as shown in Table 6), a pilot study was conducted in a senior secondary school to understand the validity of the different types of questions asked and the analytical methods used for deriving the weighting scheme for this context.

4.3.1 Pilot study

For the pilot study, a senior secondary school (KVS) was selected in Guwahati, India. Where 9th and 12th standard (ages 13-18 years) students were selected for participation in this study, of which approximately 60% were boys and 40% were girls. The study was conducted in April for two consecutive days (one day for each classroom), where data was collected once in the morning and once in the afternoon.

A *questionnaire* was developed specifically for the pilot study, which had four types of questions (developed from literature), for weighting the major four IEQ parameters, as mentioned below (Q1-Q4). A note was also mentioned at the beginning of the questionnaire that the IEQ parameter that causes more discomfort is more important. Then the data from the questionnaire was analyzed with AHP for Q1 and Q3, the mean score for Q2, and multiple linear regression for Q4.

Q1- Please rank the major four IEQ parameters? (From 1 = most important, to 4 = least important).

Q2- Please weight the major four IEQ parameters? (From 1 = least important, to 7 = most important).

Q3- Please weight the major four IEQ parameters based on pair-wise comparison? (A graphical table was provided with each pair of IEQ parameters along with weights); and

Q4- How satisfied are you with the air temperature/light level/ noise level/ air quality/overall IEQ of the classroom at the moment?

Findings from the pilot study - A total of 124 questionnaires were filled out by the students. It was found that most of the students could not understand Q3, and hence, it was left incomplete by many. There were a lot of mistakes in the values given by students for Q1, where the same value was given for each parameter. Whereas Q2 and Q4 were well understood and filled correctly by most of them. But when all the data were analyzed with their respective method, it was found that the weighting scheme derived by Q1, Q2, and Q3 correlated with each other, where TC was given the highest weight, followed by AC, VC, and AQ the lowest. However, Q4 showed peculiar results, where AQ was given the highest weight, followed by TC, VC, and AC, the lowest.

With this, it was concluded that the most valid type of question for deriving the weighting scheme for IEQ parameters was Q2, where the direct weight of each IEQ parameter was asked with a (7-point) rating scale. The internal consistency (reliability) of the overall questionnaire with this type of question was also within the acceptable range (i.e., 0.70). Therefore, for the main study, only this type of question was asked to derive the final weight of the four major IEQ parameters.

4.3.2 Main study

It is important to mention that a single questionnaire form was developed for deriving the IEQ parameters comfort models (chapter 3) and the weighting scheme (chapter 4), even though the questions were completely different for both studies. Therefore, the schools and their respective classrooms were the same for both studies (as mentioned in section 3.3).

In the Questionnaire survey for the main study, ‘importance of IEQ parameters’ was asked, where four questions, one for each IEQ parameter, were posed, i.e., How important is TC/VC/AC/AQ of the classroom at the moment compared to other IEQ parameters? A 7-point rating scale, from least important to most important, was given for each question (an example is shown in Figure 19). Along with this ‘cause for discomfort’ was also asked, for each IEQ parameter, with 7 multiple-choice responses mentioning different causes (an example is shown in Figure 20). The complete questionnaire is available in Annexure 1, developed in conformance with ICMR Guidelines for Research Involving Human Subjects.

The questionnaire survey was taken twice a day in each classroom, once in the morning and once in the afternoon during class hours, during both the summer and winter periods from April 2023 to January 2024. The study was longitudinal, such that each student participated only once throughout the study; however, some survey participants were repeated across the season due to a smaller number of senior secondary classrooms in a few schools.

Q1. How important is **thermal comfort** of the classroom at the moment in comparison to **visual comfort**, **acoustic comfort**, and **air quality**?

Least Important	Less Important	Little Less Important	Equally Important	Little More Important	More Important	Most Important
☐	☐	☐	☐	☐	☐	☐

Figure 19: Example of a question for the importance of thermal comfort.

Q1. What are the causes for **thermal discomfort (temperature)** at the moment?

(1) No causes for discomfort (temperature is satisfactory) in the classroom.
(2) Cold wind from outside coming through the window in the classroom.
(3) Lack of natural ventilation in the classroom.
(4) Direct sunlight is heating my space in the classroom.
(5) Fan air speed is too high in the classroom.
(6) School dress is not appropriate for summer.
(7) Others: ____________________

Figure 20: Example of a question for causes of thermal discomfort.

4.4 Results

During this study, a total of 1087 questionnaires were filled out by the students, where 65% were collected during the summer season and 35% during the winter season. Very few questionnaires were left completely blank as the surveys were monitored by researchers, and in case of any doubt regarding any question while filling out, it was explained personally. Yet some questions were found unanswered when checked. Note that all qualitative values were converted to quantitative values before conducting any kind of statistical analysis. Then, outliers were identified for each observation through the mean deviation method.

4.4.1 Weighting scheme of IEQ parameters

It was found that for the TC question, there were 8 missing values, and 34 outliers (3.9%); for the VC question there were 8 missing values, and 69 outliers (7.1%); for the AC question, there were 8 missing value, and 68 outliers (7.0%); and for the AQ question, there were 10 missing value, and 91 outliers (9.3%). Even after removing all the outliers, there were approximately 1000 valid responses for each question, which were then averaged for each question and normalised (summed to one) for deriving the weighting scheme.

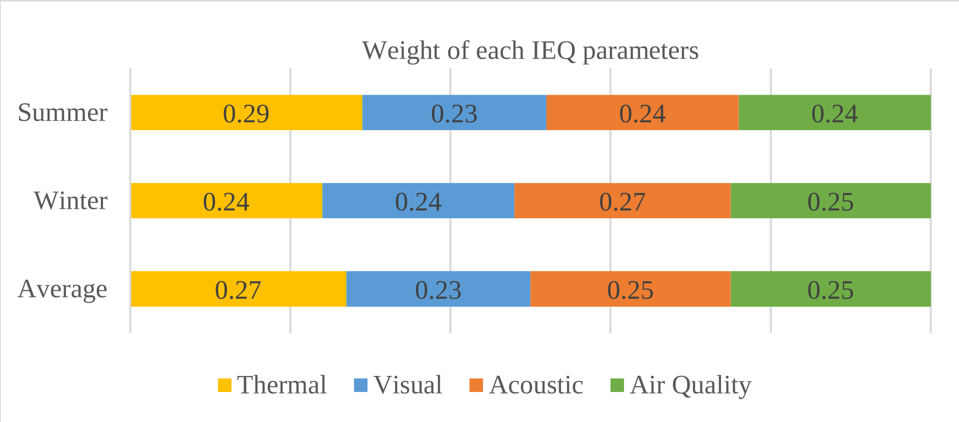

Figure 21: Derived weight for each IEQ parameter for NV schools in a warm-humid climate.

It was found that during the summer season, TC was given the highest weight (0.29), followed by AQ (0.25), AC (0.24), and VC the lowest (0.22). Whereas, during the winter season, AC was given the highest weight (0.26), followed by TC (0.25), AQ (0.25), and VC the lowest (0.24). *On average, it was found that TC was given the highest weight (0.27), followed by AC/AQ (0.25), and VC the lowest (0.23) (as shown in* Figure 21*)*, with a standard deviation of 0.04, 0.02, 0.04, and 0.03, respectively.

4.4.2 Causes of discomfort for each IEQ parameter

For the questions related to causes of discomfort, only missing values were identified, and it was found that for the thermal discomfort question, there were no missing values; for the visual discomfort question, there were 9 missing values; for the acoustic discomfort question, there were 8 missing values; and for the poor air quality question, there was 9 missing value. Upon excluding all the missing values, there were 1000+ valid responses for each question. These qualitative values were converted to quantitative values for statistical analysis (where ticked options = 1 and unticked options = 0), and the sum of all the values was calculated for each option in each question, to calculate the comparative percentage for each response option.

It was found that the results for **thermal discomfort** and poor air quality varied for the winter and summer seasons, whereas for visual and acoustic discomfort, there were no major differences (as shown in Figure 22 to Figure 23). It is further seen that the causes for thermal discomfort during the summer season were mainly due to '*fan air-speed too low*' (66%) and '*school dress not appropriate*' (42%); and during the winter season, there was '*no cause for discomfort*' for most of them (47%), even though for a considerable percentage of student '*cold wind coming from the window*' was the cause (27%).

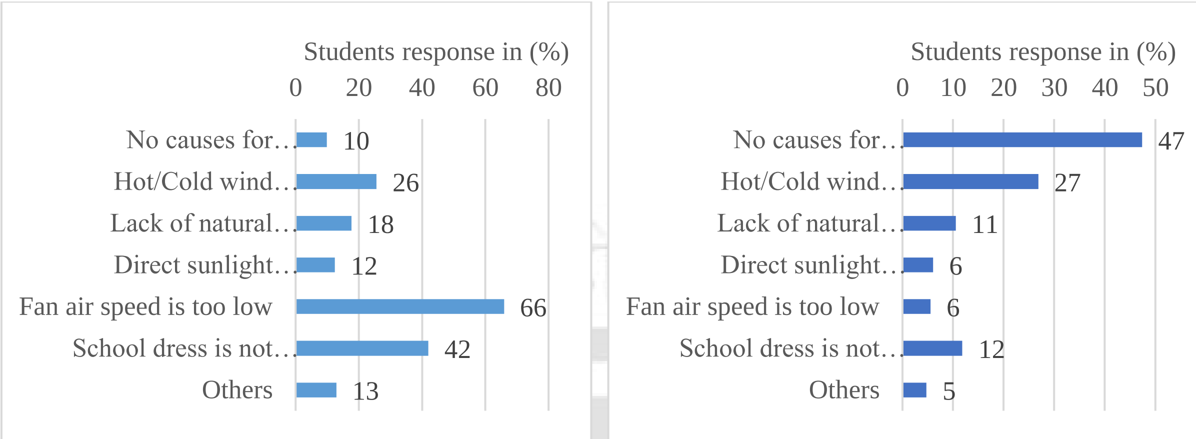

Figure 22: Causes for thermal discomfort during the summer and winter seasons.

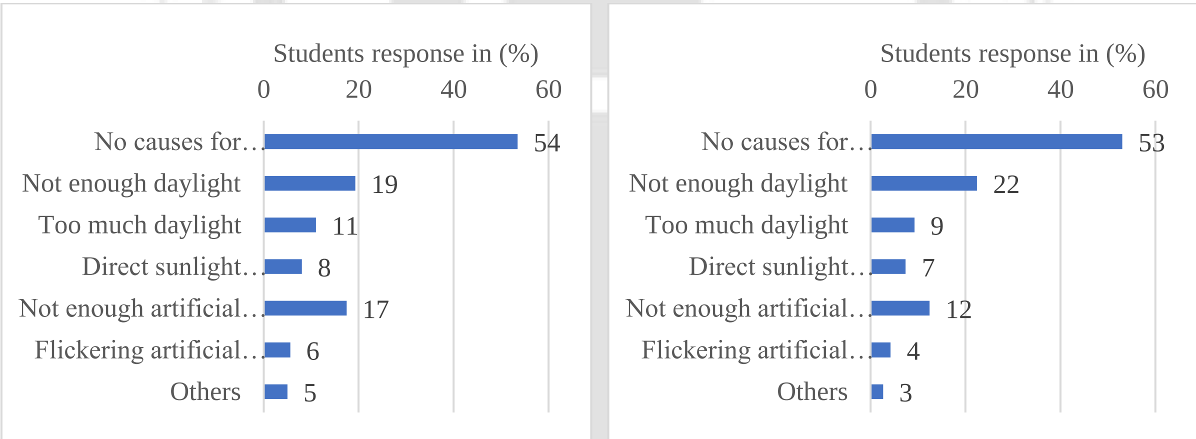

Figure 23: Causes for visual discomfort during summer and winter.

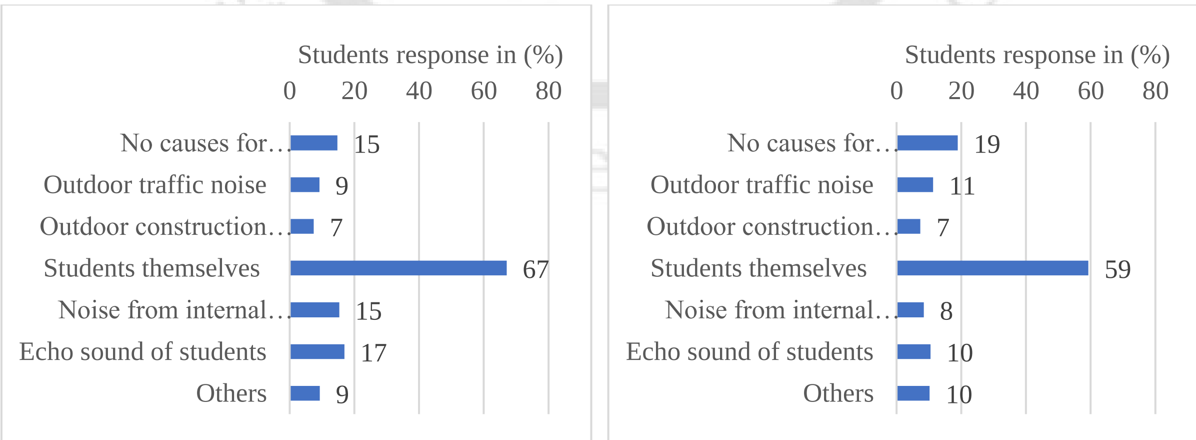

Figure 24: Causes for acoustic discomfort during summer and winter.

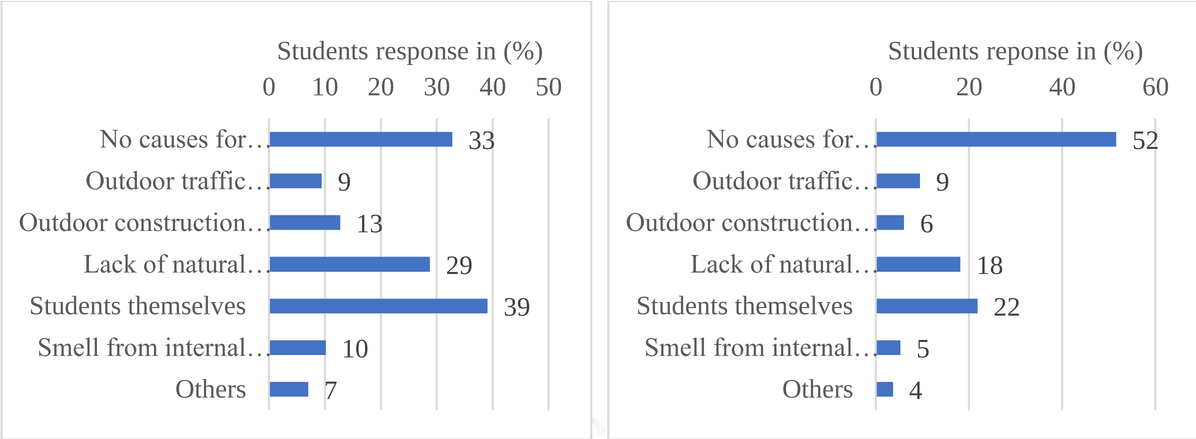

Figure 25: Causes for poor air quality during the summer and winter seasons.

For poor air quality during the summer season '*smell from the students themselves*' was the major cause (39%), followed by '*lack of natural ventilation*' (29%), even though a large percentage of them have ticked '*no cause for discomfort*' (33%); and during the winter season there was '*no cause for discomfort*' for most of them (52%). For acoustic discomfort during both summer and winter, the major cause was '*noise from the students themselves*' (67% and 59% respectively). For visual discomfort during both summer and winter, there was '*no cause for discomfort*' (54% and 53%, respectively).

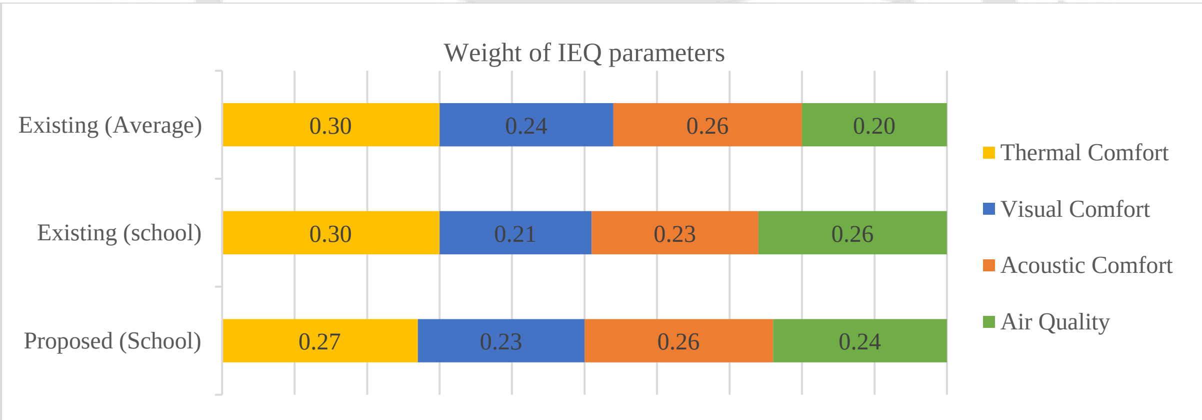

Figure 26: Comparison of the derived and existing weighting schemes for educational buildings.

4.5 Discussions

When the proposed average weighting scheme for NV school classrooms was compared with the existing average weighting scheme for educational buildings, it was observed that TC is over-weighted, AQ is under-weighted, and VC and AC are appropriate. This indicates that a universal weighting scheme for educational buildings may not be appropriate; rather, a case-by-case weighting scheme needs to be proposed for specific contexts.

Similarly, if the existing average weighting scheme for school classrooms is compared with the proposed, it can be seen that TC and AQ are over-weighted, whereas VC and AC are under-weighted (as shown in Figure 26). The reason for this difference could mainly be due to the building ventilation system, or other factors, like students' socio-economic background, adaptability, etc.

