PhD Thesis

Study on Adaptive Thermal Comfort, Natural Ventilation Effect, and Thermal Improvement in Nepalese School Buildings

Rijal Laboratory

Graduate School of Environmental and Information Studies

Tokyo City University

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Mishan Shrestha

Abstract

Education plays a crucial role in society's development and intellectual development. Indoor environmental quality (IEQ) which is essential for students' health and academic performance in school buildings must be improved in order to meet this challenge. Major factors such as thermal comfort and indoor air quality determine whether the indoor environment is comfortable or not, and they should be maintained as required. School buildings have different characteristics than residential or office buildings because they usually accommodate a large number of students and are run during the day.

Most Nepalese school buildings rely on natural ventilation through windows or doors. They are constructed using local materials, but little consideration is given to the thermal environment required for comfort during construction. Also, they are poor in passive design, such as thermal insulation of walls and roofs and solar control over windows; they also do not have mechanical heating and cooling systems. As no major concerns were raised on IEQ associated with the thermal comfort of students, natural ventilation, and thermal environment improvement, which has not yet been known in Nepalese schools, we investigated them through field surveys, modelling, and simulation techniques in the temperate climatic region of Nepal. The major objectives of this study are to: investigate the comfort temperature based on the thermal perception of students; analyse how their clothing insulation affects their thermal comfort; investigate the indoor air quality using measured indoor CO_2 concentration; develop a new method of estimating the ventilation and indoor CO_2 concentration; estimate the natural ventilation in terms of air change rate and compare with previous studies; and investigate how passive design strategies are effective in maintaining the operative temperature at a level that is suitable for thermal comfort.

Field surveys were conducted during the autumn 2017 and the summer of 2019 in naturally ventilated secondary school buildings. The measurement of environmental quantities such as air temperature, globe temperature, relative humidity, CO_2 concentration, and so on was performed indoors and outdoors during school hours. Altogether, 818 students participated in the 2017 survey; they voted three times: at the beginning, in the middle, and at the end of each 45-minute lesson. In the 2019 survey, altogether, 246 students participated, and they voted three times: in the morning, in the midday, and in the afternoon of a regular lesson. Based on the transient mass balance, a numerical estimation method was developed for estimating the number of air change per hour (ACH) and the indoor CO_2 concentration. The simulation was conducted to improve the operative temperatures in a classroom of a case study school building. Designbuilder software

was used to create the base model, and the simulated operative temperature was validated using measured globe temperature. Afterward, strategies such as natural ventilation, insulation, and thermal mass were applied and analysed.

Under the condition of naturally occurring ventilation, the indoor globe temperature was close to the outdoor air temperature. Approximately 76% of the students felt comfortable at an average temperature of 27 °C. The comfort temperature of 27 °C is almost the same for both autumn and summer. The estimated comfort temperatures are distributed over a wide range, but the values of comfort temperature are mostly between 24 °C and 30 °C. Private school students chose a low estimated comfort temperature, which may be due to them wearing more clothing insulation. Even though there is a dress code, students reduced their clothing to adapt to outdoor air temperatures above 30°C.

The indoor CO_2 concentration was much lower than the acceptable limit. Most students accepted the indoor air quality (IAQ) under such conditions of classrooms. The estimated ACHs were found to be higher than 25 h^{-1}, and thereby confirming that ventilation was performed very well. The indoor CO_2 concentrations estimated using the estimated ACHs were compared and found to be well fit with the measured CO_2 concentration. The estimation of how the reduction of the ACH to a half or a quarter affects the indoor CO_2 concentrations was conducted and found that the CO_2 concentration would be still quite low in school buildings.

The individual simulation results of the passive design strategy showed that the operative temperature was improved if the passive design strategies were applied and the temperature was maintained at approximately 28 °C. Further, the operative temperature was reduced below 27 °C with a maximum reduction of 3.3 K due to the integrated passive design impact, which is within the comfortable limit required during the school hour.

Overall, this study investigated the current situation of adaptive thermal comfort of students, indoor air quality associated with natural ventilation and CO_2 concentration, and the passive improvement of the thermal environment for the hot season. The outcomes should be valuable in improving the IEQ associated with thermal comfort, indoor air quality, and thermal environment improvement and its awareness in school buildings in Nepal.

Finally, this study pioneers research on IEQ in naturally ventilated secondary school buildings in the temperate climate of Nepal. The findings and outcomes of this study are valuable information for school building designers and policymakers. With the availability of adaptive behaviours, students accept higher or lower indoor temperatures and tolerate their comfort temperature over a wider range, which is connected to their energy use behaviour in the future. In terms of indoor air quality, Nepalese school buildings are so far much better than those in some of the developed countries. This is good for all of us to rethink the role of natural ventilation for rational indoor air quality from the perspective of global environmental issues in association with energy use. Furthermore, this study gives insight into how passive improvement can best be used to ensure awareness of energy savings for future generations. This work's concept contributes to discouraging the use of mechanical heating or cooling that consumes a lot of energy while maintaining thermal comfort in school buildings in the future in the study area.

概要

論文主題名: ネパールの校舎における適応的温熱快適性、自然換気の効果と温熱環境改善に関する研究

教育は社会の発展と知的生産において重要な役割を果たしている。この課題に対応するには、校舎での生徒の健康と学業成績に必要な室内環境を改善する必要がある。室内環境の快適性の有無は、温熱快適性や室内空気質などで決まる。校舎では通常、多数の生徒が日中に利用し、住宅やオフィスとは異なる特徴を持っている。

ネパールの多くの校舎は、窓やドア開放して自然換気を行っている。校舎は現地の材料を用いて建設されているが、熱的快適性について殆ど考慮されていない。また、壁や屋根の断熱や窓の日射遮蔽などのパッシブデザインも十分に考慮されていない。また、ネパールの殆どの校舎では冷暖房設備が設置されておらず、生徒たちは自然換気に依存した室内環境を利用している。校舎における生徒の熱的快適性、自然換気、温熱環境の改善に関連した問題を改善する必要がある。従って、ネパールの温帯気候における自然換気校舎にフィールド調査、シミュレーションなどを行なった。本研究の目的は、生徒の快適温度の検討、着衣量が熱的快適性に与える影響、CO_2 濃度の測定による室内空気質の分析、換気回数と CO_2 濃度を予測できる新しい手法の開発などを行った。また、熱的快適性を考慮した作用温度を維持するためパッシブデザインの有効性を検討した。

2017 年の秋と 2019 年の夏に、自然換気されている中学校でフィールド調査を行なった。本研究では環境要因として室内と屋外の気温、グローブ温度、相対湿度、CO_2 濃度などの測定を行った。2017 年の調査では 818 人の生徒に調査し、45 分間の授業に 3 回申告を行った。2019 年の調査では 246 人の生徒に調査し、通常授業の午前、正午、午後に 3 回申告を行った。1 時間あたりの換気回数と CO_2 濃度を推定するため推定法を開発した。シミュレーションでは教室の作用温度の改善を行った。Designbuilder ソフトウェアを用いて基本モデルを形成し、測定したグローブ温度を用いてシミュレーションで得た作用温度を検証した。その以後、自然換気、断熱、熱容量などを改善し、分析を行なった。

自然換気時におけるグローブ温度は外気温度に関連している。寒暑感申告を分析した結果、約 76%の生徒が室内の温熱環境を許容し、算出された平均快適温度は 27˚C、快適範囲は 24-30˚C である。快適温度は秋も夏も同程度だった。私立校の生徒の快適温度は公立校より低いが、これは着衣量が多いためと考えられる。制服規定はあるが、外

気温が 30 ˚C を超えると室内環境に適応するため、着衣量を減らす傾向がみられた。

室内 CO_2 濃度は基準より低かった。殆どの生徒は教室の室内空気質を許容していた。推定した換気回数は 25/h より高く、換気量が非常に高かった。実測した CO_2 濃度と推定した室内 CO_2 濃度がよく一致していた。換気回数を 50%、25%に減らして、室内 CO_2 濃度を推定した結果、室内の CO_2 濃度はかなり低くかった。

パッシブデザイン戦略でシミュレーションを行った結果、作用温度が約 28℃に維持することができた。さらに、総合的改善の効果では、作用温度は最大 3.3℃低下し、授業中に快適な環境を作ることができる。

本研究では、生徒の適応的な熱的快適性、自然換気、CO_2 濃度に関連した室内空気質について明らかにし、夏季の温熱環境の改善効果について定量的に示した。研究成果は、校舎の設計やガイドラインの作成に役立ち、既存の建物の改修や新しい校舎の建設に利用でき、快適でエネルギー使用の少ない校舎の実現に貢献できる。

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Chapter 1: Introduction

1.1 Introduction

This chapter presents a brief and basic overview of indoor environmental quality (IEQ) associated with thermal comfort, natural ventilation, and improvement of the thermal environment using passive design in school buildings. It also provides a literature review and states the research gaps, problems, research questions, and objectives of IEQ in Nepalese school buildings. In addition, this chapter describes the thesis structure.