To **test the hypothesis**, a two-tailed Z-test (parametric test) for variance was conducted at 5% level of significance for each IEQ parameter (calculation provided in Annexure 3b). It was found that there is a significant difference between the existing and proposed weights for TC, VC, AC, and AQ. Therefore, **H2:** The IEQ parameters weighting scheme of NV school classrooms in a warm-humid climate is significantly different from the existing literature in different contexts, which is **completely true for TC, VC, AC, and AQ**.

Apart from deriving the weighting scheme for the major four IEQ parameters, this study has also identified the ***cause for discomfort*** for each of them, lending a comprehensive understanding of the phenomenon of 'occupant comfort'. It was observed that there was always a cause for acoustic discomfort, irrespective of the season, where students themselves were the major cause for the noisy environment (note: all the schools studied in this case were located in quiet neighborhoods).

Whereas, the opposite is true for the visual environment, where there was never a cause for discomfort during both the summer and winter seasons. As for the thermal environment and indoor air quality, there was a cause for discomfort during the summer season, whereas for the winter season, there was no cause for discomfort. The most interesting finding is that the causes for both thermal discomfort and poor air quality were related to high air temperature, with students sweating profusely indoors, and not due to lack of natural ventilation (high CO_2 level). *This articulates that TC is the most important parameter for improving the IEQ of NV school classrooms in a warm-humid climate.*

4.5.1 Overall IEQ assessment model for NV school classrooms

The overall IEQ assessment model is derived by the weighted sum of the individual comfort models derived in the previous chapter for this context (M_{TC}, M_{VC}, M_{AC}, and M_{AQ}) with respect to its weighting scheme (W_{TC}, W_{VC}, W_{AC}, and W_{AQ}), as shown in Equation 1.

It is worth mentioning that, the AQ model was not considered in the overall IEQ model, since the model was found to be less reliable (very small R^2 value) and not valid (p-value greater than 0.05), and also the trend between the perception and CO_2 level was in the wrong direction (occupant felt fresher when the CO_2 level was increasing), may be due to low CO_2

level in NV classrooms (less than 1000ppm), which could not be perceived by the occupants. Hence, the weight was normalized again for TC, VC, and AC so that the sum is equal to 1, and then the overall IEQ assessment model is formed (as shown in equation 2). A constant value (i.e., 0.7) was also added to the final equation to simplify the highest and lowest IEQ values (from +1 to -1, respectively). Since the model was derived specifically for school classrooms in a warm-humid climate, it is effective within the measured range given in Table 7 for the respective IEQ parameters. A scale for overall IEQ condition is also provided for the assessment (as shown in Figure 27). IEQ assessment of a simulated classroom, as an example, is shown in Annexure 4.

$$\mathbf{IEQ = W_{TC} \times M_{TC} + W_{VC} \times M_{VC} + W_{AC} \times M_{AC}} \quad \text{(Eq 1)}$$

Where,

$M_{TC} = -0.2877 \times Tc + 7.3536$; (where, Tc = operative temperature in the classroom)

$M_{VC} = 0.0046 \times Vc - 0.2231$; (where, Vc = light level in the classroom)

$M_{AC} = -0.0401 \times Ac + 1.5626$; (where, Ac = noise level in the classroom)

Then,

$$\mathbf{IEQ = 0.36\,(-0.2877 \times TC + 7.3536) + 0.31\,(0.0046 \times VC - 0.2231) + 0.33\,(-0.0401 \times AC + 1.5626) + 0.7} \quad \text{(Eq 2)}$$

Table 7: Measurement range for the IEQ parameters valid for the model

IEQ parameters	Range	Measurement unit
Thermal Comfort (TC)	20.0 to 40.0 °C	Operative temperature
Visual Comfort (VC)	0 to 500 lux	Light level
Acoustic Comfort (AC)	40 to 80 dB	Noise level

Note: Values only within this range will provide an accurate prediction.

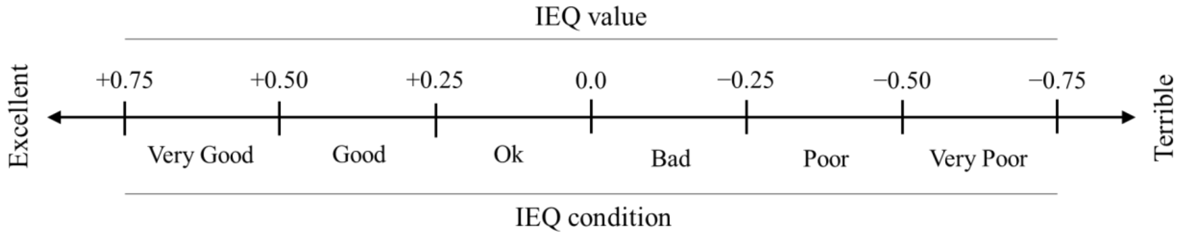

Figure 27: IEQ assessment scale based on the overall IEQ value.

4.6 Chapter summary and conclusions

The importance of prioritizing the IEQ of a building is undeniable, particularly in schools, as it has a lasting impact on occupant productivity, performance, health, and well-being. Many researchers have tried to understand the most important IEQ parameters for consideration during the design of new buildings or retrofitting existing buildings and have confirmed that a single weighting scheme cannot be used universally for all building typologies, climates, and building ventilation systems. Rather, a case-by-case identification of contextual needs through empirical study is recommended for deriving appropriate weighting schemes, and hence, many studies have done so for their specific contexts (building typology, location climate, ventilation system, etc.). As very few studies derived the weighting scheme for NV buildings in warm-humid climate, and none were for schools, this study was conducted to address this gap in line with the aim to support improved learning in school children by assuring occupant comfort.

After a rigorous empirical study conducted throughout the year, it was found that there was a difference in the weighting scheme for the summer and winter periods, but on average, TC was given the highest weight (0.27), followed by AC (0.26), AQ (0.24), and VC the lowest (0.23) by occupants. Additionally, the cause for discomfort was also identified for better understanding, and it was found that, in the summer, the major cause for thermal discomfort was '*fan air-speed too low'*, and the cause for poor air quality was '*smell from students themselves*'. Whereas, irrespective of the season, the cause for acoustic discomfort was '*noise from students themselves'*, and there was no cause for visual discomfort during both the summer and winter periods.

However, on corroborating the survey findings for each IEQ parameter with on-site observation, it was found that the cause for discomfort due to AQ was mainly due to high indoor air temperature, which is a TC issue and not per se an AQ one. Hence, deriving only the weight of IEQ parameters for understanding their importance, assuming that the factor that causes more discomfort is more important, is not sufficient. Therefore, understanding the cause of discomfort for each parameter needs to be studied in tandem to arrive at an overall picture and develop a contextually appropriate IEQ Assessment model that can support existing and newly conceptualized school classrooms achieve holistic occupant comfort.

Chapter 5

Assessing the effectiveness of passive strategies for thermal comfort

5.1 Introduction

Buildings consume the highest amount of energy to fulfil various functions, out of which half of the energy is used for providing thermal comfort [113]. The more we cool, the more we heat our planet. By 2050, the use of air conditioners (AC) will triple, and nearly 1000 cities worldwide will experience an average high temperature of 35°C. ACs are the biggest contributor to global warming; they account for around 30% of all greenhouse gas emissions, 20% of global energy consumption, and are also responsible for sick building syndrome [114], [115]. A sustainable alternative solution to this is 'passive cooling strategies' (PCs), which consume low or no energy, in many cases involve no or low cost, and also provide a comfortable & healthy indoor environment [116], [117]. Long before the invention of the mechanical cooling system, human civilization used passive strategies for cooling living spaces in hot climates, which are now known as traditional wisdom. Later, when the adverse effects of mechanical cooling systems were prevalent, the term 'passive cooling strategies' was coined and recognized as an alternative to conventional cooling [118], [119]. These strategies reduce the indoor temperature below the outdoor temperature during hot days by either preventing the heat from entering the indoor space or by dissipating it to the natural heat sinks [119], [120]. Since PCs are specific to different climates and building typologies, these strategies cannot be generalized universally to all building typologies and locations. Hence, the implementation of PCs requires an understanding of the local climate and building typology [121]. Studies have shown that the overall building energy consumption can be reduced by 2.35%, and up to 78% reduction in cooling energy consumption can be achieved using PCs in buildings [119], [122]. For residential buildings in hot climates, the effectiveness of passive design on indoor TC and energy savings is significant, as PCs can, on average, save 31% energy, reduce 29% cooling load, increase 23% TC hours, and decrease 2.2°C indoor air temperature [118]. Functionally, school buildings are very different from other building typologies, in terms of the density of the classrooms, operation, activity, etc. Also, most developing countries lie in tropical and sub-tropical regions, and their schools are NV (free running), hence, being more vulnerable to extreme heat stress [34]. The IEQ of classrooms is one of the most important factors that can affect teaching and learning performance, which in turn can affect students' academic achievement [6], [7].

Table 8: Summary of the papers selected for literature review.

Author and Year	Location	Building Typology	Passive Strategies
Wong and Li 2007 [123]	Singapore	Residential (apartment)	Orientation and Double roof
Zinzi et al. 2021 [124]	Milan, Italy	Educational (school)	Insulation (ceiling, walls, and windows), Shading, and ventilation for different orientations
Tong et al. 2019 [125]	Singapore	Residential (apartment)	WWR, Corridor, Window operation
Nematchoua et al. 2020 [126]	Madagascar	Simulation (Office building)	Insulation, Shading, PCM, and combination
Murtyas et al. 2024 [127]	Kuala Lumpur, Malaysia	Simulation (Residential house)	Shading, Insulation, solar reflectance, Nocturnal ventilation, and combination
Iqbal et al. 2023 [128]	Indonesia (multiple locations)	Numerical Simulation (Residential house)	Insulation and opening ratio
Tong et al. 2014 [129]	Singapore	Experimental setup and numerical simulation	Cool roof, Double roof, Insulation, radiant barrier, and combination
Tuck et al. 2020 [130]	Kuala Lumpur, Malaysia	Residential (house)	Roof cover (HDPE net black colour)
Pingel et al. 2017 [131]	Pondicherry, India	Residential (dormitories)	Ventilated double roof and cross-ventilation
Gong et al. 2023 [132]	Hong Kong	Experimental setup	Radiative cooling (cool paint)
Zhang et al. 2024 [133]	Hefei, China	Experimental setup and Simulation (residential apartment)	Radiative cooling (metamaterial)
Diallo et al. 2024 [134]	Conakry and Kankan, Guinea	Simulation (Residential house)	Attic ventilation, Ceiling insulation, Cool roof, and a combination
Al-Absi et al. 2021 [135]	Penang Island, Malaysia	Simulation (Residential apartment)	PCM (wall)
Pena et al. 2021 [136]	Bucaramanga, Colombia	Experimental setup	EAHE (air cooling)
Samuel et al. 2018 [137]	Bangalore, India	Experimental setup (full-scale office room)	EATS (air cooling)

Samuel et al. 2018 [138]	Chennai, India	Experimental setup (full-scale room)	TABS (thermal mass cooling)
Bravo and Gonzalez 2013 [139]	Maracaibo, Venezuela	Residential (house)	IEPCS (indirect evaporative cooling)
Han et al. 2020 [140]	Singapore	Experimental setup	Radiative cooling (cool paint)
Han et al. 2022 [141]	Singapore	Experimental setup	Radiative cooling (cool paint)
Lapisa et al. 2024 [142]	Padang, Indonesia	Experimental setup	EWAHE (air cooling)
Ruiz-Valero 2022 [143]	Dominican Republic, Caribbean	Experimental setup	Living wall system
Xiong et al. 2024 [144]	Singapore	Experimental setup	PCM

5.2 *Literature review*

To identify the effective PCs in warm-humid climate, a systematic literature review was conducted where literature was identified from the ‘Scopus’ and the ‘Web of Science’ databases. Initially, keywords such as Naturally, Ventilated, Building, Passive, and Cooling were searched with ‘AND’ operation within the article title, abstracts, and keywords in both databases. From this, we have identified a total of 232 documents that were relevant. Then again, a combination of slightly different keywords was used, such as Building, Passive, Cooling, Tropical, and Climate with ‘AND’ operation, and an additional 303 documents were identified. Hence, the total number of documents identified for screening was 535. After various layers of screening for relevant and quality papers that are studied in warm-humid climate (tropical climates) that have reported the effectiveness of the passive cooling strategies in degrees Celsius, we have included 22 papers for data extraction and analysis (as shown in Table 8). It was found that 13 papers have studied a single passive strategy and have reported its effectiveness, whereas 9 papers have studied multiple passive strategies and have reported combined effectiveness along with their comparison. In total, 14 passive cooling strategies are reported to be effective in a warm-humid climate. Note, to avoid extensive review, only the studies that have shown high effectiveness of these strategies are discussed below, in order from conventional to the most advanced.

5.2.1 Orientation

Wong and Li [123] conducted a field experiment in an NV residential apartment in Singapore. The apartment building is fourteen stories tall, and each floor has four units arranged in a straight line oriented towards the north-south direction. Two units towards the East and West from different floors were studied. It was found that the external surface temperature of the South walls was between 32-33°C, whereas the west walls were between 36-37°C. Hence, there was about a 4°C difference between the South and West walls, which suggests that buildings oriented towards the South will heat up less compared to the West. Similarly, Zinzi et al. 2021 [124] have conducted a numerical simulation study of a NV educational school in Milan, Italy. The school building was a proposed Net Zero Energy Building (NZEB), which is super-insulated to prevent heat loss in winter but has a negative effect during summer, which is numerically simulated to understand its performance compared to a conventional school building (RB). It was found that the proposed NZEB internal maximum operative temperature (OT_{max}) was 7.1°C higher than RB (23.6°C) when oriented West and 5.9°C higher than RB (23.0°C) when oriented North. Hence, there was about a 1.2°C difference between the two orientations, which suggests that the NZEB oriented towards the North performed better than the West.

5.2.2 Corridor position

Tong et al. [125] have conducted a field experiment in many NV residential apartments in Singapore. One of the apartment buildings was five stories tall, and each floor had seven units arranged in a straight line oriented towards East-West direction. Air temperature was recorded in four rooms and a semi-outdoor location (corridor). It was found that the maximum air temperature (AT_{max}) of a room with a corridor on the West was lower by 4.4°C to 30.8°C, compared to a room without a corridor (35.2°C).

5.2.3 Shading devices

Nematchoua et al. [126] have conducted a simulation study of a NV office building in Madagascar. The office is a single-story building with many rooms that are arranged randomly to form a rectangular plan that is oriented towards the North-South direction. The shading devices were added to the windows for solar protection, and then the average air temperature of the office building was simulated for all three tropical climates. It was found that the average air temperature (AT_{avg}) dropped by 0.05°C to 26.95°C from the existing case of 27.0°C; even though the value looks insignificant, it was concluded as an effective passive strategy due to the AT_{avg} drop. Similarly, Murtyas et al. [127] have conducted a simulation study of a NV residential house in Kuala Lumpur, Malaysia. The house is a two-story building with a 3-BHK setting, which is arranged to form a rectangular plan. The master bedroom is located on the first floor, which is oriented towards the West direction. Shading devices were added in all levels, and then the operative temperature of the master bedroom was simulated. It was found that the average operative temperature (OT_{avg}) dropped by 0.2°C to 29.4°C from the existing case of 29.6°C.

5.2.4 Window wall ratio

Iqbal et al. [128] have conducted a simulation study of a NV residential house in multiple locations in Indonesia. Where the house is a single-storey building with a 2-BHK setting, which is arranged to form a rectangular plan, the living room is oriented towards the East direction. The Louver area was increased by four times from the existing case to enhance ventilation, and then the air temperature of the living room was simulated. It was found that by increasing the opening size, the night-time air temperature drops by 0.3°C, but the daytime AT_{max} rises by 1.0°C to 33.0°C above the ambient temperature of 32.0°C, which shows that for this climate, increasing the opening size may not be an effective passive cooling strategy during the daytime. Tong et al. [125] have conducted a study as mentioned above in Section 5.2.2. Where one of the apartment buildings was sixteen stories tall and had several 3-BHK units on a floor, one of the units in the North-West corner was studied, where the air temperature in the living room and master bedroom was recorded. It was found that the air temperature of the master bedroom (33.1°C) with a window wall ratio (WWR) of 0.35 was cooler by 6.5°C, compared to the living room (39.6°C) with a WWR of 0.65 during the daytime. This suggests that smaller window openings can be beneficial for tropical climates during the daytime to enhance TC.

5.2.5 Insulation

Nematchoua et al. [126] have conducted a study as mentioned above in Section 5.2.3. The office building walls and ceiling were insulated with a 5cm thick layer of expanded polystyrene (EPS) to prevent heat gain, and then the average air temperature of the office building was simulated for all three tropical climates. It was found that the AT_{avg} of the office building dropped by 0.25°C to 26.75°C from the existing case of 27.0°C. Similarly, Tong et al. [129] have conducted a field experiment followed by a numerical simulation study on a NV residential apartment in the tropical rainforest (Af) climate of Singapore. The apartment is a sixteen-storey building whose roof is covered by a 3 cm-thick ferro cement slab, leaving a 22cm air gap in between for ventilation (double roof). For testing the impact of insulation with and without a double roof, a 2.5cm EPS was added below the main slab and then the surface temperature of the ceiling was calculated for comparison. It was found that the maximum surface temperature (ST_{max}) of the ceiling reduced by 1.8°C to 29.0°C for the double roof with EPS and by 5°C to 30°C for the single roof with EPS.

5.2.6 Radiant barrier

Tong et al. 2014 [129] have conducted a study as mentioned in section 5.2.2. For testing the impact of radiant insulation with a double roof, a layer of radiant material was added below the main slab, and then the surface temperature of the ceiling was calculated for comparison. It was found that the ST_{max} of the ceiling was reduced by 2.0°C to 28.7°C for the double roof with a radiant barrier. Hence, it was concluded that the radiant barrier has a significant impact on reducing radiant temperature.

5.2.7 Double roof

Tong et al. [129] have conducted a study as mentioned in section 5.2.2. For testing the impact of a double roof, a 3 cm-thick ferro cement slab was added to the main slab, and then the surface temperature of the ceiling was calculated for comparison. It was found that the ST_{max} of the ceiling reduced by 4.0°C to 30.7°C for the double roof compared to the single roof, 34.7°C. Tuck et al. [130] conducted a field experiment in a NV residential house in Kuala Lumpur, Malaysia. The house is a duplex building with a 2-BHK setting, which is arranged to form a rectangular plan oriented towards the East-West direction. A black HDPE net was used to cover the existing roof for shading (double roof), and then the external surface temperature of the roof was recorded for comparison. It was found that the external ST_{max} of the existing roof decreased by 20°C close to the ambient air temperature of 35.8°C when a double roof was added. Pingel et al. [131] conducted a field experiment in NV residential dormitories in Pondicherry, India. The building is a four-storey structure with dormitories linearly arranged, forming a rectangular plan oriented towards the North-South direction. The roof of the building is shaded with precast concrete shells with an air gap of 10-30cm in between (double roof) to prevent solar exposure. The external roof surface and ceiling surface temperatures were recorded throughout the year. It was found that during the hottest days, there was a temperature damping of 15°C compared to the external roof ST_{max} 54.0°C due to the ventilated double roof.

5.2.8 Cool roof

Tong et al. [129] have conducted a study as mentioned in section 5.2.2. For testing the impact of a cool roof with different surface solar reflectivity, a surface paint was added on the external side of the double and single roofs, and then the surface temperature of the ceiling was calculated for comparison. It was found that the ST_{max} of the ceiling was reduced by 8.0°C to 29.3°C for a single roof and 3.5°C to 28.4°C for a double roof when the reflectivity of the roof was changed from 0.1 to 0.9. Gong et al. [132] conducted an experimental study in an outdoor condition on the roof of Hong Kong Polytechnic University. Where an aluminium plate 10cm in diameter was coated with radiative cooling paints, which was placed within a polystyrene box with the top open (radiant cooler). The surface temperature of the aluminium plate was recorded during the peak heating period along with the outdoor air temperature. It was found that the ST_{avg} of the radiant cooler was 2°C below the ambient temperature (32°C) and 12°C cooler compared to a concrete surface (36.8°C) even during midday. Zhang et al. [133] have conducted an experimental study in an outdoor condition on the roof of a building. Two identical rooms (1m x 1m x 0.8m) were constructed with 5cm thick white concrete board; one of the roofs of a room was covered with high solar reflective meta-material (cool roof). The indoor air temperature and the inner surface temperature of both experimental rooms were recorded for all four seasons. It was found that the air temperature and internal ST_{max} of the room with a cool roof were reduced by 5.5°C to 42.5°C and 15.6°C to 41.4°C, respectively, compared to the reference room during the summer period.

5.2.9 Attic ventilation

Diallo et al. [134] have conducted a simulation study of a NV residential house in multiple locations in Conakry and Kankan, Guinea. Where the house is a single-storey building with a 3-BHK setting, which is arranged to form a square plan, the living room is oriented towards the South direction. Natural ventilation of the rooms and attic space was added to remove excess heat accumulated, and then the operative temperature of the living room was simulated. It was found that by incorporating natural ventilation into the attic space, the OT_{max} of the living room decreases by 1.92°C to 34.8°C during the peak summer period.

5.2.10 Cross ventilation

Pingel et al. [131] have conducted a study as mentioned in section 5.2.7. All the rooms are cross-ventilated through the louvers in both the North and South directions (single-loaded corridor). The outdoor and indoor air temperatures of the room were recorded throughout the year. It was found that during the hottest days, the AT_{max} of the room was 2.8°C below the ambient temperature of 36.8°C.

5.2.11 Nocturnal ventilation

Murtyas et al. [127] have conducted a study as mentioned in section 5.2.3. Nocturnal ventilation was scheduled (8 pm to 8 am) for the window operation of all rooms, and then the air temperature of the master bedroom was simulated. It was found that the OT_{avg} was reduced by 1.8°C to 27.8°C from the existing case of 29.6°C, which was the highest compared to other passive strategies.

5.2.12 Phase change material (PCM)

Al-Absi et al. [135] have conducted a simulation study of a NV residential apartment in Penang Island, Malaysia. The apartment is a thirty-two-storey building with eight 3-BHK units on each floor, linearly arranged forming a rectangular plan oriented towards the North-South direction. For testing the impact of PCM, layers of PCM sheet (6mm thick) were added on all walls and ceiling internally, and then the operative temperature of the master bedroom was simulated for comparison. It was found that the indoor OT_{max} was reduced by 5.0°C to 29.0°C from the existing case of 34.0°C. Nematchoua et al. [126] have conducted a study as mentioned above in Section 5.2.3. Where the office building walls and ceiling were insulated with a 5cm thick layer of EPS, with which a 7cm layer of PCM was added, and then the average air temperature of the office building was simulated for all three tropical climates. It was found that the AT_{avg} dropped by 0.21°C to 26.79°C from the existing case of 27.0°C.

5.2.13 Earth air heat exchanger (EAHE)

Pena et al. [136] have conducted a simulation study of a NV educational building in Bucaramanga, Colombia. The structure is a four-story building with multiple rooms arranged along a central corridor forming a rectangular plan oriented towards the North-South direction. A design laboratory on the first floor oriented towards the North direction was incorporated with EAHE with different variants, and then the air temperature of the laboratory was simulated for comparison with all cases. It was found that the best results between 21.1-24.3°C were obtained when the PVC pipes 8 inches in diameter, and 150m long, were buried at a depth of 1.5m. Where the AT_{max} was reduced by 7°C to 23°C from the ambient temperature of 30°C. Samuel et al. [137] conducted a field experiment of a NV home office in Bangalore, India. The structure is an experimental setup that consists of a single floor with three rooms linearly arranged, forming a rectangular plan oriented towards the East-West direction. All the rooms are well insulated and ventilated, it is further cooled by EAHE, which is constructed by a 72m polypropylene pipe of 400mm diameter buried at a depth of 4.2m. It was found that during the summer period, the AT_{max} was 27°C, which is 2.9°C below the ambient air temperature of 29.9°C.

5.2.14 Indirect evaporative cooling (IEC)

Samuel et al. [138] conducted a field experiment in a NV room in Chennai, India. The structure is an experimental setup that consists of a single room with windows on three sides and a door on one side. The room is incorporated with a Thermally Activated Building System (TABS), which is supplied with water from the cooling tower. A 1/2" PVC pipe was arranged in a serpentine layout with 10cm spacing on all walls, roof, and floor. It was found that during the summer period, the OT_{max} was reduced by 3.6°C to 30.4°C from the existing case (without cooling), 34.0°C. Bravo and Gonzalez [139] conducted a field experiment on a NV residential house in Maracaibo, Venezuela. The structure is a single-story building designed according to bioclimatic architecture, which consists of four rooms positioned around a central courtyard forming a rectangular plan oriented towards the North-South direction. The master bedroom, located in the northeast corner, was incorporated with an Indirect Evaporative Passive Cooling System (IEPCS) in the ceiling. It was found that during the summer period the AT_{max} was reduced by 5.1°C to 30.1°C form the adjacent living room (without IEPCS) 35.2°C.

5.2.15 Combined passive cooling strategies

Nematchoua et al. [126] have conducted a study as mentioned above in Section 5.2.3. The combined effectiveness of passive cooling strategies was tested by adding insulation with a shading device and insulation with PCM in the existing office building, and then the average air temperature was simulated for the complete building. It was found that the AT_{avg} dropped by 0.4°C to 26.6°C and 0.2°C to 26.8°C, respectively, from the existing case of 27.0°C. Tong et al. [129] have conducted a study as mentioned in section 5.2.2. The combined effectiveness of cool paint, double roof, and radiant barrier was calculated for a top-floor unit of a residential apartment. It was found that the ceiling ST_{max} dropped by 6.6°C to 28.2°C from the existing case of 34.8°C. Diallo et al. [134] have conducted a study mentioned in section 5.2.9. The combined effectiveness of attic ventilation, ceiling insulation, and cool roof coating was simulated for the living room. It was found that the OT_{max} decreased by 4.4°C to 31.8°C from the existing case of 36.2°C.

Table 9: Summary of the effective passive cooling strategies and their effectiveness.

<table>
<tr><th>S/N</th><th>Passive Cooling Strategies</th><th>Type</th><th>Heat</th><th>Energy</th><th>Maximum Effectiveness</th></tr>
<tr><td>1</td><td>Orientation</td><td rowspan="4">Building Design</td><td rowspan="8">Prevents Overheating</td><td rowspan="12">Free Cooling</td><td>ST_{max} ↓ 4.0°C to 32.5°C from 36.5°C</td></tr>
<tr><td>2</td><td>Corridor Position</td><td>AT_{max} ↓ 4.4°C to 30.8 °C from 35.2°C</td></tr>
<tr><td>3</td><td>Shading Device</td><td>OT_{max} ↓ 0.2°C to 29.4°C from 29.6°C</td></tr>
<tr><td>4</td><td>Opening Ratio</td><td>AT_{max} ↓ 6.5°C to 33.1°C from 39.6°C</td></tr>
<tr><td>5</td><td>Insulation</td><td rowspan="4">Building Material</td><td>ST_{max} ↓ 5.0°C to 30.0°C from 35.0°C</td></tr>
<tr><td>6</td><td>Radiant Barrier</td><td>ST_{max} ↓ 2°C to 28.7°C from 30.7°C</td></tr>
<tr><td>7</td><td>Double Roof</td><td>ST_{max} ↓ 4°C to 30.7°C from 34.7°C</td></tr>
<tr><td>8</td><td>Cool Roof</td><td>ST_{max} ↓ 8.0°C to 29.3°C from 37.3°C</td></tr>
<tr><td>9</td><td>Attic Ventilation</td><td rowspan="3">Ventilation System</td><td rowspan="3">Removes Heat</td><td>OT_{max} ↓ 1.9°C to 34.8°C from 36.7°C</td></tr>
<tr><td>10</td><td>Cross Ventilation</td><td>AT_{max} ↓ 2.8°C to 34.0°C from 36.8</td></tr>
<tr><td>11</td><td>Nocturnal ventilation</td><td>OT_{max} ↓ 1.8°C to 27.8°C from 29.6°C</td></tr>
<tr><td>12</td><td>Phase Change material (PCM)</td><td rowspan="3">Advance System</td><td>Stores Coolth</td><td>OT_{max} ↓ 5°C to 29.0°C from 34.0°C</td></tr>
<tr><td>13</td><td>Earth Air Heat Exchange (EAHE)</td><td rowspan="2">Cooling</td><td rowspan="2">Low Energy Cooling</td><td>AT_{max} ↓ 7°C to 23.0°C from 30.0°C</td></tr>
<tr><td>14</td><td>Indirect Evaporative Cooling (IEC)</td><td>AT_{max} ↓ 5.1°C to 30.1°C from 35.2°C</td></tr>
</table>

Note: ST_{max} – Max Surface Temperature; AT_{max} – Max Air Temperature; and OT_{max} – Max Operative Temperature

5.2.16 Inferences from the literature review

It is inferred that the attributes of the 14 effective PCs can be categorised with respect to design principles: (i) building design – 4 strategies; (ii) building material – 4 strategies, (iii) ventilation system – 3 strategies, and (iv) advanced systems - 3 strategies.

With respect to heat flux, (i) prevent heating - 8 strategies, (ii) remove heat accumulated indoor – 3 strategies, (iii) store the coolth when ventilated during the night - only 1 strategy, and (iv) cool the building – 2 strategies.

With respect to operational energy used, (i) do not require any energy (free cooling) – 12 strategies, and (ii) require a small amount of energy or low energy cooling – 2 strategies (as shown in Table 9).

Upon analysis of the effectiveness of each passive strategy, it is seen that comparison is done based on air temperature, operative temperature, and surface temperature differences, discussed below;

- In terms of air temperature reduction, 'EAHE' is the most effective (7.0°C), followed by 'window wall ratio' (6.5°C), IEC (5.1°C), 'corridor position' (4.4°C), and 'cross ventilation (2.8°C).
- In terms of operative temperature reduction, 'PCM' is the most effective (5.0°C), followed by 'attic ventilation' (1.9°C), 'nocturnal ventilation' (1.8°C), and 'shading device' (0.2°C); and
- In terms of surface temperature reduction, 'cool roof' is the most effective (8.0°C), followed by 'insulation' (5.0°C), 'double roof' (4.0°C), 'orientation' (4.0°C), and 'radiant barrier' (2.0°C).

Even though the effectiveness of these passive cooling strategies in warm-humid climate is justified, where in some cases complete TC could be achieved in even peak summer days, none of the studies were conducted in NV school classrooms.

Therefore, the *objective of this study* (in line with RQ3) is ***to find the effectiveness of existing passive cooling strategies for the context of NV school classrooms in a warm-humid climate through building simulation software, and assess if Thermal Comfort can be achieved throughout the year in this context with passive strategies alone.***

5.3 Methodology for finding the effectiveness of identified passive strategies

A dynamic building simulation software was used to model a section of the existing school building that adheres to national building codes, identified as the ‘ideal’ or base-case. The details of the base-case classrooms and the simulation method are discussed in the following sub-section.

5.3.1 The school studied and the base-case classroom

One of the schools previously studied (KVS) was selected for building simulation, since it is one of the best-designed schools in terms of bio-climatic architecture in this location and completely adheres to the National Building Code (NBC2016). All classrooms are identical and repeated linearly along a corridor forming a rectangular plan oriented towards the North direction. The occupant density of the classrooms is at an average of 1.0 m^2/student, where all the classrooms are NV. One of the classrooms on the top floor was studied (as shown in Figure 28) to understand the thermal discomfort. The top-floor classroom was chosen as **the base case** because it has greater exposure to the solar radiation and wind, due to which top-floor classrooms have the most adverse thermal conditions compared to the lower floors. It was also observed during onsite study that the indoor air temperature for the top-floor classrooms had greater fluctuation compared to the lower floors during both the summer and winter periods.

Figure 28: Indoor and outdoor images of the studied school classroom.

5.3.2 Data logger on-site measurements

Indoor temperature (°C) and relative humidity (%) were recorded by METRAVI (DL-TH-01) data logger for approximately a week in the selected classrooms during the hottest month (17th to 22nd August 2023) and the coldest month (18th to 23rd January 2024). The data were logged every 10 minutes, and then an average of an hour was taken for analysis. Outdoor hourly average temperature (°C), relative humidity (%), wind direction (degrees), and wind speed (m/s) were collected from a weather station located nearby, on the campus of IITG (as shown in Figure 29).

Figure 29: Temperature-humidity data logger and IITG weather station

5.3.3 Simulation and validation of the base-case classroom

A validated 'EnergyPlus' building simulation software 'DesignBuilder' [145], [146], [147] was used to model the base-case classroom. The base-case classroom is chosen as the exemplar on behalf of all the NV school classrooms of the warm-humid climatic region to demonstrate the assessment of IEQ with the application of passive strategies.

The base-case classroom was simulated with a pair of adiabatic components on both sides of the internal walls, since there was negligible heat flow through internal walls (between classrooms). The physical characteristics, occupant density, ventilation systems, etc., of the simulated classroom are input according to the existing classroom details collected during the case study. For validation of the simulation model, only the days for which on-site measurements were recorded have been simulated, and the air temperature of the base-case classroom was correlated between existing measurements and simulated data. It was seen that the results were; highly correlated for the summer period, where the Pearson Correlation value (R^2) was 0.9 (excepted above 0.8) and the normalised root mean square error (NRMSE) percentage was 14% (excepted below 30%); and moderately correlated for the winter period, where R2 was 0.8 and NRMSE was 21% (as shown in Figure 30). Hence, the model was validated for undertaking further simulations and analysis.

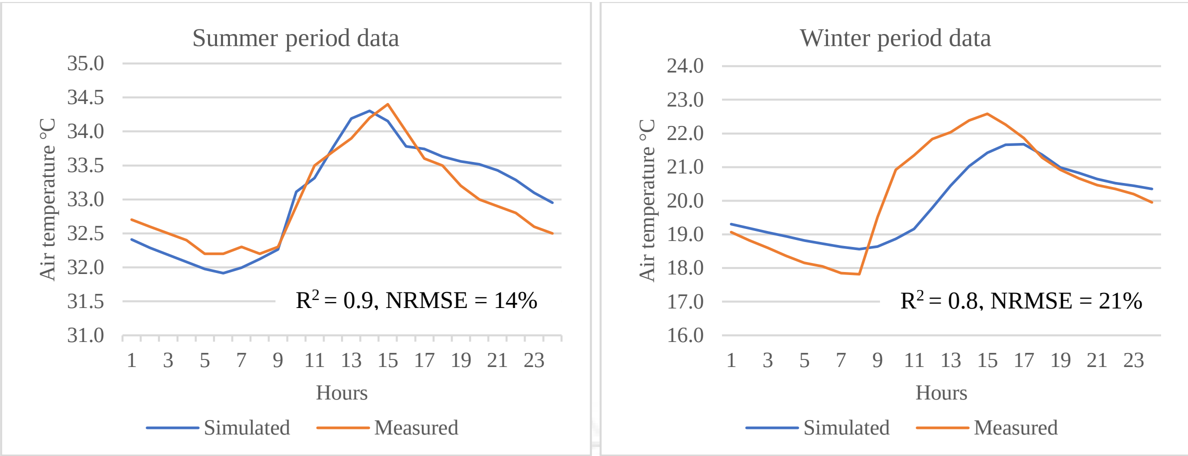

Figure 30: Correlation between on-site measurement and simulated data for the base case classroom for the summer and winter periods, respectively.

Figure 31: South elevation (3D view) of the school selected for base case classrooms.