1.2 Overview of indoor environmental quality in school buildings

Let us think of a question. How do we think to achieve good exam results or academic performance of students? Many of us may think that admission to expensive schools, having a good teacher, eating healthy food, and so on are the key factors. But have we considered the negative impact that the indoor environment of school buildings can have on student performance? We are overlooking the most important aspect, the school buildings' infrastructure, and the buildings' thermal environment, especially in the context of developing countries like Nepal. School is an important place to help students grow in their various capabilities. They spend approximately 30% of their daily lives in schools for their educational activities (De Giuli et al. 2012). Since students spend a significant portion of their day indoors, the indoor environment should be optimized to meet their needs with regards to light, heat, air, and sound. Studies conducted in classrooms have shown that noise-related problems are most frequently reported (58%), followed by temperature (53%), air (22%), and light (16%) (Bluyssen et al. 2020).

Education plays a crucial role for the development of society and individual intellectual growth. Indoor environmental quality (IEQ), which is essential for students' health and academic performance in school buildings, must be improved in order to meet this challenge. For better well-being, the indoor environment is determined and judged in terms of thermal comfort, air quality, lighting quality, acoustic comfort, and so-called indoor environmental quality (IEQ). It assesses how well the built environment performs, how it impacts occupant health and productivity, and how it relates to energy use (Fig. 1). Whenever we raise a discussion on the IEQ of the built environment, it is concerned with how we could improve health and reduce energy use. The factors affecting IEQ–thermal comfort, indoor air quality (IAQ), lighting comfort, and acoustic comfort–are potentially linked to each other and necessary to discuss together, especially thermal comfort and indoor air quality. For a better design parameter of the building environment, improving to these factors is urgent. Building types affect these conditions differently, such as school buildings. IEQ associated with above mentioned four major factors plays a critical role in student' health and academic performance based on the school buildings' design. In the context of

Nepal, the consideration of such factors with the proper designation of buildings is lacking. Therefore, this thesis is focusing on the investigation and analysis of two major factors, thermal comfort, and indoor air quality, and how to improve the thermal environment using passive design considering the future global environmental issues to design out thermal discomfort.
Lighting and acoustic comforts are the factors that affect visual perception and the presence of noise sources in the given indoor environment, respectively. These topics are beyond the scope of this thesis.

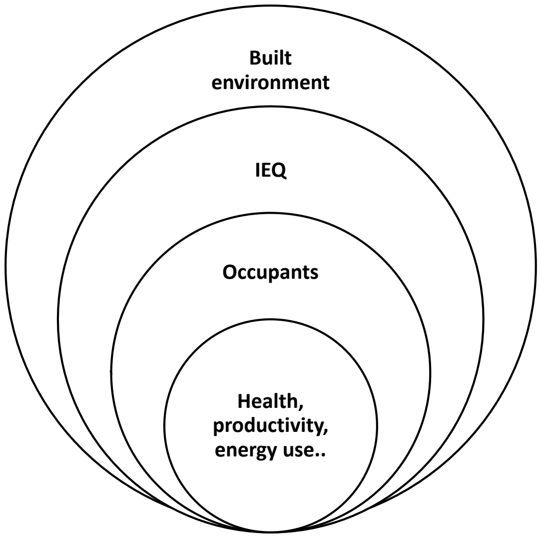


Figure 1.1 Indoor environmental quality (IEQ) in the built environment for the occupant's health and productivity

1.2.1 Thermal comfort in school buildings

Thermal comfort assesses the thermal environment of spaces and whether or not those spaces can provide a quality environment. Occupants are no longer passive recipient of their thermal environment, but instead an active interacting with their thermal environment through an action of adaptation (Brager & de Dear 1998 & Nicol et al. 2012). The adaptations are physiological, behavioural, and psychological. Behavioural adaptation is the major contributor to thermal comfort (Rijal et al. 2019). Thermal comfort achieved by the occupants using behavioural adaptations or various strategies such as clothing changes, windows open or close, etc. is said to be adaptive thermal comfort. Although thermal comfort—the satisfaction with the thermal environment—is one of the environmental attributes, it has garnered less attention than others (ASHRAE 2017). The comfort conditions depend on the interaction of physical, physiological, and psychological factors of occupants' body where the exchanges of mass and energy occur between the occupant and environment (Fabbri 2015).
Thermal comfort in school buildings has long been a topic of interest for researchers as the link

between the immediate thermal environment, long exposure, and impact on the learning ability and health of the students were not clearly visible (Singh et al. 2018). In general, schools are not thermally comfortable. In terms of the thermal comfort of the students, in the absence of proper insulation and ventilation in school buildings or classrooms, two things happen: they may feel too cold or too hot, as depicted in Fig. 1.2. If such incidents occurred in classrooms, it would be more difficult for students to focus and concentrate on academic work.

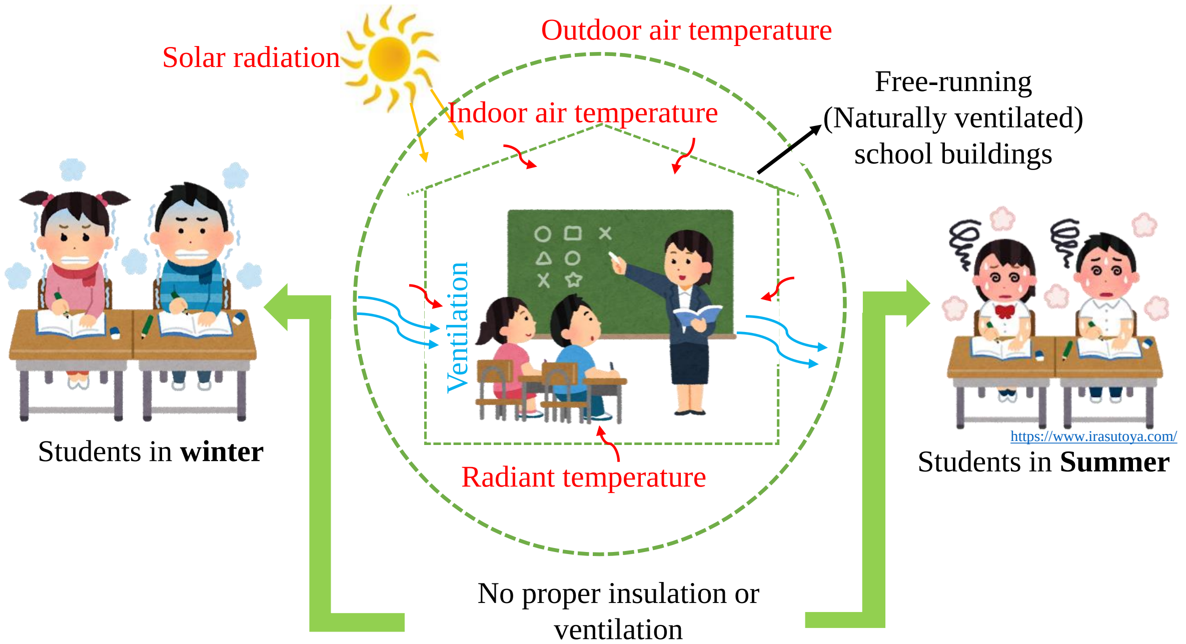


Figure 1.2 Schematic representation of thermal comfort of students in the absence of a proper indoor thermal environment in school buildings