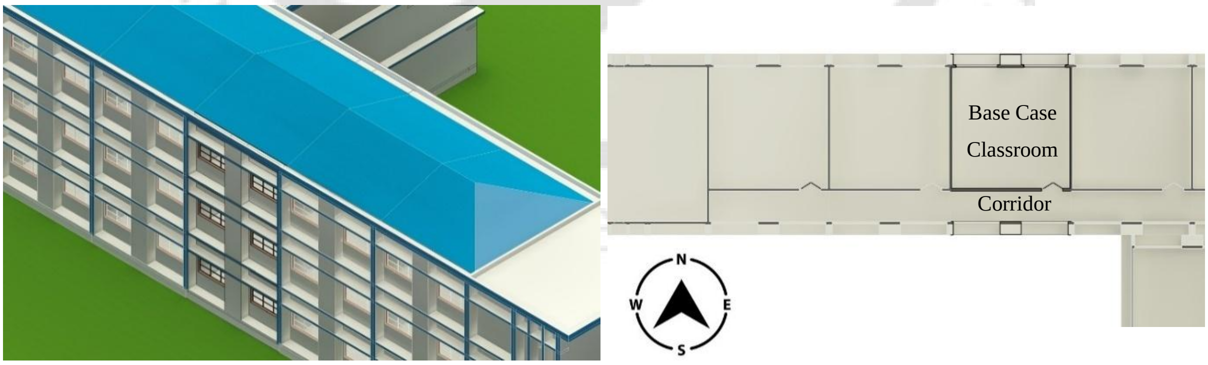

Figure 32: Base case classrooms 3D view (north elevation) and plan.

The validated model was used to simulate the indoor air temperature of the top-floor classroom for the hottest month (August) and coldest month (January), respectively, to understand the peak thermal discomfort during both the summer and winter periods. It was found that the hottest day was 18 August and the coldest day was 9 January.

In a warm-humid climate, summer (high temperatures with rains overlapping into monsoon) and winter (dry with intermittent rains) are the two seasons that can be oppressive, while the remaining seasons of spring and autumn are hard to distinguish and hence are not accounted for. It is assumed that if TC for the hottest and the coldest day of the year is achieved, then TC throughout the year can be achieved.

5.4 Results and discussions

5.4.1 Base-case classroom's thermal environment

It is worth mentioning that what humans perceive in an indoor environment is the operative temperature, which is an average of radiant and air temperature. Hence, in this study, the OT_{max} is compared with the upper limit of TC during the summer period, and the OT_{min} with the lower limit of TC during the winter period. According to the Indian Model for Adaptive thermal Comfort (IMAC), promoted by NBC-2016, the upper and lower limits of thermal comfort for this climate data are approximately 30°C and 20°C, respectively. Whereas, as per the TC model derived in Chapter 3 for this context, the upper and lower limits of TC were 29.1°C and 22.1°C, respectively. Upon comparison of the upper limit of TC with the OT_{max} of the top floor classroom during class hours (8:30 am to 2:30 pm, highlighted in dashed red box), the operative temperature is higher by 4.8°C, i.e., 33.9°C, which is very high (as shown in Figure 33).

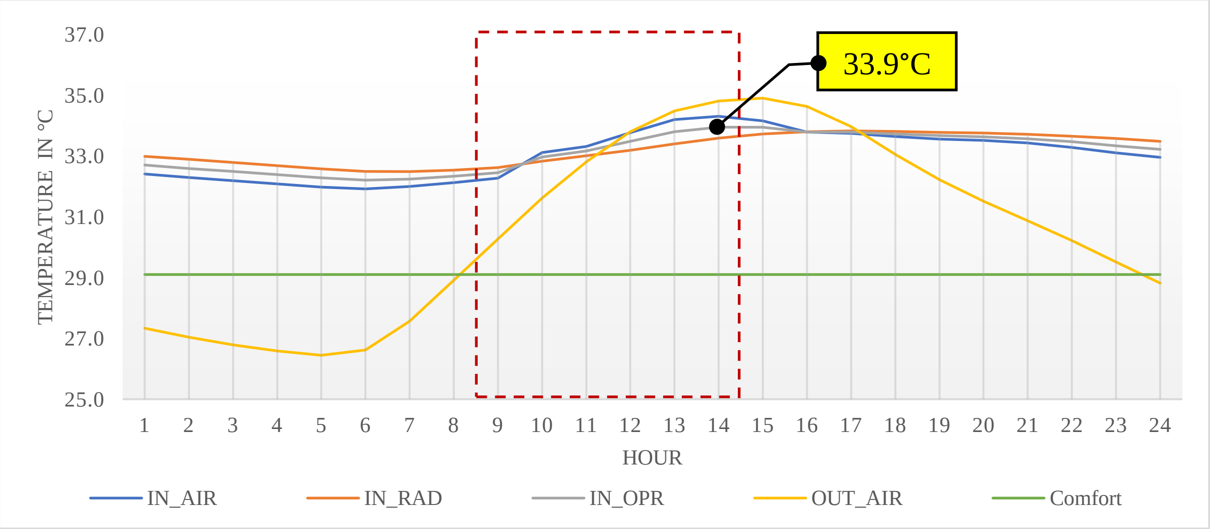

Figure 33: Simulated indoor and outdoor temperatures of the base-case classroom for the hottest day of the year.

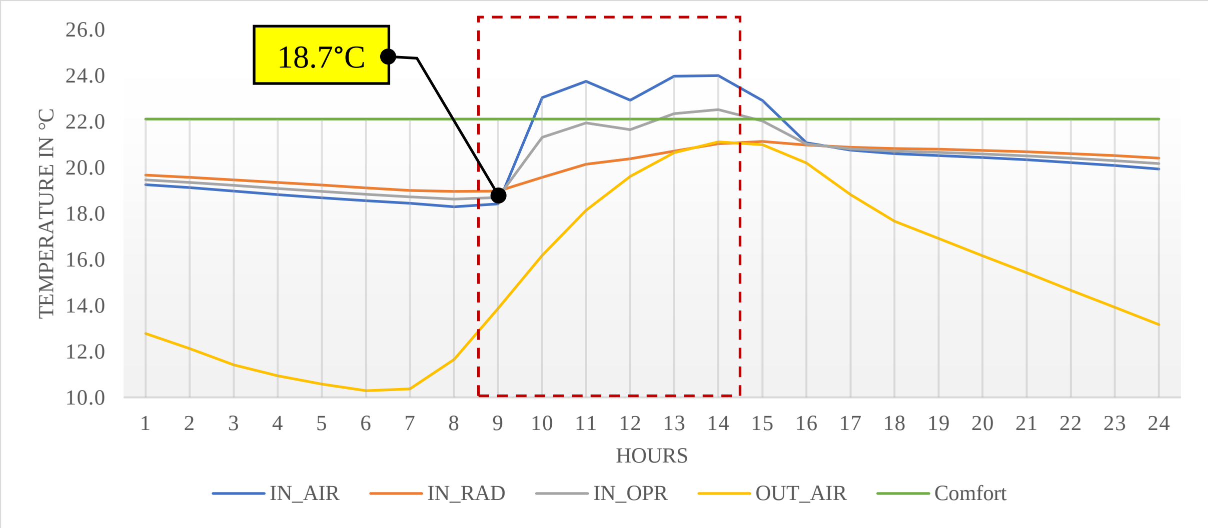

Figure 34: Simulated indoor and outdoor temperatures of the base-case classroom for the coldest day of the year.

On comparing the lower limit of TC with the OT_{min} of the ground floor classroom during class hours (8:30 am to 2:30 pm, highlighted in dash red box), the operative temperature is lower by 4.3°C i.e., 17.8°C, which is very low but rises-up very sharply very close to the lower limit of TC (as shown in Figure 34), it is also worth mentioning that in this location only few days are cold compare to hot days in a year. Therefore, achieving TC for the top-floor classrooms (base case) during the summer period is considered as the 'problem statement', with which the effectiveness of the 14 PCs, identified from the literature, is assessed for the base case classroom on the hottest day of the year.

5.4.2 Orientation

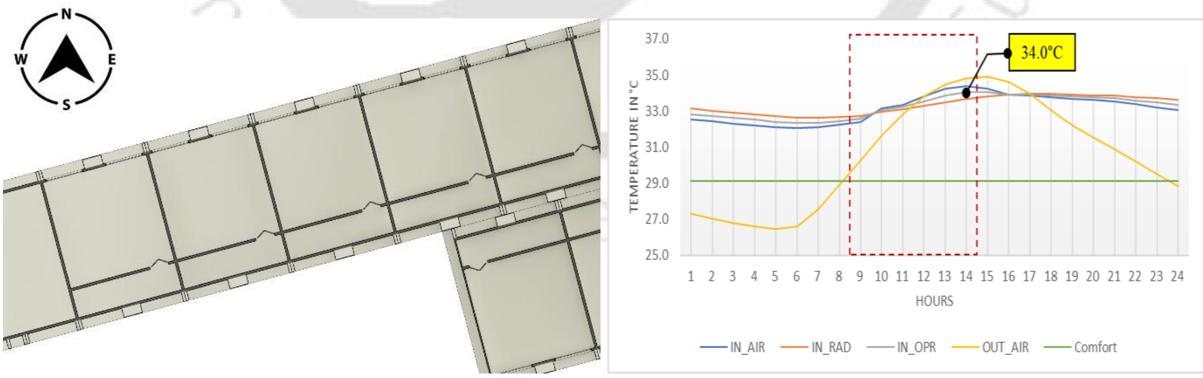

Figure 35: Operative temperature of the base-case classroom when oriented 15°West from North.

The orientation of the base case classrooms is North, which is already the best. But in one of the papers, a case study of a well-designed building (Golconda Dormitory) oriented North was shown to have a slight tilt towards West, which could also be effective for school classrooms, and hence, it was tested. The base case classroom orientation was tilted by 15°

towards the west, and then the model was simulated again. The results show that the OT_{max} during the class hours is increased by 0.1°C to 34.0°C from 33.9°C (as shown in Figure 35). Hence, it is **not an effective** passive cooling strategy for the base case classrooms.

5.4.3 Corridor position

The corridor of the base case classroom was on the South side (as shown in Figure 4), which protects the classroom from the summer sun but also has a disadvantage during the winter months when the low altitude sun could be used for heating the classrooms. Hence, the base case classroom was oriented towards the South, keeping the corridor position North, and then the model was simulated again. The results show that the OT_{max} during the class hours is increased by 0.1°C to 34.0°C from 33.9°C (as shown in Figure 36). Hence, it is **not an effective** passive cooling strategy during the summer period, but it may be effective for the winter period.

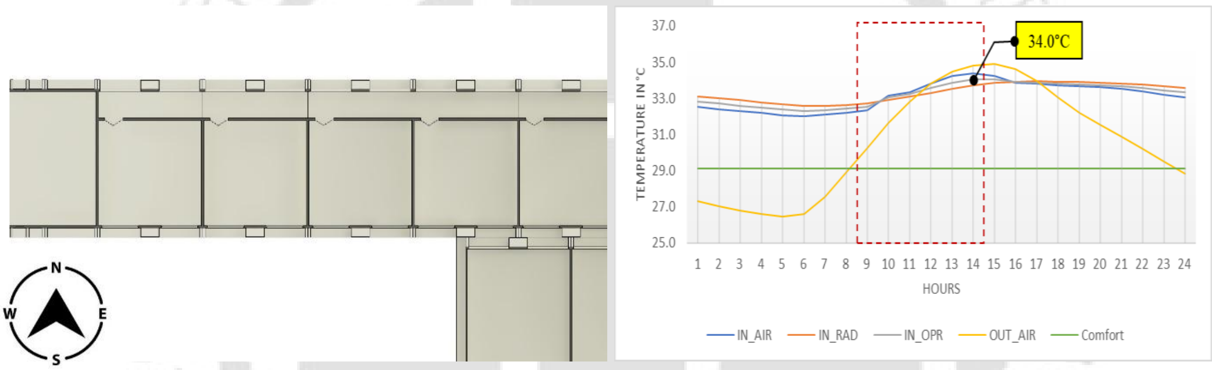

Figure 36: Operative temperature of the base-case classroom when the corridor is positioned North.

5.4.4 Shading device

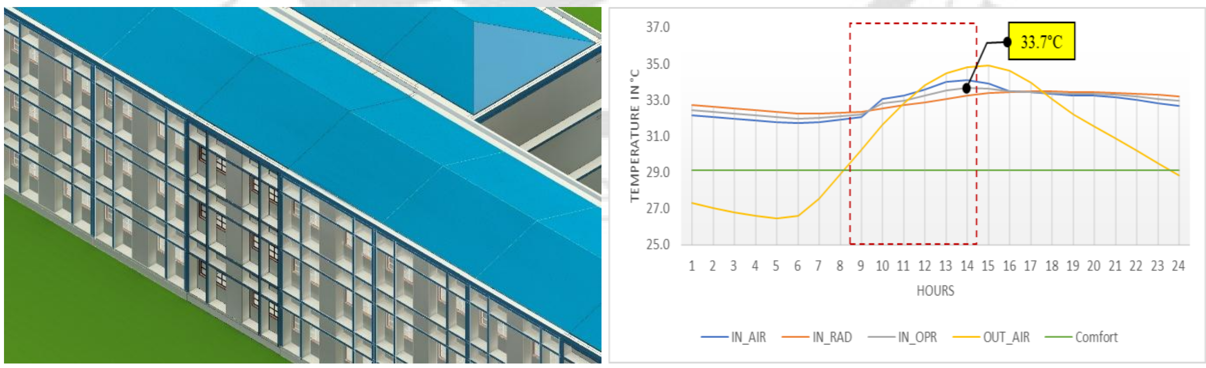

Figure 37: Operative temperature of the base-case classroom when vertical shading devices are added

The shading devices of the base case classroom are of sufficient depth of 0.70m and placed every after three windows of a total width of 2.4m in the North direction (as shown in Figure 4). To check if adding more shading devices would improve the thermal condition, a vertical fin was added between every two existing shading devices, and then the model was simulated again. The results show that the OT_{max} during the class hours is decreased by 0.2°C to 33.7°C from 33.9°C (as shown in Figure 37), which is not very significant. Hence, it is **not an effective** passive cooling strategy for the base case classroom.

5.4.5 Window wall ratio (WWR)

The WWR of the base case classroom is 0.3, which is as per the NBC 2016, but the literature suggests that decreasing the WWR will improve the thermal condition, as the indoor air temperature (Ti) is found to be lower than the outdoor air temperature (To).

To check if this is true, the WWR of the base case classroom was reduced to 0.2, and then the model was simulated again. The results show that the OT_{max} during the class hours is decreased by 0.5°C to 33.4°C from 33.9°C (as shown in Figure 38), which is considerably significant. Hence, it is **an effective** passive cooling strategy for the base case classroom.

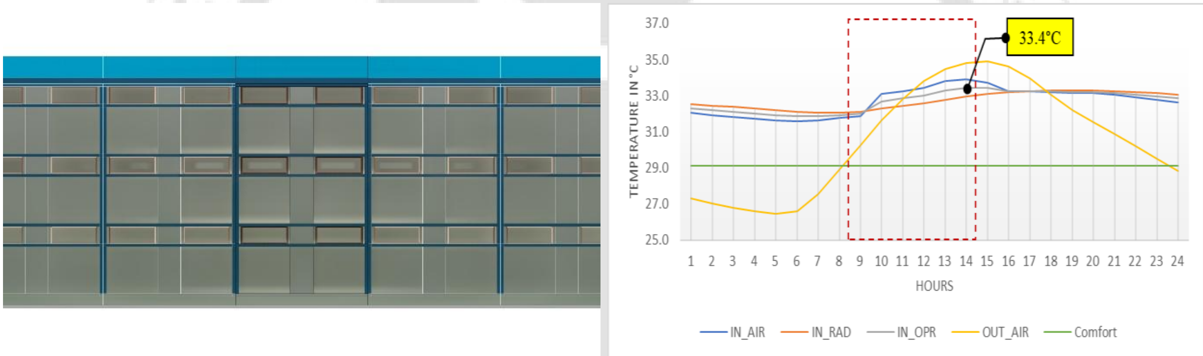

Figure 38: Operative temperature of the base-case classroom when the window wall ratio is changed to 0.19.

5.4.6 Insulation

The external wall of the base case classroom has a thick column (1.2m width) which acts as insulation, and the internal walls do not require insulation, since there is negligible heat flow between classrooms. Hence, the ceiling of the classroom is the only place where insulation can be added, which already has an insulating board 0.02m thick. To check if adding another layer of insulating board improves the thermal condition, a layer of extruded polystyrene (EPS) board 0.02m thick was added to the existing wood particleboard, and then the model was simulated again.

The results show that the OT_{max} during the class hours is the same (33.9°C) (as shown in Figure 39). This means that there is no difference if we add more insulation to the ceiling. Hence, it is **not an effective** passive cooling strategy for the base case classroom.

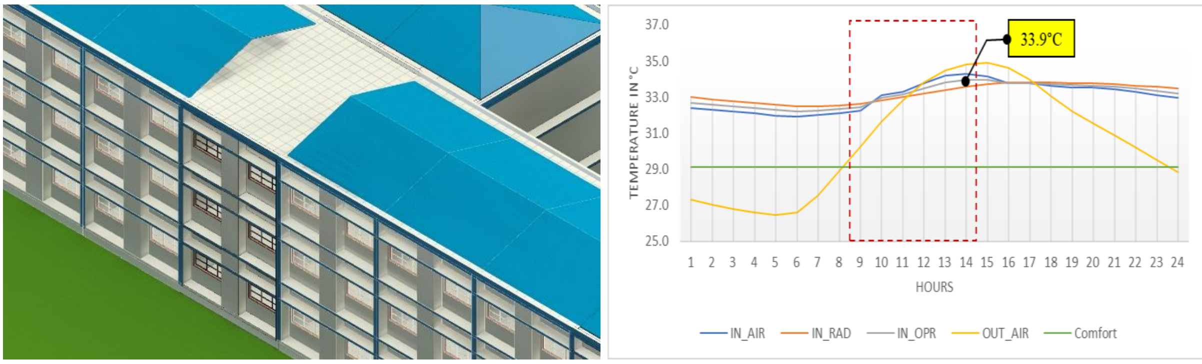

Figure 39: Operative temperature of the base-case classroom when insulation was added to the ceiling.