Thermal discomfort may cause irritation. Extreme thermal environment of classrooms affects students' concentration. In addition to causing reduced concentration, such an environment could also cause tiredness, sluggishness, and health problems (Mendell et al. 2005, Sudo et al. 2011, & Bluyssen et al. 2018). Thermal discomfort prompts people to restore their comfort by changing their environmental conditions or clothing (Humphreys 1978, Humphreys & Nicol 1998, Nicol et al. 2012). The various actions taken subconsciously or consciously are categorised as adaptive behaviour. In residential and office buildings that are not mechanically conditioned, occupants generally adopt adaptive behaviour to optimise their thermal comfort (de Dear & Brager 1998, Liang et al. 2012, & Rijal 2018), for example, wearing less or more clothes or changing indoor air temperature by opening or closing the windows (Rijal et al. 2018). Such behaviours may also appear in classrooms, but they could be different from those in residential and office buildings. It may not be easy for students to use adaptive behaviour because of the school rules, including the dress code. The students in the classroom tend to become passive recipients, creating desired conditions, which is central to the adaptive thermal comfort theory (de Dear et al. 2020). Therefore, the thermal comfort perceived by students within classrooms could be different from that perceived by adults in offices. Several thermal comfort studies conducted in classrooms for comfort predictions and requirements are inconsistent with those conducted with adults in residential and office buildings (Teli et al. 2012, de Dear et al. 2015, Haddad et al. 2016, & Liu et al. 2020).

Furthermore, as discussed before, comfort achieved using adaptive behaviours refers to adaptive thermal comfort. Nicol & Hymphreys (2002) have made a clear distinction between the thermal comfort perceived by occupants in heated or cooled buildings and free-running or naturally ventilated buildings. According to them, thermal comfort, as indicated by the comfort or neutral temperature in heated or cooled buildings, mostly does not change if the outdoor temperature changes. But this is not so in naturally ventilated spaces. Their comfort temperature changes as the outdoor temperature changes, and the comfort temperature ranges are wider (Nicol & Humphreys 2002).

Generally, two approaches are employed to evaluate thermal comfort: a climate chamber study in environmental control conditions and a field study in actual buildings with occupants. The former approach is mostly based on a heat balance model developed by Fanger (1972) and the subjects usually have no control over their immediate indoor thermal environment. The latter is adaptive thermal comfort, where the occupants engage in behavioural, physiological, and psychological adaptations (de Dear & Brager 1998, Humphreys & Nicol 2018). The PMV-PPD model for thermal comfort prediction can underestimate or overestimate in naturally ventilated buildings (ul Haq Gilani et al. 2015, Cheung et al. 2015, & de Dear 1995), and more emphasis is given to the adaptive approach to assessing the thermal environment and comfort. Therefore, this study is based on the latter approach, adaptive thermal comfort, in actual naturally ventilated school buildings.

1.2.2 Indoor air quality associated with ventilation and CO_2 concentration

Ventilation, whether natural or mechanical, is essential for better indoor air quality. Considering the perspective of global environmental issues, energy savings, indoor air quality, and thermal comfort, adequate natural ventilation (NV) should be prioritized. The purpose of natural ventilation driven by outdoor wind effect or by buoyancy effect is to bring fresh and quality air in and contaminated air out so that it dilutes indoor CO_2 concentration, and removes excess heat or moisture essential for thermal comfort and well-being (Yang & Clements-Croome 2018 & Heiselberg 2004). NV in school buildings provides fresh air that improves indoor air quality (IAQ); it could help improve the condition for the academic activity of students (Wargocki et al. 2020 & Asif & Zeeshan 2020). It is necessary to provide enough fresh air to maintain healthy breathing conditions, especially in highly occupied spaces as shown in Fig. 1.3. Since the number of students in a classroom is usually larger than that in residential or office buildings, insufficient IAQ could easily emerge and thereby result in health problems because of the accumulation of discharged CO_2, heat, and so on. These problems can be improved by using a proper window opening pattern (Heracleous & Michael 2019).

Looking back at the academic year 2020 worldwide, many school communities, especially in cities, were closed to reduce the risk of COVID-19 infection. One of the safety measures implemented has been to utilise natural ventilation in classrooms when the schools are to be reopened. A study (Dai & Zhao 2020) ensured that inadequate ventilation rates increase the risk of infection by COVID-19 in confined spaces where less air flow or recirculated air is used for a long period of time. Adequate NV may provide students with an effective and easiest solution to reduce such risk of infection and CO_2 concentration (Lipinski et al. 2020 & Asanati et al. 2021).

Measuring contaminants and modelling their mass balance help to quantify the indoor environmental quality. There are a couple of methods used in previous studies, such as so-called build-up, steady-state, and decay methods. Although their appearance may look different, they are all based on the fundamental mass balance equation (Batterman 2017, Hänninen et al. 2017, Luther et al. 2018, & Kabirikopaei & Lau 2020). These methods were developed under the assumption of a constant air change rate for ventilation and a constant CO_2 emission rate in the targeted room space. However, in reality, there is always the variation in the number of occupants that is the source of CO_2 emission and also the amount of air coming in and out through the room space varies due to the change in outdoor wind conditions. In order to meet such conditions, existing methods may not be applicable, so a new method is necessary to be developed for the evaluation of the performance of NV and its resultant indoor CO_2 concentration.

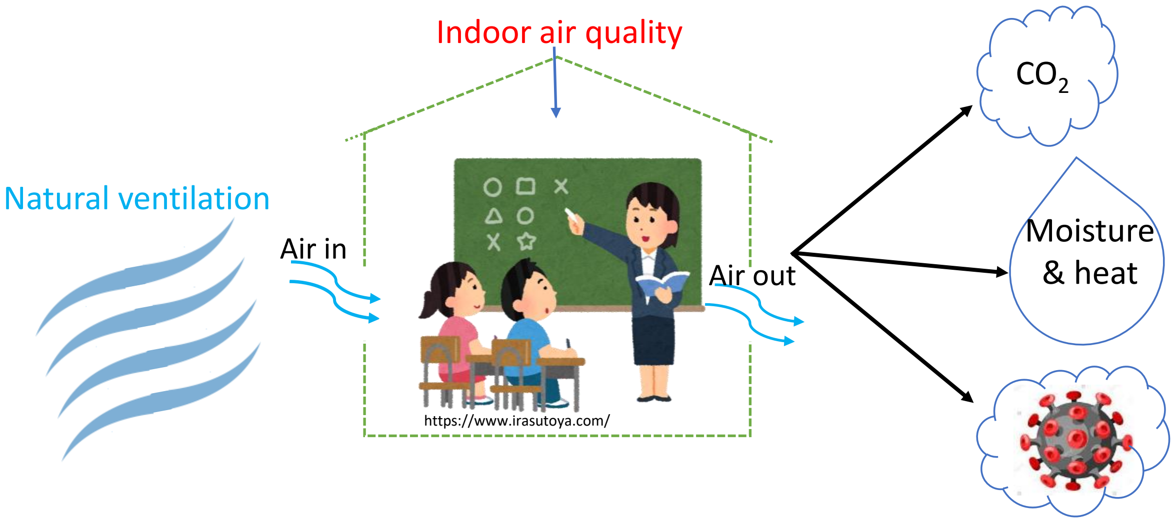


Figure 1.3 Schematic representation of natural ventilation (NV) and its importance in the classroom

1.2.3 Thermal environment and its improvement in school buildings

Thermal environment is the characteristic of the environment that affects occupants' heat loss, and the thermal environment would be acceptable if the majority of the occupants found it thermally acceptable (Fabbri 2015). Basic environmental quantities such as air temperature, relative humidity, mean radiant temperature, and air velocity judged the perception of comfort.