5.4.7 Radiant barrier

There is no radiant barrier (shiny polished surface) in the existing base case classroom, which is effective only in the ceiling due to high long-wave radiation from the roof. Hence, the ceiling of the classroom is the only place where a radiant barrier can be added to the existing insulating board. To check if adding a layer of radiant barrier on the existing ceiling improves the thermal condition, a layer of the polished aluminium sheet was added to the existing wood particleboard, and then the model was simulated again. The results show that the OT_{max} during class hours is the same (33.9°C) (as shown in Figure 40). This means that there is no difference if we add a radiant barrier to the ceiling. Hence, it is **not an effective** passive cooling strategy for the base case classroom.

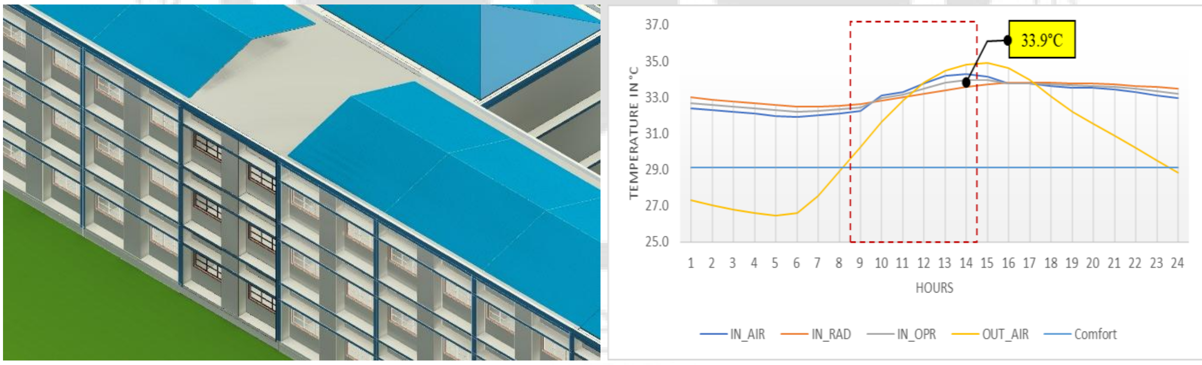

Figure 40: Operative temperature of the base-case classroom when the radiant barrier was added to the ceiling.

5.4.8 Double roof

The roof of the base case classroom is a single tin roof. A roof is called a double roof when a shade is added to the primary roof to prevent solar heat gain. To check if this strategy is effective for the base case classroom, a secondary layer of shade was added to the existing tin roof, and then the model was simulated again. The results show that the OT_{max} during the class hours is decreased by 0.5°C to 33.4°C from 33.9°C (as shown in Figure 41), which is considerably significant. Hence, it is **an effective** passive cooling strategy for the base case classroom.

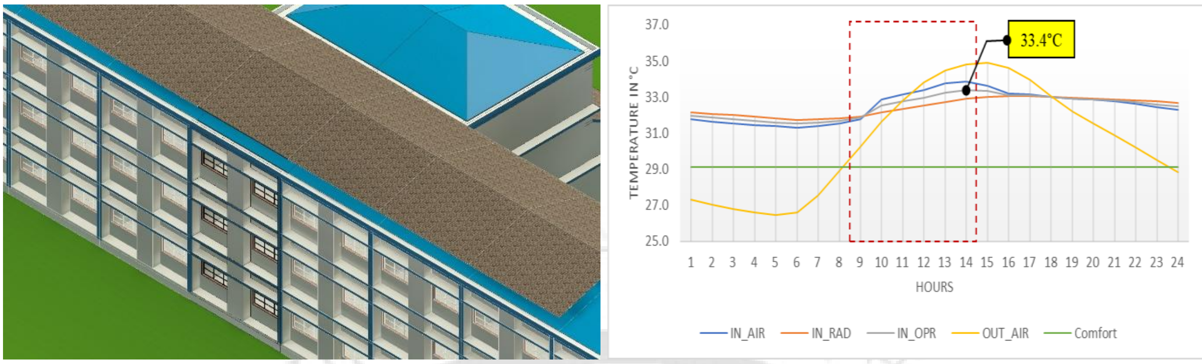

Figure 41: Operative temperature of the base-case classroom when a double roof was added.

5.4.9 Cool roof (CRoof)

The roof of the base case classroom is a tin roof that is painted blue. A roof is called a cool roof when the external surface of the roof is painted white with very high solar reflectance and emissivity. To check if this strategy is effective for the base case classroom, the existing roof was painted white with a solar reflective paint of value 0.9 for both reflectance and emissivity, and then the model was simulated again. The results show that the OT_{max} during the class hours is decreased by 0.8°C to 33.1°C from 33.9°C (as shown in Figure 42), which is considerably significant. Hence, it is **an effective** passive cooling strategy for the base case classroom.

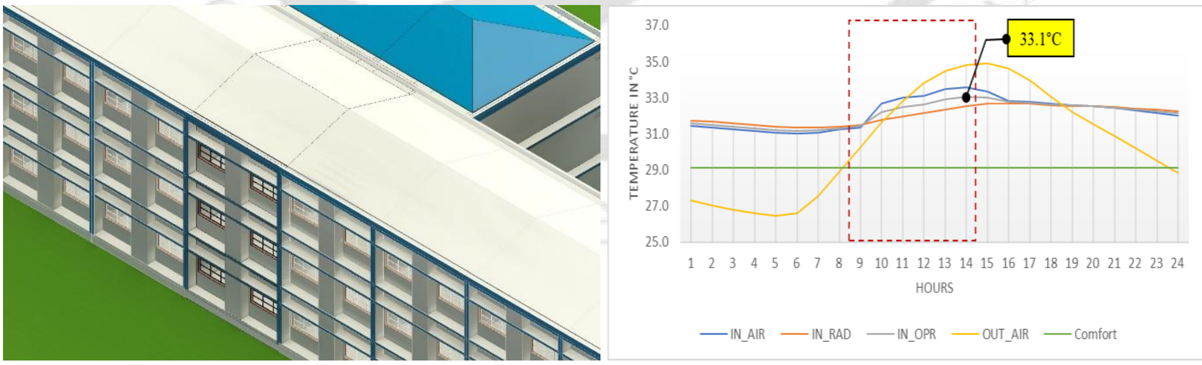

Figure 42: Operative temperature of the base-case classroom when a cool roof was applied.

5.4.10 Attic Ventilation

The attic space (between the roof and ceiling) of the existing base case classroom is not ventilated due to its enclosed roof design, which traps the heat from solar gain. Ventilating the roof may improve the thermal condition of the base case classroom. To check if this strategy is effective for the base case classroom, the existing roof was ventilated naturally, and then the model was simulated again.

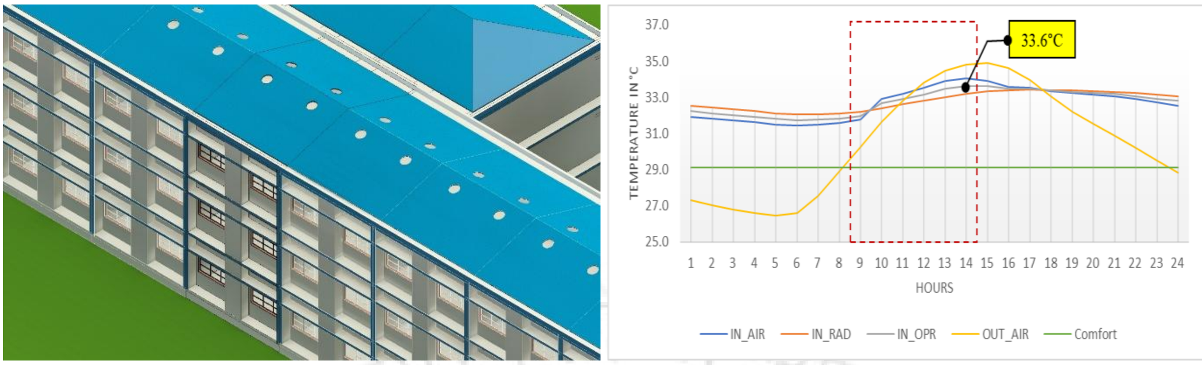

Figure 43: Operative temperature of the base-case classroom when the attic space was ventilated.

The results show that the OT_{max} during the class hours is decreased by 0.3°C to 33.6°C from 33.9°C (as shown in Figure 43), which is not very significant. Hence, it is **not an effective** passive cooling strategy for the base case classroom.

5.4.11 Cross ventilation

The existing base case classroom is ventilated with windows only on one side, and hence, it is not cross-ventilated; cross-ventilation windows are required on the opposite side of the classroom. In general, cross ventilation is suggested for tropical climates throughout the literature [148], [149]. To check if this strategy is effective for the base case classroom, an additional window was added on the opposite side of the base case classroom, and then the model was simulated again. The results show that the OT_{max} during the class hours is increased by 0.2°C to 34.1°C from 33.9°C (as shown in Figure 44). Hence, it is **not at all effective** as a passive cooling strategy for the base case classroom in this climate (as suggested by our previous study [150]).

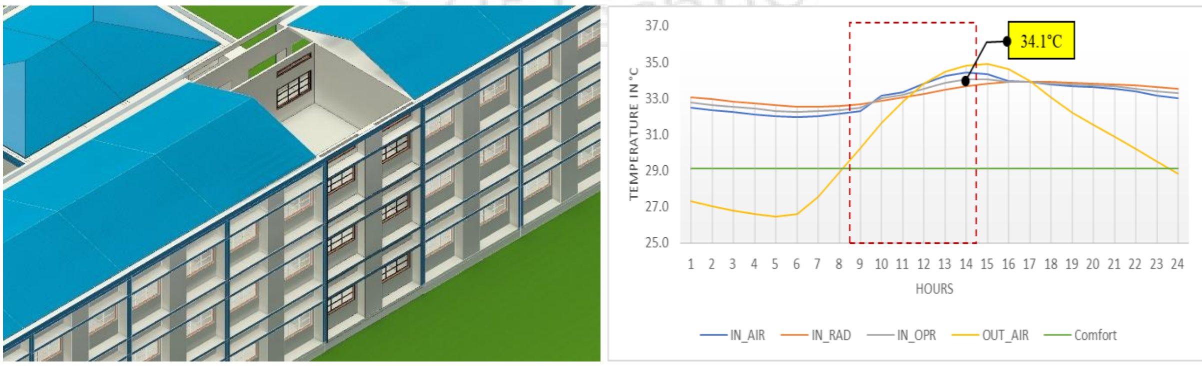

Figure 44: Operative temperature of the base-case classroom when the attic space was ventilated.

5.4.12 Nocturnal ventilation (NVent)

The existing base case classroom is ventilated only during class hours and not during off-class hours (night-time). For nocturnal ventilation, windows are required to be opened during the nighttime when the outdoor temperature is lower than the indoor temperature, and windows should be closed during the daytime when the outdoor temperature is higher than the indoor temperature. To check if this strategy is effective for the base case classroom, the operation of the windows was rescheduled from 8 pm to 6 am for the base case classroom, and then the model was simulated again. The results show that the OT_{max} during the class hours decreased by 1.0°C to 32.9°C from 33.9°C (as shown in Figure 45), which is an effective passive cooling strategy for the base classroom. Hence, it is the **most effective** conventional passive strategy for the base case classroom.

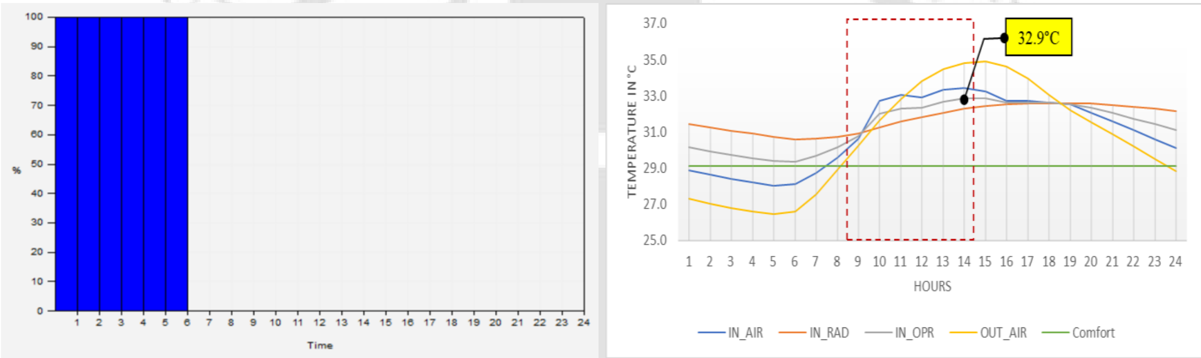

Figure 45: Operative temperature of the base-case classroom when windows were scheduled for nocturnal ventilation.

5.4.13 Phase change material (PCM)

In the existing base case classroom, only conventional passive cooling strategies are used, and no advanced systems are used. PCM is an advanced passive cooling strategy that comes in the form of a sheet where PCM is encapsulated. These materials are unique for having high melting and freezing points (21-29°C). To test if this strategy is effective for the base case classroom, all the walls and ceiling were covered with a 6mm sheet of InfiniteR29 PCM (melts above 29°C and freezes below 29°C), and then the model was simulated again. The results show that the OT_{max} during the class hours was the same (33.9°C) (as shown in Figure 46).

This indicates that this **strategy does not apply** to the existing base case classroom because the indoor temperature was never below 29°C throughout, and hence, the freezing and melting cycle was not completed.

Figure 46: 3D view of the base-case classrooms with PCM added in all walls and ceilings.

5.4.14 Earth Air Heat Exchanger (EAHE)

Similarly, EAHE is an advanced passive cooling strategy that takes advantage of the constant temperature underground throughout the year, usually the annual average temperature. To test if this strategy is effective for the base case classroom, a high-density polyethylene (HDPE) pipe of 0.1m diameter and 200m length was buried at a depth of 2m for the heat exchange between the earth, 10 air changes per hour (ACH), and then the model was simulated again. The results show that the OT_{max} during the class hours is almost the same (33.9°C) (as shown in Figure 47).

This means that this strategy is **not effective** for the existing base case classroom, because the indoor air and radiant temperature were constantly very high throughout, and hence, the supplied cool air was not sufficient for cooling the base case classroom.

Figure 47: 3D view of the base-case classrooms with EAHE installed in the classrooms.

5.4.15 Indirect evaporative cooling (IEC)

Similarly, IEC is also an advanced passive cooling strategy that takes advantage of the evaporation cooling effect of water, which can cool the maximum to the outdoor due point temperature, which is, in most cases, lower than the air temperature (as shown in Figure 48).

However, this strategy could not be simulated because of the limitation of the software, which cannot simulate the evaporation of water and its cooling effect. It also **may not apply** to this climate due to the high humidity level.

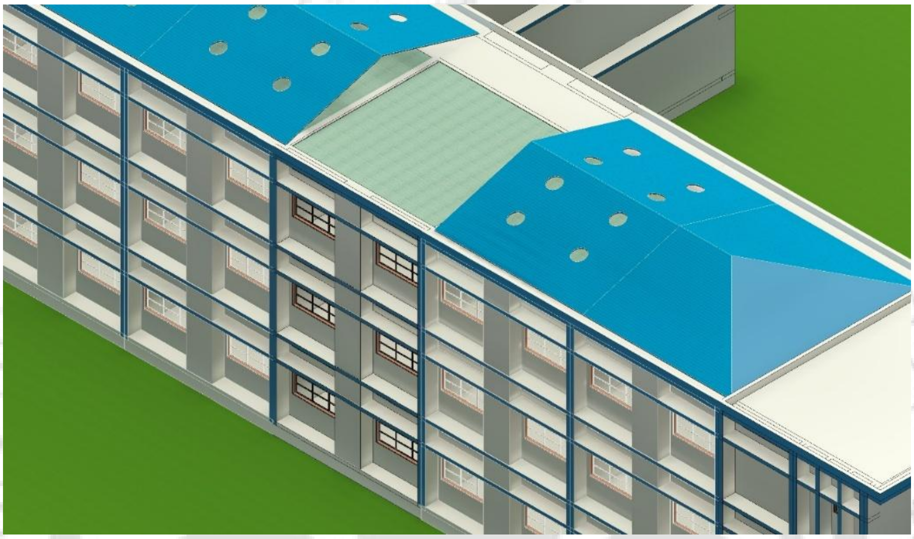

Figure 48: 3D view of the base-case classrooms with the IEC pond installed in the classrooms.

5.4.16 Combination-1: WWR + CRoof + NVent

Further, the combination of effective passive cooling strategies (PCs) was tested to see if TC can be achieved in the base case classroom for the hottest day of the year. Initially, only the conventional passive strategies that are effective and can contribute together were combined. Where WWR of 0.2, cool roof with high solar reflective paint (0.9), and nocturnal ventilation (8 pm-6 am) with exhaust fans were incorporated in the base case classroom, and then it was simulated again. The results show that the OT_{max} during the class hours has decreased by 2.0°C to 31.9°C from 33.9°C (as shown in Figure 49).

Hence, Combination-1 is collectively an effective PCs for the base classroom in this climate, but **not adequate** to achieve TC on the hottest day of the year. However, it has paved the path for implementing advanced passive strategies that otherwise were not applicable.