After or before building construction, such as schools, offices, residences, hotels, and so on, an important aspect to consider is how it performs in providing a comfortable and acceptable indoor thermal environment. If the thermal environment is maintained by mechanical equipment, there would be no worry about the indoor thermal environment. However, this may not be the case for naturally or free-running indoor spaces where no active equipment such as heating or cooling is used, even during peak summer or winter. Factors such as climate, location, orientation, the building's materials, and so on, of course, significantly influence the indoor thermal environment under such free-running conditions. Classrooms, as a part of school buildings, are particularly important as they must accommodate a large number of students for extended periods of time. They have special characteristics compared to other buildings as they are used mainly during the day for academic activities. There is a high possibility of influencing the indoor thermal environment by the outdoor climate, such as solar radiation during the day. So, what approach is required to create a comfortable indoor environment while lowering the level of thermal discomfort is a key issue? Therefore, it is important to investigate the indoor thermal environment for improvement through field surveys and building simulation.

The built environment is the dominant source of energy use, which uses approximately 40% of global annual energy along with the emission of greenhouse gases (Anderson et al. 2015 & UN Environment Programme 2021). From a global environmental point of view, to reduce the consequences of global warming, alternative ways of grasping the benefits of freely available natural resources in the building sector are needed to use less energy and be more sustainable. This could be possible by employing passive measures, as illustrated in Fig. 1.4, which are more sustainable, use less energy, and also improve thermal comfort. To achieve it, designers could examine the building's thermal performance and thermal comfort at the early stage of design and make rational decisions by utilizing various design strategies with building simulation tools. These kinds of studies are unfortunately overlooked in school buildings in Nepal. Through research, there is a need for awareness and implementation of the fact that the use of passive design can improve a building's thermal performance and, therefore, its occupants' thermal comfort. In order for Nepal to follow the medium path for sustainable development in terms of global environmental issues, one of the important aspects of creating or improving the thermal environment of indoor spaces is the role of passive design solutions (Shahi et al. 2021), which is an appropriate approach for connecting building thermal comfort with human thermal comfort (Szokolay 1980). Nepal is still at a stage where it can rethink these opportunities to be used in the future to reduce its dependency on the use of fossil fuels, such as natural gas, coal, etc. We are free to apply passive design control depending on our requirements. The local climatic conditions determine the types of passive strategies that are appropriate for a climate design adaptation to address indoor thermal environmental issues. Having sufficient knowledge of such climatic information potentiates energy-saving scenarios and thermal comfort.

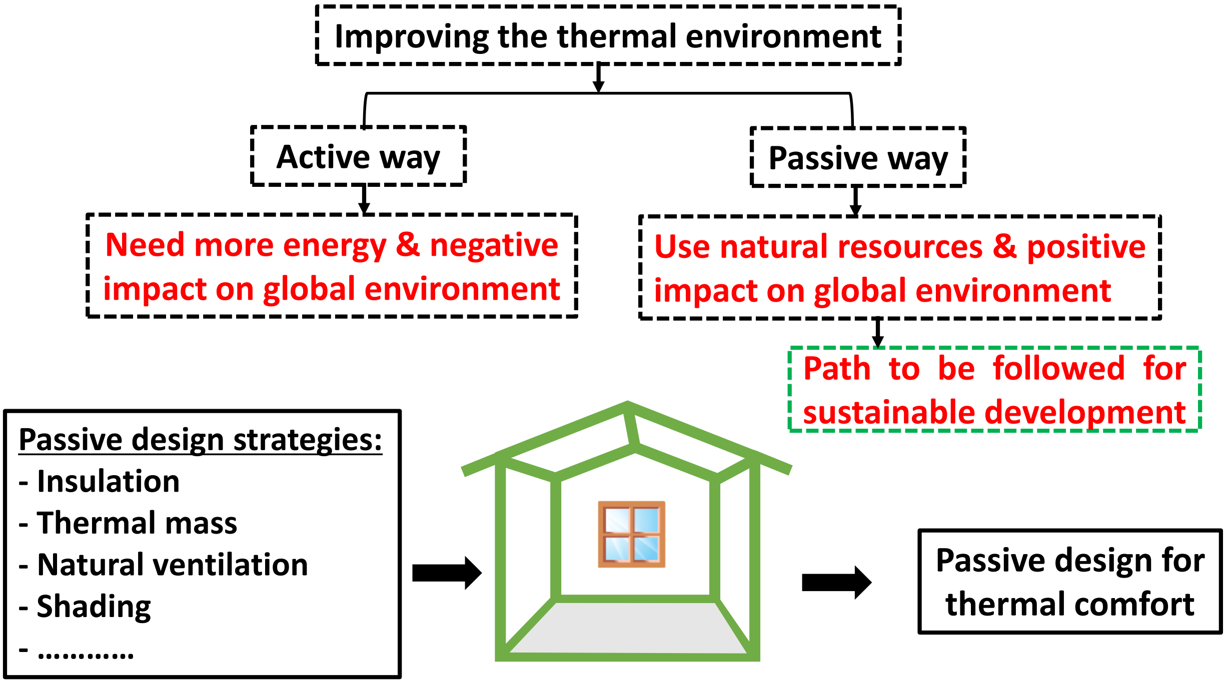


Figure 1.4 Relationship between climate and passive design control

1.3 Literature review of indoor environmental quality in school buildings

This section aims to present a literature review on indoor environmental quality (IEQ) associated with thermal comfort, ventilation, CO_2 concentration, and passive thermal environment improvements in school buildings, which are important and directly connected to students' academic performance, comfort, and classroom environment.

1.3.1 The previous studies on thermal comfort

Several studies have clarified the importance of adaptive thermal comfort and the performance of school buildings (de Dear et al. 2015, Hamzah et al. 2018, Corgnati et al. 2009, & Kwok 1998). These studies established their own comfort models and comfort temperatures suitable to their local climates. The thermal comfort of students in school buildings has been studied in temperate (Teli et al. 2012, & Teli et al. 2014), sub-tropical (Hwang et al. 2006, Hwang et al. 2009, de Dear et al. 2015, Zaki et al. 2017, & Kim & de Dear 2018), tropical (Kwok 1998, Hamzah et al. 2018, Fletcher et al. 2020, & Talukdar et al. 2020), Mediterranean (Corgnati et al. 2009, d'Ambrosio

Alfano et al. 2013, & Nico et al. 2015), and hot humid climates (Liang et al. 2012 & Munonye & Ji 2020). Kwok (1998) conducted a thermal comfort field study in air-conditioned and non-air-conditioned school buildings in Hawaii, studying over 3,544 students. The study established that 75% of the classrooms did not meet the comfort requirements prescribed by ASHRAE (American Society of Heating, Refrigerating, and Air-conditioning Engineers) 55 (2017) and estimated that the students preferred temperatures higher than the comfort temperature in naturally ventilated school buildings compared to air-conditioned buildings. The thermal neutrality of the students is different from that of adults because of their activity in the classroom, their clothing, and environmental parameters. This was found in the adaptive thermal comfort study by Teli et al. (2012) & Teli et al. (2 013), which concluded that the comfort temperature of students is 2 °C lower than that of adults. Haddad et al. (2016) arrived at similar results for naturally ventilated classrooms in Iran. The students in all classrooms of primary, secondary, and university (adults) felt comfortable on the cooler side of the thermal sensation (Singh et al. 2019), with the primary school students being the least sensitive to the outdoor air temperature. A study by Hwang et al. (2009) on the application of the adaptive thermal comfort model in naturally ventilated schools found that the acceptability of the students had a wider range of comfort zones than thermal comfort standards. Moreover, studies conducted in Taiwan in the summer months found that the thermal sensitivity of the students is higher in summer than in winter (Hwang et al. 2006 & Hwang et al. 2009). de Dear et al. (2015) conducted a study in Australian primary classrooms and found the same value of comfort and a preferred temperature of 22.5°C, which is lower than that of adults under the same thermal environments. They also reported that adaptation to the thermal environment is influenced by factors such as age, climate, and mode of buildings operation. The comfort temperature of the university students under high metabolic rates during autumn was well fitted within the temperature limits of the ASHRAE standard (Kumar et al. 2020). A one-year study on university campuses in Portugal showed that clothing behaviour and clothing insulation are key issues in the estimation of comfort temperature (de Carvalho et al. 2013). They clarified the effect of short-term outside thermal memory on clothing insulation. The thermal history older than the previous day is insufficient to consider clothing. Ngarambe et al. (2019) found gender differences in clothing insulation in Korea, which is associated with culture and climate dress. Further, Liang et al. (2012) investigated the effects of building envelope energy regulations on thermal comfort level in naturally ventilated primary and secondary schools. They found that building energy regulations had a significant impact on thermal comfort levels.

The students' thermal comfort is not determined by indoor microclimatic conditions alone. Previous studies (Montazami et al. 2017, Trebilcock et al. 2017, & Campano et al. 2019) suggested that their thermal comfort is significantly correlated with social parameters such as socio-economic background, culture, and what they experience at home.

According to the overall findings of the literature review on students' thermal comfort, their perceptions differ depending on their age group and activity level. The comfort temperature of students is affected by the type of school building and the season.

1.3.2 The previous studies on IAQ associated with ventilation and CO_2 concentration

Many field studies conducted for classrooms in school buildings in the USA, UK, Germany, France, Denmark, Finland, and Serbia have identified a significant negative impact on IAQ and thermal comfort because of ventilation rates below the required rates (Deng & Lau 2019). Most of them address the issue of ventilation and indoor CO_2 concentration. Mechanical ventilation provided with supplied outdoor air, which does not account for air infiltration into the buildings, also has such an issue (Santamouris et al. 2008). A very limited number of studies have investigated the acceptable level of CO2 concentration in occupied classrooms (Simanic et al. 2019).

In classrooms, usually exceeding the CO_2 concentration of 1000 ppm is not surprising because of the high occupancy for long periods of time. According to ASHRAE (2016) and REHVA (2010), indoor CO_2 concentrations should be maintained below 1000 ppm and 1500 ppm, respectively, to mitigate the negative effects of IAQ on health. In Switzerland, the Federal Office of Public Health (FOPH) made an acceptable hygienic CO_2 limit below 2000 ppm for existing school buildings with NV (Vassella et al. 2021). The COVID-19 pandemic has exposed the people involved in the science and engineering of ventilation to the requirement of urgent re-development to protect health by providing safe IAQ. For this, NV strategies should be able to provide an effective solution (Lipinski et al. 2020).

ASHRAE has recommended a ventilation rate of 8 l/(s·p) for educational classrooms (ASHRAE 2016). Fisk (2017) concluded from the pieces of literature that ventilation rates in classrooms are often below the minimum required by the guidelines. Then he stated that insufficient ventilation rates in classrooms are identified when ventilation rates are lower than 7 l/(s·p) or the average CO_2 concentrations are greater than 1000 ppm. Almeida et al. (2017) found that the maximum ventilation was 8.3 h^{-1} and 14.2 h^{-1} for window cross ventilation and window-door cross ventilation, respectively, in Portuguese school classrooms. A study by Park et al. (2021) in South Korea found that the prevention of airborne virus infection can be maintained at less than 1% by securing 6.5 ACH (number of air change per hour), and restricting exposure time to less than 3 hours.

Hanninen et al. (2017) found very low ventilation rates, high CO_2 concentration, and very stuffy air due to low temperature and high occupancy in winter in Albanian schools' classrooms. A study conducted in an Italian school found lower CO_2 concentration during spring than in winter, but there was an effect of other contaminants when windows were opened for a longer period of time (Fuoco et al. 2015). Rashidi et al. (2012) in Kuwait found that indoor CO_2 concentration was more than double that of the naturally ventilated in ten elementary classrooms under mechanical ventilation with air recirculation. But, by having small breaks in those classrooms between the continuous lectures along with the main break, the CO_2 concentration was maintained at around 1500 ppm.

A study conducted in university classrooms in Italy found that if the occupancy was about 70% of the total, the energy use for ventilation was 9.2 kWh/hour, while it was 2.1 kWh/hour under 20% occupancy (Franco & Schito 2020). Gil-Baez et al. (2017) in Spain found that 18 to 33% of primary energy per annum can be saved using natural ventilation while maintaining thermal comfort of students. Haddad et al. (2021) found that demand-controlled ventilation, which can either switch natural or mechanical ventilation, provided an energy-saving scenario, reducing the indoor CO_2 concentration with the increased ventilation rate of classrooms. Duarte et al. (2017) conducted a study for two years and found energy-saving potential when natural ventilation is made using manual window opening; appropriate ventilation and thermal comfort were achieved for approximately a quarter of the academic year. The above-mentioned studies showed that natural ventilation plays an important role in maintaining the required range of indoor CO_2 concentration and ventilation.

According to the overall results of the literature on ventilation and CO_2 concentration mentioned above, educational buildings should provide adequate ventilation and need to maintain indoor CO_2 concentrations within the acceptable limit.

1.3.3 The previous studies on the improvement of the thermal environment for thermal comfort and energy savings

Thermal comfort is one of the major indicators of indoor environmental quality, especially in school buildings, which is potentially linked to architectural building design (Alghamdi et al. 2022). In the absence of a thermally comfortable indoor environment in naturally ventilated school buildings, the vulnerability of the students toward their academic performance tends to be high. This could be improved by employing passive design techniques (Zahiri & Altan 2016).

Previous simulation studies (Taleb 2014, Kang et al. 2015, Popescu et al. 2021, & Zilberberg et al. 2021) found that the improvements applied by passive strategies in existing buildings saved a significant amount of energy. Studies conducted for educational buildings have validated and shown the effectiveness of passive design strategies in their respective climatic conditions to maintain an indoor thermal environment as well as energy-saving, as shown in Table 1.1. Lopez et al. (2022) identified passive design intervention strategies such as green roofs, thermal insulation, natural ventilation, shading, orientation, thermal mass, solar walls, Trombe walls, evaporative cooling systems, solar chimneys, wind catchers, and so on in schools in 43 different countries and Koppen climate zones from the literature. Subhashini and Thirumaran (2018) explored a shading device design for warm and humid climates that reduced the heat gain from the windows and external walls and maintained the indoor air temperature. Galal (2019) found that the north, north-east, and north-west orientations could be the most suitable for heat gain and daylighting factors together in the Lebanese climatic coastal zone. Mohamed et al. (2021) revealed considerable reductions in indoor air temperature from 30.3–44.8 °C before and to 18.9–26.5 °C after activating a passive wall system. Alwetaishi et al. (2021) observed that vertical shading is efficient shading from 7:00 to 9:00, and after that, 45° vertical shade is more efficient to maintain the classroom temperature in the local climate of a hot region. Park et al. (2020) found that the phase change materials (PCM) applied to the shading system reduced the cooling energy use by 44% and improved the number of thermal comfort hours by 34% in educational buildings. Kükrer and Eskin (2021) found that discomfort hours were decreased by 17.6% and productivity was increased by 46% because of ambient temperature, airflow, HVAC (Heating, ventilation, and air conditioning), and shading element operational schedules. Stavrakakis et al. (2016) concluded from an experimental and numerical assessment that the cool roof is an efficient solution for school buildings in warm climates as it improves summer thermal comfort and ensures annual energy savings. Lakhdari et al. (2021) found that the combined passive strategy of the window-to-wall ratio (WWR), wall materials, glass types, and shading devices can provide better thermal comfort in hot and dry regions.