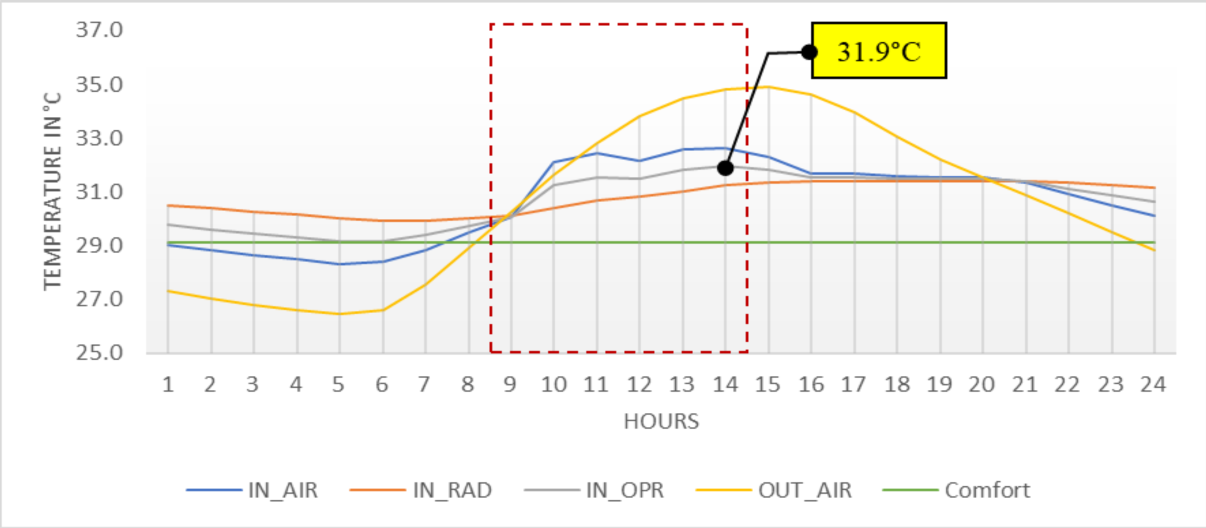

Figure 49: Operative temperature of the base-case classroom with combinations 1.

5.4.17 Combination-2: WWR + CRoof + NVent + PCM

Now, an advanced passive strategy is also used along with conventional passive strategies, which are effective and can contribute together. Where WWR, cool roof, nocturnal ventilation, and PCM (InfiniteR29-6mm sheet) were incorporated in the base case classroom, and then it was simulated again. The results show that the OT_{max} during the class hours has decreased by 3.2°C to 30.7°C from 33.9°C (as shown in Figure 50).

Hence, Combination-2 is collectively **very effective** PCs for the base classroom in this climate, but not enough to achieve TC on the hottest day of the year.

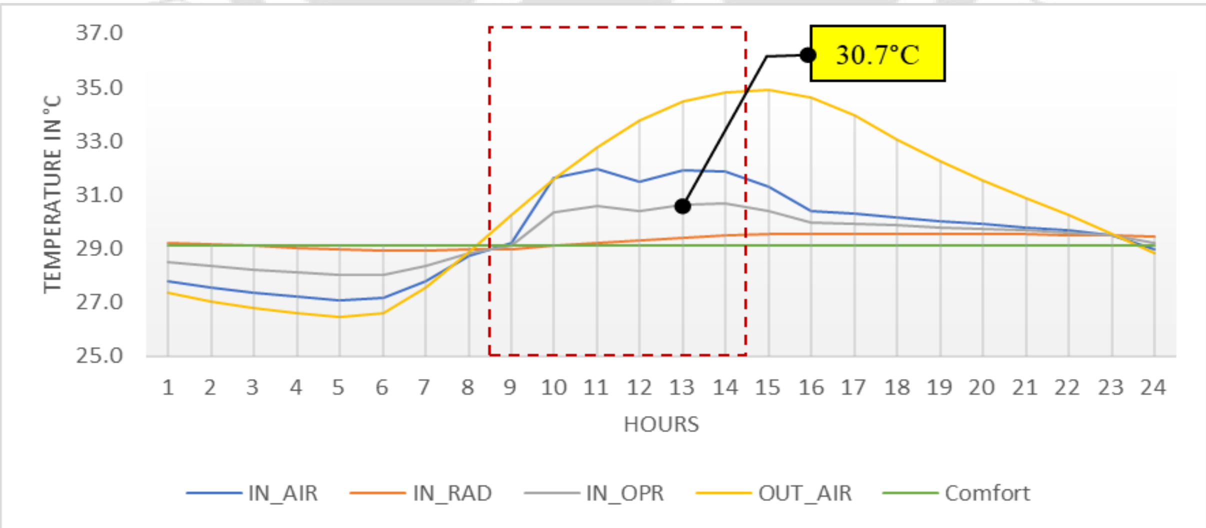

Figure 50: Operative temperature of the base-case classroom with combinations 1 and 2, respectively.

5.4.18 Combination-3: WWR + CRoof + NVent + PCM + EAHE

Another advanced passive strategy is used along with other effective passive strategies. Where WWR, cool roof, nocturnal ventilation, PCM, and EAHE (10ACH) were incorporated in the base case classroom, and then it was simulated again. The results show that the OT_{max} during the class hours for the hottest day in the top-floor classroom decreased by 4.8°C to 29.1°C from 33.9°C (as shown in Figure 51). It is important to mention that the air temperature with EAHE could be reduced further, but it was optimised to reduce up to the upper limit of TC derived in this study.

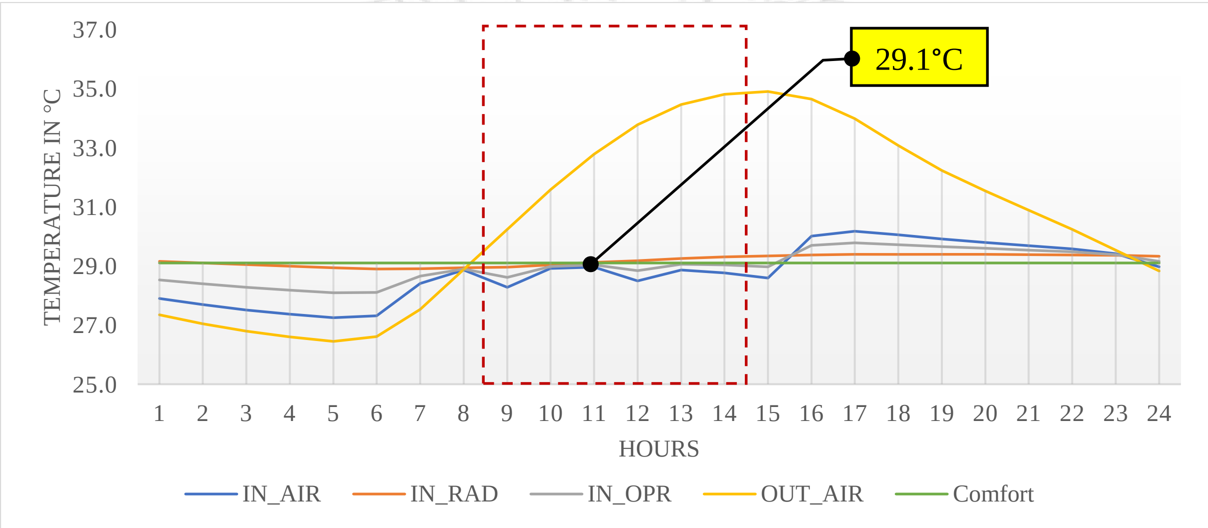

Figure 51: Operative temperature of the base-case classroom with combination-3 for the hottest day.

Hence, Combination-3 is a collectively **very effective** passive strategy for the base case classrooms in this climate and has achieved TC on the hottest day of the year. Therefore, it is assumed that TC during the summer months of a year can be achieved with these combinations of PCs.

5.4.19 Combination-4: WWR + Cool Roof + Nocturnal Ventilation + PCM + EAHE + Orient

To further improve the thermal condition for the coldest day of the year, the orientation of the base case classrooms was changed to South, and then it was simulated again. The results show that the OT_{min} at 9 am for the coldest day increased by 1.4°C to 20.1°C from 18.7°C, which is close to the lower limit of the TC, and for the rest of the class-hours it is within the lower limit of thermal comfort (as shown in Figure 52). Hence, just by shifting the class hours by 1hour (9:30 am to 3:30 pm), thermal comfort throughout the month can be achieved. It is worth mentioning that changing the orientation did not change the OT_{max} of the base-case classroom for the hottest day of the year, i.e., 29.1°C.

Hence, Combination-4 is a collectively **effective passive strategy** for both the hottest and coldest day of a year for the base case classrooms in this climate. Therefore, it is assumed that TC throughout the year can be achieved with these combinations of PCs.

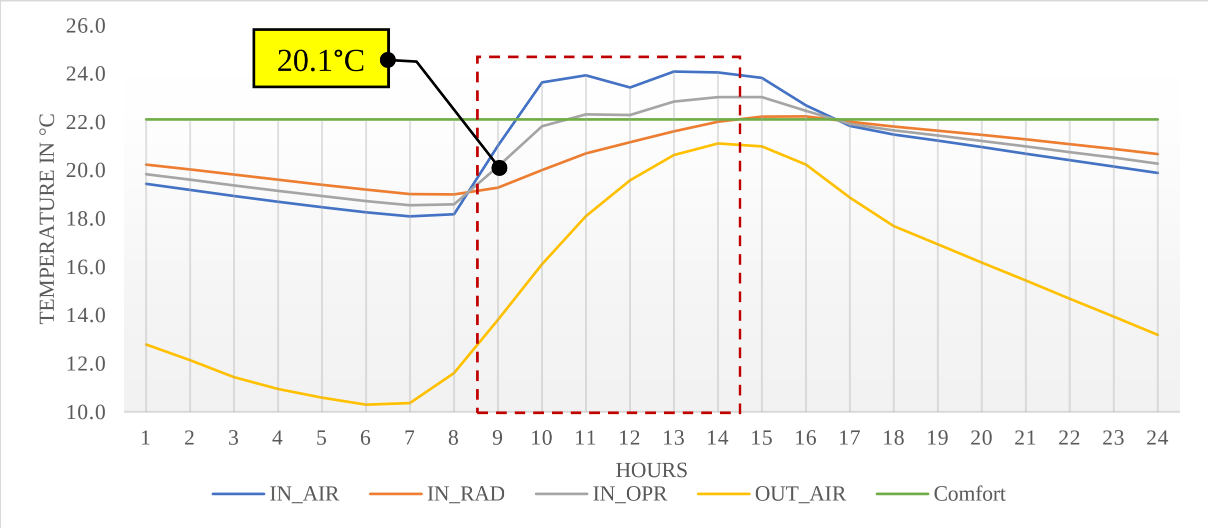

Figure 52: Operative temperature of the base case classroom with combination-3 for the coldest day.

5.5 Chapter summary and conclusions

The chapter reflects on the validity of the Model through simulations of real scenarios with the application of passive cooling strategies and assessing their effectiveness in achieving Thermal Comfort. It was identified from the literature that there are 14 widely accepted, effective PCs for warm-humid/tropical climates, and though their effectiveness seems justified through field experiments and building simulations, none have been validated in NV school classrooms. Hence, the effectiveness of these strategies is unknown and unclear in this context. Therefore, a building simulation study was conducted with the existing base case classroom, where each strategy was tested separately and in combinations, to assess its effectiveness and, in turn, determine the best PCs.

It was seen from the simulation results that, individually, the most effective passive cooling strategies for the base case classroom on the hottest day of the year were 'nocturnal ventilation', which could reduce the indoor operative temperature by 1.0°C, followed by 'cool roof', which reduced it by 0.8°C, and 'small opening ratio' reduced by 0.5°C. It is worth mentioning that advanced passive cooling strategies like 'phase change material' (PCM), and 'earth air heat exchanger' (EAHE) are individually not applicable/effective to the existing base case classroom due to very high indoor air and radiant temperature. However, when the conventional PCs were combined, the collective effectiveness was 2.0°C (reduction of the OT_{max}), and additionally, the night-time air temperature dropped below 29°C, which opened the door for the implication of the advanced system. Hence, when PCM was combined with the conventional effective strategies, there was a reduction of 3.2°C (OT_{max}), and further, when EAHE was combined, the reduction was 4.8°C. Thus, complete TC was achieved throughout the class hours on the hottest day of a year.

Further, the orientation of the base-case classrooms was changed to the South direction to improve TC during the colder period of the year, and it was seen that the OT was increased above the lower limit of thermal comfort for most of the class-hours. But did not increase the OT_{max} of the top floor classroom for the hottest day of the year.

Therefore, it was ***concluded that complete TC throughout the year for the class hours can be achieved for NV school classrooms in a warm-humid climate by adopting a complementary combination of passive cooling strategies (PCs),*** which are highly sustainable. Hence, sustainable design of school buildings that achieve good IEQ can be proposed for future construction, and existing schools can be retrofitted through the adoption of the appropriate combination of effective passive strategies.

Chapter 6

Overall Conclusions, Limitations, and Future Directions

This research thesis presents a comprehensive investigation into the Indoor Environmental Quality (IEQ) of educational buildings, focusing on naturally ventilated (NV) school classrooms in a warm-humid climate - a context that has been largely overlooked in existing literature. A systematic literature review presented in Chapter 2 revealed that while several studies have attempted to develop IEQ comfort models and weighting schemes, very few have done so in a context-specific manner. Among the limited studies that exist, the majority focus on university buildings, buildings in cold climates, or structures with mechanical or mixed-mode ventilation systems. No existing research has critically addressed NV school buildings in warm-humid or tropical climates, highlighting a significant research gap.

In response to this gap, an empirical study was carried out in Guwahati, a city representative of India's warm-humid climate zone (presented in Chapter 3). The study was conducted across four schools and 14 classrooms, engaging over 1,000 respondents across the summer and winter months between April 2023 and January 2024. Data was gathered through both instrumentation and perception-based surveys, evaluating key IEQ parameters—thermal comfort (TC), visual comfort (VC), acoustic comfort (AC), and air quality (AQ). The results showed that while classrooms were visually comfortable and acoustically neutral throughout the year, they were thermally uncomfortable during the summer period, and students were unable to perceive AQ even in the winter period, which was likely due to sensory limitations. Finally, the upper and lower limit of TC was derived as 29.1°C and 22.1°C, respectively; the lower limit of VC was derived as 48 lux; the upper limit of AC was derived as 64 dB; and the limits for AQ were invalid (for NV classrooms).

These findings confirmed the initial hypothesis that the IEQ comfort limits, derived mostly for non-tropical contexts, are not directly applicable to NV school classrooms in warm-humid regions. Therefore, defining context-specific comfort thresholds for each IEQ parameter is a critical contribution of this research. Doing so not only improves student comfort and performance but also has implications for school building design. For instance, adjusting design elements—such as reducing window size, based on these findings can lead to lower construction costs and reduced embodied energy, promoting environmental sustainability.

Further building on this, the relative importance of each IEQ parameter is determined through a context-specific weighting scheme (presented in Chapter 4). The year-long empirical study revealed seasonal variations in perceived importance. On average, TC received the highest weight (0.27), followed by AC (0.26), AQ (0.24), and VC the lowest (0.23). Furthermore, the research identified the main causes of discomfort. In the summer, thermal discomfort was mainly due to low fan speeds and inappropriate school uniforms, while AQ concerns stemmed from body odours in densely occupied classrooms. Acoustic discomfort was consistently attributed to student noise across both seasons, while VC was not found to be an issue at any point. Interestingly, the study found that discomfort perceived as poor air quality was often a result of high indoor temperatures rather than actual air pollutants. This highlights the need for a more integrated understanding of IEQ, where perceived causes of discomfort are not misattributed. It also underscores that merely assigning weights to IEQ parameters is insufficient; a detailed understanding of the root causes behind each discomfort type is essential for effective design solutions.

Finally, in Chapter 5, the research turns to passive cooling strategies (PCs), identifying 14 effective techniques for tropical climates based on literature. However, these strategies had not previously been evaluated for NV school classrooms in a warm-humid climate. To assess their effectiveness, a building simulation study was conducted using a base case classroom. Each strategy was tested individually and in various combinations to determine the best outcomes for TC. The simulations showed that among individual strategies, nocturnal ventilation reduced indoor temperatures by 1.0°C, cool roofs by 0.8°C, and small window opening ratios by 0.5°C. Advanced technologies like phase change materials (PCMs) and earth-air heat exchangers (EAHEs) were not effective on their own due to the already high indoor temperatures. However, when conventional strategies were combined, they achieved a total reduction of 2.0°C in peak temperatures. This reduction was enough to make conditions suitable for integrating PCM and EAHE, which then led to a 3.2°C and 4.8°C reduction, respectively, sufficient to ensure TC throughout class hours on the hottest day of the year. The study also explored adjusting classroom orientation for better winter performance. Changing orientation to face south improved indoor conditions on the coldest day, raising the minimum operative temperature by 3.7°C on the ground floor, without adversely affecting summer performance on upper floors.

Ultimately, this research concludes that full-year TC in NV school classrooms in a warm-humid climate can be achieved using a strategic combination of passive cooling techniques, without the need for active systems like air conditioning. This provides a viable pathway toward sustainable, cost-effective, and resilient school buildings. The findings have practical applications for both new school constructions and retrofits, offering data-driven guidelines for future building design.

6.1. Assumptions and limitations

To ensure rigor in methodology, practices commonly used in empirical studies and ascribed by standards were applied. These assumptions, however, have certain limitations, discussed as follows:

- Only the major four IEQ parameters – TC, VC, AC, and AQ, were considered as they have the most influence on the occupant performance and productivity, even though many parameters can affect the overall comfort of a student in school classrooms.
- The TC level of the students was measured with operative temperature in (°C) to enable fair comparison with the existing literature and the standards, as most have considered operative temperature, but it does not consider humidity level, which distorts the perception of comfort in warm-humid climate.
- The VC level of the students was measured through light level in lux, as is commonly practiced in literature and building standards, and does not consider a cumulative value encompassing other factors, like colour temperature, glare level, etc., which may cause discomfort.
- Similarly, the AC level was measured with sound level in dBA, which does not encompass other factors, like sound frequency, echo, etc.
- Likewise, the AQ level was also measured with a single parameter (CO_2 level), which does not encompass other factors, like PM level, CO level, etc.
- All the IEQ parameters were measured with instruments in the centre of the classroom, assuming the measurements at the centre would be closer to the average of the classroom. Due to the limited number of instruments and human resources (members in the team).