From the literature review, we can say that passive design strategies are a major complement to active design, which contributes to energy savings, maintains thermal comfort, and finally reduces global environmental issues.

Table 1.1 Summary of passive design strategies research in school/educational buildings with their major findings

References	Country	Climate	Simulation methods	Thermal environment improvement strategy	Major findings
Zahire & Altan (2016)	Tehran	Hot & dry	DesignBuilder	Orientation, thermal mass, glazing, insulation	Reduction in T_i by 4–5 K.
Mohamed et al. (2021)	Sudan	Hot	EDSL TAS ANSYS ICEM CFD	Passive wall system that combines natural ventilation and evaporative cooling	Reductions in T_i from 30.3–44.8 ˚C before and to 18.9–26.5 ˚C after activating a passive wall system.
Boutet & Hernández (2021)	Argentina	Hot & humid	Simedif & Radiance - Ecotect	Regulation of glazed area, sun shading, & opaque envelope treatment	T_i reductions of up to 6 °C and 40–60% cooling load reductions on average.
Alwetaishi et al. (2021)	Saudi Arabia	Hot & dry	EDSL TAS	Vertical and horizontal shadings with different titled angles to control access to solar radiation	Vertical shading is efficient from 7:00–9:00, and after those 45° vertical shades are more efficient in maintaining the classroom temperature.
Cuce et al. (2019)	Japan	Hot-humid summers & mild winters	CFD	Natural /Passive ventilation	Natural ventilation strategies reduce the T_i and purifies the air.
Garg et al. (2016)	India	Warm	Experiment	Cool roof coating	The application of cool roof coating results in a 1.5–2°C reduction in T_i on average. This technology will significantly impact lowering and improving the T_i for thermal comfort in un-conditioned rural school buildings.
Trebilcock et al. (2016)	Chile	Arid, Mediterranean, & oceanic temperate	DesignBuilder	Orientation, window size, glazing, insulation, infiltration rate	North orientation to lower heating demands, south to lower cooling demands, high insulation, lower heating demands in southern zones, low infiltration rate in the southern and coldest diminish the heating demand, glazing is not effective for the energy performance.
Galal (2019)	Lebanon	Coastal	DesignBuilder	Orientation on heat gain and daylighting	The north façade receives the lowest heat gain and the lowest cooling load,

					south, west, and east are the preferred orientations for minimum daylighting level.
Nejat et al. (2021)	Malaysia	Tropical	Experimental & (CFD)	Passive cooling & natural ventilation by windcatcher	Increased ventilation if the length of the wind cater is increased. The windcatcher provides a maximum of 9.6 kW of cooling power if the wind speed is set at 4 m/s the and outdoor temperature at 23 °C
Park et al. (2020)	South Korea	Cold climate	DesignBuilder	Retrofit of applying PCM on shading	Cooling energy use decreased by 44%, and the number of hours of thermal comfort improved by 34%.
Emil & Diab (2021)	Egypt	-	EnergyPlus	Retrofitting of roof, wall, glazing and shading, daylighting, WWR	Combining various envelope retrofitting strategies reduced energy use by more than 36%.
Stavrakakis et al. (2016)	Greece	Mediterranean	DesignBuilder	Cool roof	The cool roof is an efficient solution for school buildings as it improves summer thermal comfort and ensures annual energy savings when heat pumps are used for cooling purposes.
Gil-Báez et al. (2014)	Spain	Mediterranean	LIDER & ViSol	Insulation, shading, and glazing	A high potential for energy efficiency improvement, with savings of up to 17.7% for heating and up to 15.9% for cooling, is obtained by combining affordable passive actions.
Randjelovic et al. (2021)	Serbia	Mediterranean	EnergyPlus & jEPlus	Insulation, double-skin façade, green roof, Trombe wall	Maximum energy savings of up to 77% of heating and 79% of cooling energy can be saved by applying the appropriate combination of passive design.
Heracleous et al. (2021)	Cyprus	Mediterranean	IES-VE	Insulation (roof, wall, & floor), high-performance window, ventilation, & shading	Natural ventilation and insulation of the roof are very effective in improving thermal comfort. They have the potential to minimise the cooling degree hours by 96.8% and the heating degree hours by 4.3%.
Subhashinia & Thirumaran (2018)	India	Warm humid	Calculation	Shading (vertical & horizontal shading device)	With the provision of vertical shading devices, the direct rays of sunlight falling into the western windows can be prevented, and thus the heat gain from the west walls and windows can be reduced to a considerable level.
Liu et al. (2018)	China	Cold	EnergyPlus & OpenStudio	Passive solar building design (direct-gain window, Trombe wall plus direct-gain	The optimal ratio of the direct-gain window design is 0.45 and 0.5 for severe cold and cold areas, respectively. The thermal environment of

				window, & attached sun path)	school buildings can be improved using solar passive design in cold climates.
Ascione et al. (2019)	Italy	Mediterranean	DesignBuilder	PCM	The PCM with a melting temperature of 23 °C and a freezing temperature of 21°C, determines the reduction of summer energy use by 11.7% and the increase in summer thermal comfort.
Aksin & Selçuk (2021)	Turkey	Cold & moderate	Grasshopper, EnergyPlus, & OpenStudio	WWR, insulation thickness, wall & glazing materials	The energy performance has been improved by 4.1–5.1% with the insulation selection. There are no significant differences in energy use intensity even though the U-values of wall and glazing materials are reduced in optimised solutions.
Ledesma et al. (2022)	Ecuador	Mild	EnergyPlus & MATLAB	Rooftop farms (edible green roofs, rooftop greenhouses, integrated rooftop greenhouses)	Rooftops show a positive impact on improving thermal comfort, and air quality. Integrated rooftop greenhouses achieve the best overall performance with a 42% decrement in thermal load and a 0.7 °C increment in T_i.
Camacho-Montano et al. (2020)	Germany	Warm (Marine west coast)	DesignBuilder	NV, shading, glazing, & PCM	The heavyweight buildings prevent overheating by employing good ventilation. Overheating in lightweight buildings can be reduced to less than 10% of discomfort using passive measures.
Mahmoodzadeh et al. (2020)	USA, Canada	Hot & dry, hot & humid, cool & humid, humid-continental	EnergyPlus	Green roof	Plant albedo has the least effect on the thermal performance of the school. Poorly insulated buildings in heating-dominated climates can be retrofitted with green roofs to improve their energy performance.

T_i: Indoor air temperature, PCM: Phase change material, WWR: Window to wall ratio, NV: Natural ventilation

1.4 Current situation of IEQ in school buildings and research gaps in Nepal

The education system in Nepal consists of the basic, secondary, and university levels. There are two types of education: private and public. They differ in quality, infrastructure, and dress code, which will be discussed later.

The present IEQ condition of Nepalese school buildings in rural as well as urban areas is unknown; therefore, it is necessary to investigate the present condition of thermal comfort, indoor air quality, and thermal environment. Hence, we are focusing on investigating the present situation of the thermal environment of the school buildings so that we can evaluate the thermal comfort level of the students and indoor air quality, which helps to improve the indoor thermal environment of the school buildings. As Nepal is a developing country with slow economic growth, the development of school infrastructure is still very poor. For example, the installation of building envelopes with insulation, which should play an important role in maintaining the classroom environment for thermal comfort within a desirable condition, has not yet been made. The students and teachers may have been performing their tasks while being forced to adapt to the given indoor environmental conditions. Most Nepalese school buildings are poor in passive design, such as thermal insulation of walls and roofs and solar control over windows; they also do not have mechanical heating and cooling systems. They have so far been designed to accommodate the students and teachers, providing them merely with a certain amount of space without considering the effect of outdoor thermal environmental conditions, including solar radiation and wind. It has been reported that due to the elevation of indoor temperatures in schools with uninsulated roofs, the students become faint (Student faint due to heat wave, one dies in the plains, Impact of climate change on students in Nepal).

Nevertheless, there is no major concern, and hence no research is available on thermal comfort, IEQ associated with ventilation and CO_2 concentration, or its thermal environment to address these kinds of problems and improvements. The Nepalese Department of Education implements strategies to construct school buildings without the assessment of the thermal environment. According to the current School Sector Development Plan 2016/17-2022/23 implemented by the Government of Nepal, the Minister of Education (School Sector Development Plan 2016) does not mention the thermal comfort of students, indoor thermal environment, or indoor air quality in classrooms. A few studies have conducted research on Nepalese residential buildings and temporary shelters focusing on thermal comfort (Rijal et al. 2010, Thapa & Rijal 2016, Thapa et al. 2018, Gautam et al. 2019, Pokharel et al. 2020, & Rijal 2021), indoor air quality (Parajuli et al. 2016), and thermal environment improvement (Rijal & Yoshida 2005, Rashmi & Jongho 2015), but no similar study has been done with respect to school buildings.

The educational building sector in developed countries in North America, Europe, and so on suggests installing mechanical ventilation as a necessity that necessitates the use of fossil fuels to maintain ventilation and thermal comfort. However, developing countries such as Nepal in South Asia are still relying on natural ventilation. It could be different depending on the location and climate. Most Nepalese school buildings are naturally ventilated; windows and doors are the extensive major sources of ventilating air to provide daylighting and thermal comfort by opening them. The existing windows on them have wood shutters instead of glass sheets, and, in a few cases, just open windows without shutters. The provision of natural heating, cooling, and ventilation adopted rely mainly on outdoor climatic conditions. The existing buildings do not guarantee suitable conditions for thermal comfort but may provide satisfactory IAQ during the summer. Sometimes, while providing adequate ventilation by opening a window or door, occupants may have to compromise on thermal comfort. Furthermore, they may have to consider poor outdoor air quality, noise, and safety issues, particularly in urban areas. To the best of our knowledge, no scientific study and modelling study on IAQ associated with CO_2 concentration and ventilation in Nepalese school buildings has been conducted so far. Because of the diverse climate, location, building design, materials used, and so on, previous studies and regulations developed for other places cannot be generalised to the Nepalese context. There are no applicable guidelines related to ventilation or indoor CO_2 concentration. In a design document prepared by the Asian Development Bank, the Department of Education, and the Japan International Cooperation Agency in Nepal, the discussion of the importance of natural ventilation in Nepalese school buildings is discussed qualitatively but not quantitatively (Guidelines for developing type designs for school buildings in Nepal, 2016). Natural ventilation might perform very effectively due to the open windows, but we don't know how much of a ventilation rate is realized quantitatively under such conditions. We need to investigate them in reality to upgrade naturally ventilated school buildings looking into the future. In order to do so, all relevant sectors must be aware of the present qualitative and quantitative information.

The development of effective infrastructure in most school buildings in Nepal, for example, such as the installation of building envelopes with insulation, which should play an important role in maintaining the classroom environment for thermal comfort within a desirable condition, has not yet been made. Mostly, they are constructed based on a community-driven approach without considering the effect of outdoor thermal environmental conditions on an incremental and non-engineering basis (Anwar et al. 2016), which lacks appropriate design. What would be the thermal environment and thermal comfort in those buildings? How to improve them effectively? How can we achieve thermal comfort using natural resources and as little energy as possible? The effectiveness of passive design strategies has not been studied or considered to improve or make the classroom thermally comfortable. Thus, it is necessary to carry out thermal performance studies to improve or ensure energy efficiency for thermal comfort so that the impact of passive design can be known if school buildings are to be constructed or renovated in the future. A simulation study would be a better way to approach such a scenario.

1.5 Research questions

Every field of research has questions such as, “Why is this research important?” “What is the research novel?” What is the scope of the research? What is the significance, and why should we care about the outcomes of the study? Each has their own answers and outcomes based on the objectives. In a similar way, we are investigating the indoor environmental quality (IEQ) associated with thermal comfort, ventilation, and passive improvement of school buildings so that we can apply the results of the research to improve the quality of thermal environment of the school buildings in Nepal that are to be built in the future or renovated. Most school buildings in Nepal do not prioritize thermal comfort, the indoor thermal environment, or passive climate adaptation of buildings. As mentioned earlier, most school buildings rely on natural ventilation through windows. Most poorly designed buildings' infrastructures are still existing, which may not be suitable to provide an acceptable indoor thermal environment for students. And therefore, thermal comfort and indoor air quality studies should be done to address the issues created by the climate or infrastructure so that we can improve the thermal environment of the classroom for comfort. To do so the real situation is necessary and urgent to evaluate both qualitatively and quantitatively and this study is an initial attempt to investigate them. Therefore, this study articulates the following questions to draw the research outline:

1. What are the present conditions of the thermal environment in school buildings in Nepal that are naturally ventilated and the thermal comfort perceived by the students in those environments?
2. How are the students adapting to and maintaining thermal comfort in the school buildings without using a mechanical control system?
3. Is the indoor air quality associated with ventilation and CO_2 concentration sufficient and acceptable to the students?
4. In Nepal, school buildings are mostly ventilated through windows or doors. Do these ventilation methods provide adequate ventilation?
5. How can thermal environment and thermal comfort in those buildings be improved effectively using natural resources and as little energy as possible so that the impact of passive design can be known if school buildings are to be constructed or renovated?

1.6 Thesis objectives

The literature review in 1.2 shows the importance and demands of investigations on thermal comfort, ventilation, CO_2 concentration, and thermal environment to be conducted in naturally ventilated school buildings through field measurement, modelling, and simulation to enhance the proper understanding of IEQ quantitatively, especially in developing countries like Nepal where institutional infrastructure development is rapidly growing. Therefore, this study is intended to investigate them. Field surveys were conducted during the middle of autumn 2017 and the summer of 2019. The former study was to investigate the present condition of thermal comfort, and the latter study was to study the indoor air quality associated with CO_2 concentration and ventilation in naturally ventilated school buildings located in a temperate climate region in Nepal. And lastly, this study aims to investigate how to improve the thermal environment of the school buildings using passive design strategies. The major objectives of this study are as follows:

1. To clarify the students' perception of thermal comfort
2. To determine the comfort temperature based on their thermal perception
3. To analyse how their clothing insulation affects their thermal comfort
4. To investigate the indoor air quality using measured indoor CO_2 concentration as an indicator
5. To develop a new method of estimating the ventilation and indoor CO_2 concentration
6. To estimate the natural ventilation in terms of number of air change rate and compare with previous studies
7. To estimate indoor CO_2 concentrations under reduced ventilation scenarios using the developed model
8. To analyse the indoor thermal environment and how passive design strategies are effective in maintaining the operative temperature at a level that is suitable for thermal comfort

1.7 Thesis structure

The thesis is structured into six chapters in total, as shown in the flow chart (Fig. 1.5). The structure is in accordance with the study conducted, the data collected, and the data analysis, where each chapter represents a part of this work. Chapter 1 has introduced the overview on thermal comfort, natural ventilation, and the thermal environment associated with IEQ. It has stated the review of them, the research gap, the research questions, and the study objectives. Chapter 2 presents the methods of data collection, modelling, and simulation. Chapter 3 presents the adaptive thermal comfort of the students based on the field survey data analysis. Chapter 4 presents the real situation of CO_2 concentration and ventilation based on the mathematical modelling developed. Chapter 5 presents the improvement of the indoor thermal environment for summer thermal comfort. Finally, Chapter 6 presents the conclusion and the recommendations of this study. The detailed descriptions are provided in each related chapter.