The major limitation of the study is that it was conducted in a specific suburb of India, Guwahati, classified under warm-humid climate by national codes (NBC 2016) as an exemplar for the region. However, there may be highly nuanced settings for each city/town with respect to micro-climatic conditions, socio-economic abilities, and cultural heritage that influence built form. Therefore, while the results can be generalized for the broader context of (i) climate – warm humid, (ii) typology – school classroom, (iii) type of ventilation - natural ventilation, it may require nuanced considerations for similar but more specific contexts around the world. The other limitations that emerged in the study are discussed as follows :

- Except for the TC model, all other models, though valid, are comparatively less reliable due to a low R^2 value. This may be associated with the participants' ability to perceive the other parameters, namely, visual, acoustic, and air quality, or with their maturity in expressing their perception.
- The overall derived IEQ Comfort Model can only be used to assess the IEQ condition of a classroom and not other spaces in the school, such as labs, offices, and auditoriums, and requires some tweaking while the principles remain the same.
- The Model can be directly applied when the individual measurement of each IEQ parameter is within the comfort limits set in this study.
- The performance of effective passive strategies proposed for achieving TC was not simulated for the whole year, but only for the extreme cases, i.e., the hottest and coldest days of a year, to seek validation, assuming that if it works for these days, it should work for the less severe days.
- Even though the noise level in the classrooms was a major concern, the study did not propose any strategies due to a lack of simulation software that could effectively measure the acoustic environment.

6.2. Future directions

Future work entails real-world implementation of the proposed passive strategies to validate their effectiveness in actual school environments, and in turn, validate the Model, and further refine it to address the noted limitations above to create a robust design support.

A promising future direction of research of this work could be the extension of the model to cover the design of an entire school beyond its classrooms and other built spaces, to the extent of design of all facilities and overall site master planning for occupant comfort, while considering the sun path, orientation, vernacular envelope design, local material, and other sustainable design considerations. Other design considerations to be integrated are with respect to acoustic and visual comfort, such as, provision of acoustic padding on walls or movable/portable acoustic panels that can be retrofitted as and when required as per type of use; using low noise devices; provision of task lighting on boards and tables that can be controlled by each user to reduce glare from diffused light and allow customisation of visual comfort; and using exhausts and passive ventilators to mediate air flow. Further, other IEQ parameters may also be encompassed to develop a more comprehensive multi-factor IEQ Model.

Participatory methods, as employed in this research, are pivotal not only to understand and capture occupant data, but also to generate responsive knowledge that can sustain long-term. Thus, in light of the sustainable developmental agenda of 2030, a social innovation design approach may prove to be a promising means to ensure engagement of all stakeholders and representation of their cultural and social values towards attaining quality education. Additionally, it is advised to look at a school as more than just a built environment and its IEQ performance as a mere response to the built elements, but as a space that moulds resilient future citizens of a nation. A school today is a cyber-physical-social system and must inculcate the practices of assuring physical and mental comfort. Some pragmatic solutions include using natural fibres for school uniforms for thermal comfort, be it cotton in summer or wool in winter; changing class timings depending on the season, and taking breaks in between classes to go for a stroll in calm, are already in practice. Designed elements of the built-environment that can enhance learning, such as having green spaces for soothing discomfort due to noise and visual overstimulation, as well as breathing in fresh air, and having semi-formal socialising, are being incorporated. Other daily routines, for overall IEQ and specifically cooling of building through spraying water on roofs, opening and closing windows at certain times of the day for night cooling, using fans, lights, and active cooling as and when needed, can be better supported by integrating technology and using data-driven Building Management Systems, especially for naturally-ventilated or hybrid-type buildings.

All such solutions must further be enabled through social practices, such as ‘mindfulness’ and ‘yoga’ that evoke positive behavioral and psychological changes and help mitigate discomfort and foster ‘comfort’ leading to creativity, self-expression, and good mental health – the key aspiration of a good education. Future studies can explore the intricate relationship between the physical and psychological concepts of ‘comfort’.

6.3. Research outcomes and impact

This thesis proposes a **contextually-appropriate IEQ Assessment (comfort) Model**, rigorously developed through the combination of measured environmental data and empirically derived comfort limits with a weighting scheme, that challenges the generic recommendations by national and international building codes. It further reflects on the validity of the Model through simulations of real scenarios with application of passive cooling strategies and their combinations, and demonstrates that IEQ and occupant comfort in NV school classrooms in warm-humid climates are achievable. It is a ready recommendation of context-specific IEQ inputs during the design and retrofit phases, and aspires to prompt regulatory bodies to update or supplement existing design codes with region-specific IEQ criteria derived from this research.

The developed research outcomes will directly support architects, design teams, and facilities managers in objectively assessing and comparing classrooms for occupant comfort during early-stage planning, renovation prioritization, or post-occupancy review, and accordingly help design interventions and allocate resources to improve occupant comfort. And behaves as a guide to architects, designers, and decision-makers towards prioritising thermal and acoustic conditions, over visual and air quality, and applying climate-appropriate passive strategies, such as nocturnal ventilation, cool roofs, reduced window-wall ratios, and use of advanced systems—for both new construction and retrofits. This results in tailored environments that respond to the actual comfort preferences and adaptation levels of students in similar climatic conditions.

This research also highlights the importance of occupant comfort and educates school authorities, policymakers, and other key stakeholders on the benefits of improved IEQ, which may promote higher standards in school infrastructure, resulting in comfortable and more productive learning-teaching experiences. Additionally, the research also impacts the overall sustainability of the built environment by reducing the need for energy-intensive active cooling strategies, lowering operating costs and carbon emissions, and enhancing learning.

A school is an integral extension of society and is responsible for shaping the future citizens of the society and nation. It is society's onus and should be our goal to improve education, its spaces, and positive practices to achieve lasting social impact and create value.

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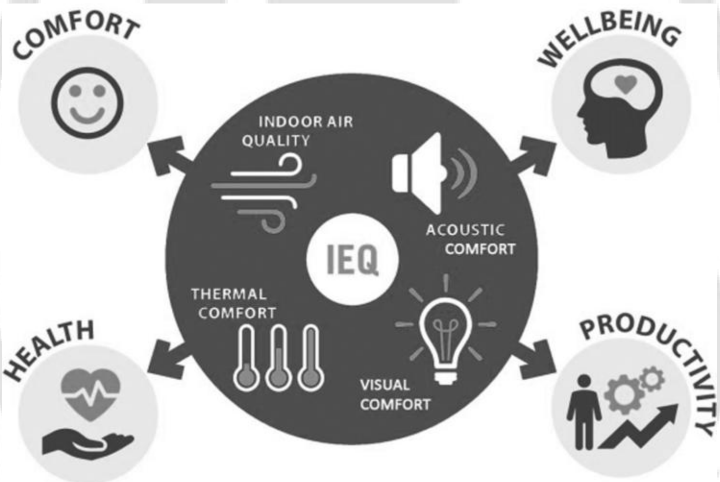
Annexure 1

Questionnaire Survey of Indoor Environmental Quality (IEQ) of Educational Buildings

IEQ refers to the quality of a building's indoor environment in relation to the health, wellbeing, comfort, and productivity of those who occupy the space. Educational buildings are one of the most important facilities in our community, where children spend more than 25% of their time. IEQ of an educational building is very critical, especially for young children as they are the most vulnerable population to the adverse effects of poor IEQ. Good IEQ of the classroom contributes positively to the quality of learning by creating an environment in which students feel more alert and pay attention to the information presented in the lecture. Many studies have shown that good IEQ in the classroom plays an important role in improving performance, health, wellbeing, and work efficiency. Also improves learning results and lowers absenteeism, which in turn increases workplace productivity and test scores in schools. There are four basic parameters of IEQ namely: thermal, visual, acoustic, and air quality. These four parameters are evaluated by temperature, light level, noise level, and Co2 level, respectively.



Aim of the study:

The study aims to understand the student's perception and satisfaction of the indoor environmental of their classroom, based on their experience during working days of their class hours. This will be finally put together to develope an IEQ assessment tool that will be beneficial for predicting IEQ in the conceptual design stage of the educational building.

General information:

Name: .... Class: ....

Age: .... Gender: ....

Time: Morning / Afternoon Day:....................................... Date:........................

1. Thermal comfort at the moment

Temperature is the measure of the hotness or coldness of an object or air. It is measured with a device called 'Thermometer'. The common unit in which temperature is measured is Celsius (°C). How comfortable you feel in the temperature is thermal comfort.

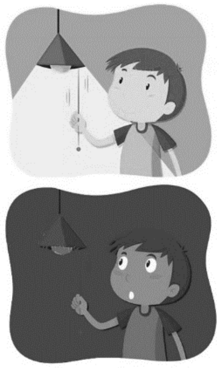
Q1. How do you feel the **air temperature** of the classroom **at the moment**?

Cold	Cool	Slightly Cool	Neutral	Slightly Warm	Warm	Hot
☐	☐	☐	☐	☐	☐	☐

Q2. How satisfied are you with the **air temperature** of the classroom **at the moment**?

Very Satisfied	Satisfied	Somewhat Satisfied	Neutral	Somewhat Dissatisfied	Dissatisfied	Very Dissatisfied
☐	☐	☐	☐	☐	☐	☐

2. Visual comfort at the moment



Light is the brightness that comes from sun, fire, or electric device that allows you to see things. It is measured with a device called 'Photometer'. The common unit in which light is measured is Lux. How comfortable you feel in the light level is visual comfort.

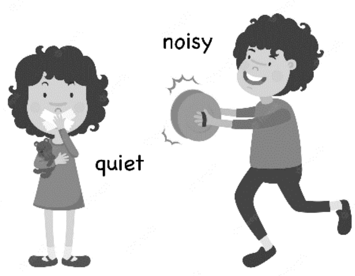
Q1. How do you feel the **light level** of the classroom **at the moment**?

Very Bright	Bright	Slightly Bright	Neutral	Slightly Dark	Dark	Very Dark
☐	☐	☐	☐	☐	☐	☐

Q2. How satisfied are you with the **light level** of the classroom **at the moment**?

Very Satisfied	Satisfied	Somewhat Satisfied	Neutral	Somewhat Dissatisfied	Dissatisfied	Very Dissatisfied
☐	☐	☐	☐	☐	☐	☐

3. Acoustic comfort at the moment



Anything that can be heard is sound and unwanted or unpleasant sound is called noise. It is measured with a device called 'Decibel meter'. The common unit in which sound is measured is decibel (dB). How comfortable you feel in the noise level is acoustic comfort.

Q1. How do you feel the **noise level** of the classroom **at the moment**?

Very Silent	Silent	Slightly Silent	Neutral	Slightly Noisy	Noisy	Very Noisy
☐	☐	☐	☐	☐	☐	☐

Q2. How satisfied are you with the **noise level** of the classroom **at the moment**?

Very Satisfied	Satisfied	Somewhat Satisfied	Neutral	Somewhat Dissatisfied	Dissatisfied	Very Dissatisfied
☐	☐	☐	☐	☐	☐	☐

4. Air Quality at the moment

Air quality is the composition of the air in terms of how much pollution it contains. It is measured with a device called 'CO2 meter'. The common unit in which air pollution is measured is carbon dioxide (CO2).

Q1. How do you feel the **air quality/freshness** of air of the classroom **at the moment**?

Very Fresh	Fresh	Slightly Fresh	Neutral	Slightly Stale	Stale	Very Stale
☐	☐	☐	☐	☐	☐	☐

Q2. How satisfied are you with the **air quality/freshness** of the classroom **at the moment**?

Very Satisfied	Satisfied	Somewhat Satisfied	Neutral	Somewhat Dissatisfied	Dissatisfied	Very Dissatisfied
☐	☐	☐	☐	☐	☐	☐

5. Overall Indoor Environment Quality (IEQ) at the moment

Note: Overall IEQ includes – thermal, visual, acoustic comfort, and air quality.

Q1. How satisfied are you with the **overall IEQ** of the classroom **at the moment**?

Very Satisfied	Satisfied	Somewhat Satisfied	Neutral	Somewhat Dissatisfied	Dissatisfied	Very Dissatisfied
☐	☐	☐	☐	☐	☐	☐

6. Importance of each IEQ parameters at the moment

Note: IEQ parameter which causes more discomfort is more important.

Q1. How important is **thermal comfort** of the classroom at the moment in comparison to **visual comfort**, **acoustic comfort**, and **air quality**?

Least Important	Less Important	Little Less Important	Equally Important	Little More Important	More Important	Most Important
☐	☐	☐	☐	☐	☐	☐

Q2. How important is **visual comfort** of the classroom at the moment in comparison to **thermal comfort**, **acoustic comfort**, and **air quality**?

Least Important	Less Important	Little Less Important	Equally Important	Little More Important	More Important	Most Important
☐	☐	☐	☐	☐	☐	☐

Q3. How important is **acoustic comfort** of the classroom at the moment in comparison to **thermal comfort**, **visual comfort**, and **air quality**?

Least Important	Less Important	Little Less Important	Equally Important	Little More Important	More Important	Most Important
☐	☐	☐	☐	☐	☐	☐

Q4. How important is **air quality** of the classroom at the moment in comparison to **thermal comfort**, **visual comfort**, and **acoustic comfort**?

Least Important	Less Important	Little Less Important	Equally Important	Little More Important	More Important	Most Important
☐	☐	☐	☐	☐	☐	☐

7. Causes for dissatisfaction at the moment

Note: You can select one or more causes for discomfort.

Q1. What are the causes for **thermal discomfort (temperature)** at the moment?

(1) No causes for discomfort (temperature is satisfactory) in the classroom.

(2) Cold wind from outside coming through the window in the classroom.
(3) Lack of natural ventilation in the classroom.
(4) Direct sunlight is heating my space in the classroom.
(5) Fan air speed is too high in the classroom.
(6) School dress is not appropriate for summer.
(7) Others: ____

Q2. What are the causes for **visual discomfort (light level)** at the moment?

(1) No causes for discomfort (light level is satisfactory) in the classroom.
(2) Not enough daylight is coming through the window in the classroom.
(3) Too much daylight is coming through the window in the classroom.
(4) Direct sunlight is causing glare in my space in the classroom.
(5) Not enough artificial electric light in the classroom.
(6) Flickering artificial electric light in the classroom.
(7) Others: ____

Q3. What are the causes for **acoustic discomfort (noise level)** at the moment?

(1) No causes for discomfort (sound level is satisfactory) in the classroom.
(2) Outdoor traffic noise is coming through the window in the classroom.
(3) Outdoor construction noise is coming through the window in the classroom.
(4) Noise caused by students themselves in the classroom.
(5) Noise from internal equipment, fan, light, etc. in the classroom.
(6) Echo sound of the teacher or students in the classroom.
(7) Others: ____

Q4. What are the causes for **poor air quality (freshness)** at the moment?

(1) No causes for discomfort (air quality/freshness is satisfactory) in the classroom.
(2) Outdoor traffic pollution/smell is coming through the window in the classroom.
(3) Outdoor construction dust/smell is coming through the window in the classroom.
(4) Lack of natural ventilation (stale air) in the classroom.
(5) Smell of students themselves in the classroom.
(6) Pollution/Smell from internal equipment, paint, furniture, etc. in the classroom.

Others: ____

Thank you for your participation, you have helped us a lot!
Please give your feedback about the survey

Q1. Was the survey easy to fill? Was there anything confusing (question, scale, etc.)?

Ans.____

____

Q2. Is there anything else which is causing discomfort in the classroom?

Ans.____

____

Q3. Can you suggest few solutions for the existing problems in the classroom?

Ans.____

____

25 Jun 2025

DECLARATION

Institute Human Ethics Clearance

We, the undersigned investigators of the study titled, "*Supporting Design for Occupant Comfort: Development of an Indoor Environment Quality (IEQ) Assessment Model for Naturally-ventilated School Classrooms in Warm-Humid Sub-tropical Climate*", from the Dept of Design, Indian Institute of Technology Guwahati (IITG), India, hereby declare that the Questionnaire Surveys conducted with human subjects were conducted with utmost regard and in accordance with ICMR guidelines.

Kind regards,

Shakuntala Acharya, PI
PhD Advisor & Assistant Professor,
Department of Design,
IIT Guwahati, ASSAM

Abdul Mohsin Ali, Co-PI
PhD Scholar
Department of Design,
IIT Guwahati, ASSAM

THE STUDY PROTOCOL:

1. **Questionnaire Survey preparation:** Questionnaire on "Perception and Satisfaction with IEQ parameters" is generated from Building Standards, codes, and other seminal studies in literature, as is best practice.

2. **Expert Validation and pilot:** The same is evaluated for its appropriateness by expert Educationists and Architects, and further, its usability was tested through a pilot test to assess the comprehensibility of the questions asked and the scale provided for qualitative assessment.

3. **Iteration of Questionnaire and idenitification of Target audience:** The Questionnaire was improved in consistency of the content, and due to the nature of the questions, it was advised by the Educationists that the Target group should be English-medium Students of Class 9 and above, with preliminary knowledge of science and the concepts of temperature, humidity, air flow, acoustics and optics or light, to be able to comprehend the questions (inclusion criteria). The final questionnaire was formulated for students in classes 9 and above.

4. **Permission/Consent:** Permission was sought from the Competent Authority, i.e., Principals of 4 English-medium High schools across Guwahati city. Upon explaining the purpose and process of the study to be undertaken, the questionnaire was shared, and written consent was received. **[Annexure A]**

5. **Non-Disclosure Agreement:** An NDA was signed that explicitly clarifies that all information collected during the study will be used solely for academic purposes and will not be shared with anyone else under any circumstances. Disclosure permissions have been taken, where the school names need to be acknowledged, and appropriate use of the accessed data is stated by the investigators. **[Annexure A]**

6. **Consent from individual participants:** The Competent Authority communicated with participants and parents of the participants (minors, below 18 years), informing them of the study, which was voluntary in nature, and informed Investigators of appropriate dates to conduct the study.

7. **Data Collection & Analysis:** Safety measures have been in place to protect the privacy and confidentiality of research participants and/or research teams in the field, and no sensitive data has been collected. Basic demographic data (name, age, class, and gender) was collected and further encoded in the format [School Name/Class Sec/Floor/Month/ Time of the Day/Session No.] for eg: [KVS/12A/GF/APR/Aft/2] to maintain confidentiality of respondents and no other private data was used for analysis. Only responses were input for further analysis and corroboration with on-site measurement. **[Annexure B]**

8. **Data Security, Dissemination, and Publication:** The investigators have taken appropriate measures for data security and confidentiality of information and appropriate use of the

accessed data. Appropriate acknowledgements have been stated, as agreed upon by due particiapting schools. **[Annexure C 1-4]**

9. **Post-research interventions:** Investigators have made every effort to provide post-research interventions, the use of findings for sustainability of public health action, by providing design strategies and material recommendations for passive cooling as an actionable result.

All the above information is true to the best of our knowledge.

Shakuntala Acharya, PI

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IIT Guwahati, ASSAM

Abdul Mohsin Ali, Co-PI

PhD Scholar

Department of Design,

IIT Guwahati, ASSAM

Annexure 2

Empirical study of a Classroom of a School for IEQ Assessment

School name: …….

Class and section: ………………………………………

Note: Please measure the desk level where the instruments are placed _______________

- **Classroom**

Location: ____________________________

Orientation: __________________________

Size: ________________________________

Full capacity: _________________________

- **Window**

Number: _____________________________

Type: _______________________________

Size: ________________________________

Material: ____________________________

- **Ventilator**

Number: _____________________________

Type: _______________________________

Size: ________________________________

Material: ____________________________

- **Door**

Number: _____________________________

Type: _______________________________

Size: ________________________________

Material: ____________________________

- **Wall**

Core material: _______________________

Finish material: ______________________

Colour In/Out: _______________________

Thickness: ___________________________

- **Roof/Floor**

Core material: _______________________

Finish material: ______________________

Colour In/Out: _______________________

Thickness: ___________________________

- **Shading device**

Type: ________________________________

Size: ________________________________

Colour: ______________________________

- **Light**

Type: ________________________________

Number: _____________________________

- **Fan**

Type: ________________________________

Number: _____________________________

- **Other equipment's**

Name: _______________________________

Number: _____________________________

- **Physical Context**

Source of noise: ______________________

Source of pollutant: ___________________

Distance from road: ___________________

Road size: ___________________________

Traffic intensity: ______________________

Vegetation: __________________________

Waterbody: __________________________

Building: ____________________________

Others: ______________________________

- **Weather**

Cloud cover: _________________________

Rain: ________________________________

Sun: _________________________________

Wind: ________________________________

On-Site Measurement and Observation for IEQ of a Classroom

Date (date/month/year)		
Time (hour : minute)		
No. of students		
No. of teachers/researchers		
	Indoor Environment	
Air temperature (^{0}C)		
Relative Humidity (%)		
Wind speed (m/s)		
Noise level (dB)		
Radiant temp. (^{0}C)		
Light level (lux)		
CO_2 level (ppm)		
	Outdoor Environment	
Air temperature (^{0}C)		
Relative Humidity (%)		
Wind speed (m/s)		
Noise level (dB)		
Radiant temp. (^{0}C)		
Light level (lux)		
CO_2 level (ppm)		
	Adaptive Measure	
Window open area (m2)		
Door open area (m2)		
No. of light on (number)		
No. of fan on (number)		
	Physical Activity	
Previous activity (words)		
Present activity (words)		
Dress Code	**Dress Code**	
Boys' head cover (words)		
Boys' body cover (words)		
Boys' bottom cover (words)		
Boys' leg cover (words)		
Girls' head cover (words)		
Girls' body cover (words)		
Girls' bottom cover (words)		
Girls' leg cover (words)		

Annexure 3 (a)

Hypothesis Testing of Comfort Limits

H1: The IEQ parameters comfort limits of NV school classrooms in humid sub-tropical climates are significantly different from the recommended by national and international standard, and existing literature in different contexts.

1. The **thermal comfort limit** of NV school classrooms in humid sub-tropical climate is significantly different from recommended, and existing.
2. The **visual comfort limit** of NV school classrooms in humid sub-tropical climate is significantly different from recommended, and existing.
3. The **acoustic comfort limit** of NV school classrooms in humid sub-tropical climate is significantly different from recommended, and existing.
4. The **air quality comfort limit** of NV school classrooms in humid sub-tropical climate is significantly different from recommended, and existing.

Thermal comfort limits

$\boldsymbol{H_1}$**:** The thermal comfort upper limit of NV school classrooms in humid sub-tropical climate is significantly different from the recommended (i.e., $\boldsymbol{H_1}$**:** $TC_{NV} \neq TC_{AC}$).

$\boldsymbol{H_0}$: The thermal comfort upper limit of NV school classrooms in humid sub-tropical climate is not significantly different from the recommended (i.e., $\boldsymbol{H_0}$**:** $TC_{NV} = TC_{AC}$).

Now, to test the null hypothesis ($\boldsymbol{H_0}$) against the alternative hypothesis ($\boldsymbol{H_1}$), a two tailed Z-test (parametric test) for variance can be conducted for 5% level of significance.

$$\chi_c^2 = \frac{(n-1)S_1^2}{S_0^2}$$

Where,

χ_c^2 = Chi-square critical value

S_1 = proposed value for thermal comfort upper limit (average)

S_0 = recommended value for thermal comfort upper limit (average)

n = no. of observation

Then,

$$\chi_c^2 = \frac{(45-1)\times 29.1^2}{31.4^2}$$

$$\chi_c^2 = 37.8$$

Then, the Z-test critical value (Z_c) would be as follows:

$$Z_c = \sqrt{2\chi_c^2} - \sqrt{2n-1}$$

$$Z_c = \sqrt{2 \times 37.8} - \sqrt{2 \times 45 - 1}$$

$$Z_c = -0.74$$

The critical value for two tailed test at 5% level of significance are −1.96 and +1.96 (obtained from t-distribution table). Since, Z_c is greater than -1.96, the $\boldsymbol{H_0}$ cannot be rejected and hence can be concluded that there is **no significant difference**.

Visual comfort limits

$\boldsymbol{H_1}$**:** The visual comfort lower limit of NV school classrooms in humid sub-tropical climate is significantly different from the recommended (i.e., $\boldsymbol{H_1}$**:** $VC_{NV} \neq VC_{AC}$).

$\boldsymbol{H_0}$: The visual comfort lower limit of NV school classrooms in humid sub-tropical climate is not significantly different from the recommended (i.e., $\boldsymbol{H_0}$**:** $VC_{NV} = VC_{AC}$).

Now, to test the null hypothesis ($\boldsymbol{H_0}$) against the alternative hypothesis ($\boldsymbol{H_1}$), a two tailed Z-test (parametric test) for variance can be conducted for 5% level of significance.

$$\chi_c^2 = \frac{(n-1)S_1^2}{S_0^2}$$

Where,

χ_c^2 = Chi-square critical value

S_1 = proposed value for visual comfort lower limit (average)

S_0 = recommended value for visual comfort lower limit (average)

n = no. of observation

Then,

$$\chi_c^2 = \frac{(45-1) \times 48^2}{267^2}$$

$$\chi_c^2 = 1.42$$

Then, the Z-test critical value (Z_c) would be as follows:

$$Z_c = \sqrt{2\chi_c^2} - \sqrt{2n-1}$$

$$Z_c = \sqrt{2 \times 1.42} - \sqrt{2 \times 45 - 1}$$

$$Z_c = -7.75$$

The critical value for two tailed test at 5% level of significance are −1.96 and +1.96 (obtained from t-distribution table). Since, Z_c is smaller than −1.96, the $\boldsymbol{H_0}$ can be rejected and hence can be concluded that there is a **significant difference**.

Acoustic comfort limits

***H*₁:** The acoustic comfort upper limit of NV school classrooms in humid sub-tropical climate is significantly different from the recommended (i.e., $\boldsymbol{H_1}$: $AC_{NV} \neq AC_{AC}$).

$\boldsymbol{H_0}$: The acoustic comfort upper limit of NV school classrooms in humid sub-tropical climate is not significantly different from the recommended (i.e., $\boldsymbol{H_0}$: $AC_{NV} = AC_{AC}$).

Now, to test the null hypothesis ($\boldsymbol{H_0}$) against the alternative hypothesis ($\boldsymbol{H_1}$), a two tailed Z-test (parametric test) for variance can be conducted for 5% level of significance.

$$\chi_c^2 = \frac{(n-1)S_1^2}{S_0^2}$$

Where,

χ_c^2 = Chi-square critical value

S_1 = proposed value for acoustic comfort upper limit (average)

S_0 = recommended value for acoustic comfort upper limit (average)

n = no. of observation

Then,

$$\chi_c^2 = \frac{(45-1)\times 64^2}{45^2}$$

$$\chi_c^2 = 89.00$$

Then, the Z-test critical value (Z_c) would be as follows:

$$Z_c = \sqrt{2\chi_c^2} - \sqrt{2n-1}$$

$$Z_c = \sqrt{2\times 89.0} - \sqrt{2\times 45-1}$$

$$Z_c = 3.91$$

The critical value for two tailed test at 5% level of significance are −1.96 and +1.96 (obtained from t-distribution table). Since, Z_c is greater than +1.96, the $\boldsymbol{H_0}$ can be rejected and hence can be concluded that there is **a significant difference**.

Therefore, **H1:** The IEQ parameters comfort limits of NV school classrooms in humid sub-tropical climates are significantly different from the recommended by national and international standard, and existing literature in different contexts is **partially-true for thermal and acoustic comfort**, **completely-true for visual comfort;** and could not be tested for air quality.

Hypothesis Testing of Weighting Scheme

H2: The IEQ parameters weighting scheme of NV school classrooms in humid sub-tropical climates is significantly different from the existing literature in different contexts.

1. The **thermal weight** of NV school classrooms in humid sub-tropical climate is significantly different from the existing literature.
2. The **visual weight** of NV school classrooms in humid sub-tropical climate is significantly different from the existing literature.
3. The **acoustic weight** of NV school classrooms in humid sub-tropical climate is significantly different from the existing literature.
4. The **air quality weight** of NV school classrooms in humid sub-tropical climate is significantly different from the existing literature.

Thermal weight

$\boldsymbol{H_1}$**:** The thermal weight of NV school classrooms in humid sub-tropical climate is significantly different from existing (i.e., $\boldsymbol{H_1}$**:** $TW_{NV} \neq TW_{AC}$).

$\boldsymbol{H_0}$: The thermal weight of NV school classrooms in humid sub-tropical climate is not significantly different from existing (i.e., $\boldsymbol{H_0}$**:** $TW_{NV} = TW_{AC}$).

Now, to test the null hypothesis ($\boldsymbol{H_0}$) against the alternative hypothesis ($\boldsymbol{H_1}$), a two tailed Z-test (parametric test) for mean can be conducted for 5% level of significance.

$$Z_c = \frac{\bar{x} - \mu_0}{\sigma/\sqrt{n}}$$

Where,

Z_c = Z-test critical value

$\bar{x}$ = proposed weight for thermal comfort

σ = sample standard deviation

μ_0 = existing weight for thermal comfort

n = no. of observation

Then,

$$Z_c = \frac{0.27 - 0.30}{0.04/\sqrt{45}}$$

$$Z_c = -5.03$$

The critical value for two tailed test at 5% level of significance are −1.96 and +1.96 (obtained from t-distribution table). Since, Z_c is smaller than -1.96, the $\boldsymbol{H_0}$ can be rejected and hence can be concluded that there is a **significant difference**.

Visual weight

***H*₁:** The visual weight of NV school classrooms in humid sub-tropical climate is significantly different from existing (i.e., $\boldsymbol{H_1}$**:** $VW_{NV} \neq VW_{AC}$).

$\boldsymbol{H_0}$: The visual weight of NV school classrooms in humid sub-tropical climate is not significantly different from existing (i.e., $\boldsymbol{H_0}$**:** $VW_{NV} = VW_{AC}$).

Now, to test the null hypothesis ($\boldsymbol{H_0}$) against the alternative hypothesis ($\boldsymbol{H_1}$), a two tailed Z-test (parametric test) for mean can be conducted for 5% level of significance.

$$Z_c = \frac{\bar{x} - \mu_0}{\sigma/\sqrt{n}}$$

Where,

Z_c = Z-test critical value

$\bar{x}$ = proposed weight for visual comfort

σ = sample standard deviation

μ_0 = existing weight for visual comfort

n = no. of observation

Then,

$$Z_c = \frac{0.23 - 0.21}{0.02/\sqrt{45}}$$

$$Z_c = 6.71$$

The critical value for two tailed test at 5% level of significance are −1.96 and +1.96 (obtained from t-distribution table). Since, Z_c is greater than +1.96, the $\boldsymbol{H_0}$ can be rejected and hence can be concluded that there is a **significant difference**.

Acoustic weight

$\boldsymbol{H_1}$**:** The visual weight of NV school classrooms in humid sub-tropical climate is significantly different from existing (i.e., $\boldsymbol{H_1}$**:** $AW_{NV} \neq AW_{AC}$).

$\boldsymbol{H_0}$: The visual weight of NV school classrooms in humid sub-tropical climate is not significantly different from existing (i.e., $\boldsymbol{H_0}$**:** $AW_{NV} = AW_{AC}$).

Now, to test the null hypothesis ($\boldsymbol{H_0}$) against the alternative hypothesis ($\boldsymbol{H_1}$), a two tailed Z-test (parametric test) for mean can be conducted for 5% level of significance.

$$Z_c = \frac{\bar{x} - \mu_0}{\sigma/\sqrt{n}}$$

Where,

Z_c = Z-test critical value

$\bar{x}$ = proposed weight for acoustic comfort

σ = sample standard deviation

μ_0 = existing weight for acoustic comfort

n = no. of observation

Then,

$$Z_c = \frac{0.26 - 0.23}{0.04/\sqrt{45}}$$

$$Z_c = 5.03$$

The critical value for two tailed test at 5% level of significance are −1.96 and +1.96 (obtained from t-distribution table). Since, Z_c is greater than +1.96, the $\boldsymbol{H_0}$ can be rejected and hence can be concluded that there is **a significant difference**

Air Quality weight

$\boldsymbol{H_1}$**:** The air quality weight of NV school classrooms in humid sub-tropical climate is significantly different from existing (i.e., $\boldsymbol{H_1}$**:** $QW_{NV} \neq QW_{AC}$).

$\boldsymbol{H_0}$: The air quality weight of NV school classrooms in humid sub-tropical climate is not significantly different from existing (i.e., $\boldsymbol{H_0}$**:** $QW_{NV} = QW_{AC}$).

Now, to test the null hypothesis **(**$\boldsymbol{H_0}$**)** against the alternative hypothesis ($\boldsymbol{H_1}$), a two tailed Z-test (parametric test) for mean can be conducted for 5% level of significance.

$$Z_c = \frac{\bar{x} - \mu_0}{\sigma/\sqrt{n}}$$

Where,

Z_c = Z-test critical value

$\bar{x}$ = proposed weight for air quality

σ = sample standard deviation

μ_0 = existing weight for air quality

n = no. of observation

Then,

$$Z_c = \frac{0.24 - 0.26}{0.03/\sqrt{45}}$$

$$Z_c = -4.47$$

The critical value for two tailed test at 5% level of significance are −1.96 and +1.96 (obtained from t-distribution table). Since, Z_c is smaller than -1.96, the $\boldsymbol{H_0}$ can be rejected and hence can be concluded that there is **a significant difference**.

Therefore, **H2:** The IEQ parameters weighting scheme of NV school classrooms in humid sub-tropical climates is significantly different from the existing literature in different contexts is **completely-true for thermal, visual, acoustic comfort, and air quality**.

Annexure 4

To demonstrate the use of the overall IEQ assessment model, a KVS classroom was simulated with 'Design Builder' software based on the physical characteristics of the classroom. After validation of the model with on-site measurement, the whole year's data was generated. To simplify the process, the average operative temperature and light level for the class hours for each month were considered for assessment (as shown in Table 4). The noise level in the classroom could not be simulated due to the limitation of the software; hence constant value was assumed (i.e., 64 dBA) based on the annual average on-site measurements. Then these values for each month were inserted into the model to derive the overall IEQ condition for the simulated classroom.

Table: Overall IEQ conditions for each month for the simulated school classroom.

Month	Operative Temperature	Light Level	Sound Level	IEQ value	IEQ condition
January	21.5 °C	190 lux	64 dBA	+0.5	Good
February	24.2 °C	242 lux	64 dBA	+0.3	Good
March	26.8 °C	275 lux	64 dBA	+0.1	Ok
April	28.5 °C	336 lux	64 dBA	+0.0	Ok
May	29.5 °C	413 lux	64 dBA	+0.0	Ok
June	31.5 °C	439 lux	64 dBA	−0.2	Bad
July	Holiday	Holiday	Holiday	Holiday	Holiday
August	31.2 °C	358 lux	64 dBA	−0.3	Poor
September	30.6 °C	313 lux	64 dBA	−0.2	Bad
October	30.5 °C	259 lux	64 dBA	−0.3	Poor
November	26.5 °C	188 lux	64 dBA	+0.0	Ok
December	24.1 °C	172 lux	64 dBA	+0.2	Ok

Note: All values for operative temperature and light level are averaged for each month.

It can be seen that for this studied classroom, the overall IEQ condition was 'Ok to Good' for the winter months; However, for the summer months it was 'Bad to Poor' (as shown in Table 4). It can be inferred from this assessment that the summer months' IEQ condition is of greater concern, where thermal comfort is the main issue, followed by AC.