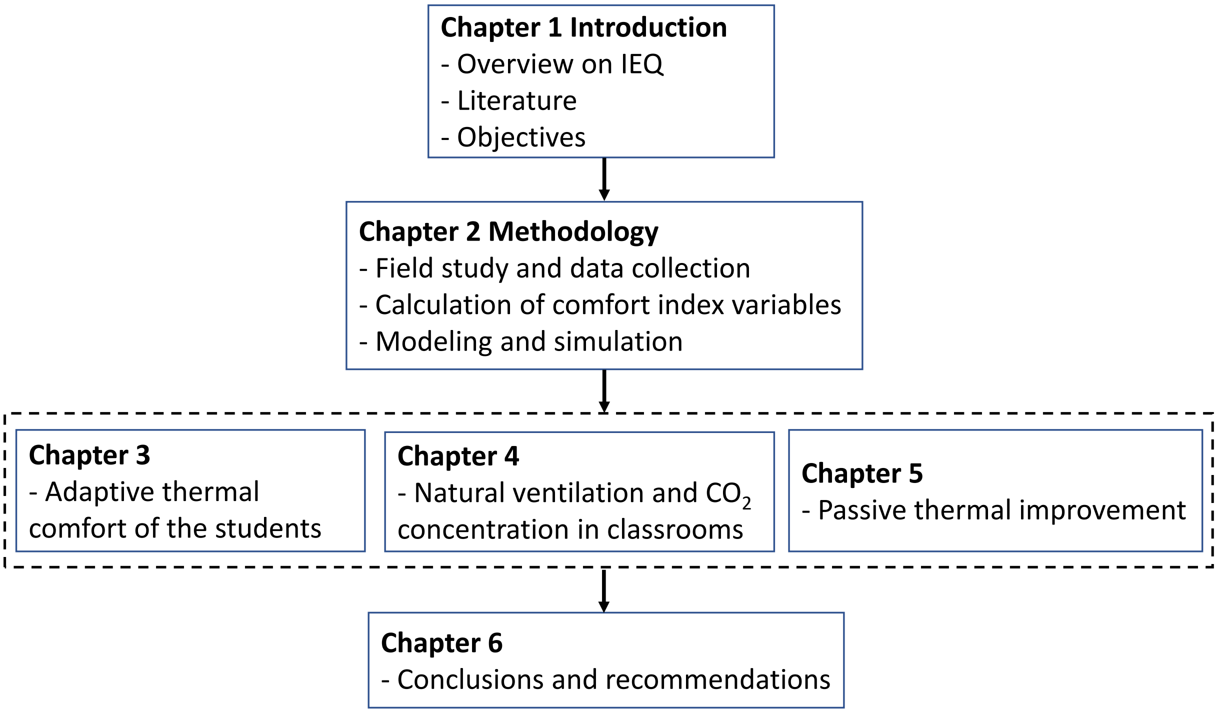


Figure 1.5 Thesis structure and chapters

Chapter 2: Methodology

2.1 Introduction

In this chapter, we have outlined and described the investigated areas with their climatic conditions, characteristics of the investigated school buildings, and methods of subjective and objective data collection. The current study follows the adaptive thermal comfort approaches to investigate the actual situation of the students' thermal comfort and thermal environment. The comfort temperature is estimated using the Griffiths method. Further, this section is mainly comprised of numerical modelling and simulations. We have developed an explicit type of discretization method based on transient mass balance to evaluate indoor air quality associated with ventilation and CO_2 concentration. We measured CO_2 concentration as an IAQ indicator because it can be measured without interrupting the regular lesson period of students. Thermal comfort is also modelled using a numerical model called the heat balance equation, which is out of the scope of this thesis.

2.1.1 Investigated areas

Nepal is a landlocked country in Asia located between China and India. It has a very diverse type of climate due to its geographic latitude, which runs from south to north. It is topographically divided into three regions: the north is a mountainous Himalayan with a cold climate; the middle is hilly with a temperate climate; and the south is Terai with a sub-tropical climate. The temperate climate is the most common dominant climate, with dry winters and hot summers (Karki et al. 2016). The distinction between summer and winter conditions according to geography is not straightforward in Nepal. A series of field studies were conducted in three areas (Dhading, Kathmandu, and Nuwakot districts) in the temperate climate region, with altitude ranges from 600 to 3000 m, as shown in Fig. 2.1. The height above sea level of eight investigated schools ranges from 860 m to 1720 m. Kathmandu, the capital of Nepal, represents the urban area, while Dhading and Nuwakot represent the rural area.

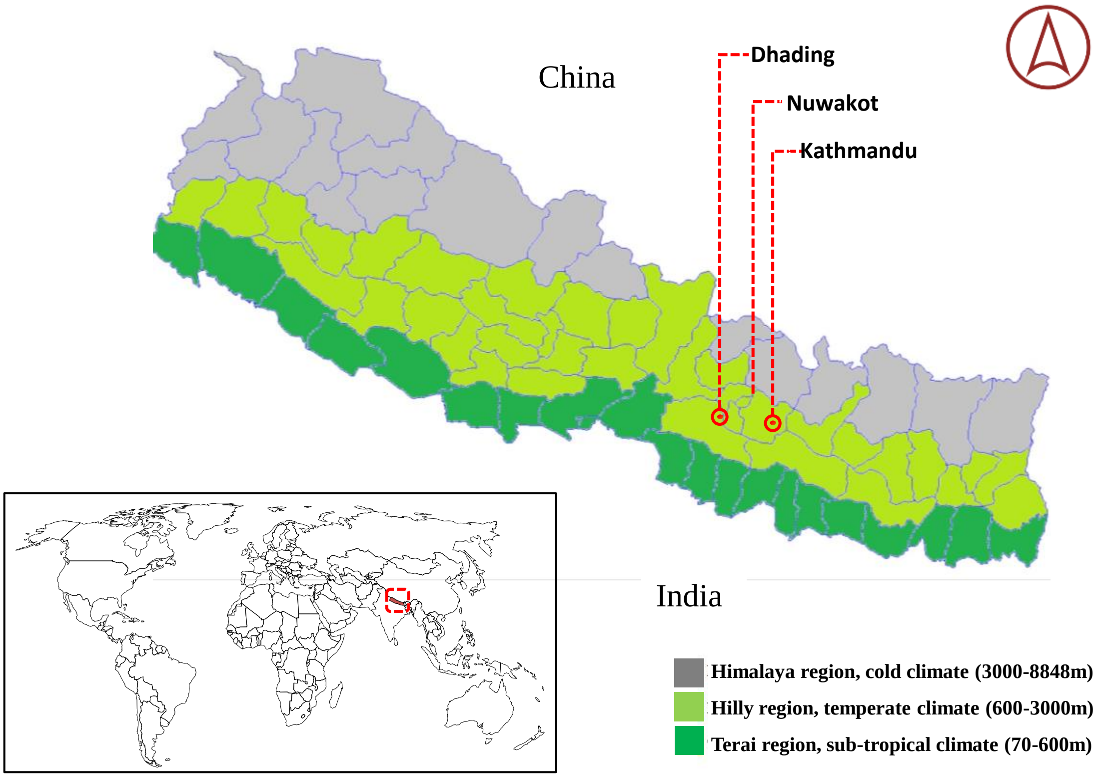


Figure 2.1 Location of the study areas in the map of Nepal

2.1.2 Climates of the investigated areas

Figs. 2.2 (a) and (b) show the variation in the monthly mean outdoor air temperature and the humidity of the investigated areas obtained from the meteorological station (Department of Hydrology and Meteorology). The variations in outdoor air temperature and relative humidity are similar to each other. June to September are the months with the hottest temperatures, highest rainfall, and relative humidity for all three of these study regions. In October, the outdoor air temperature decreases, reaching a minimum in January. The relative humidity from June to September ranges between 70-83%, probably due to the low air temperature. Fig. 2.2 (c) shows that the water vapour concentrations of the three study areas are very similar to each other, with the lowest concentration in January, at about 8 g/m^3, and the highest in August, from 19 to 22 g/m^3. The surveys were conducted in October 2017 and May to June 2019, which are relatively hot and humid months.

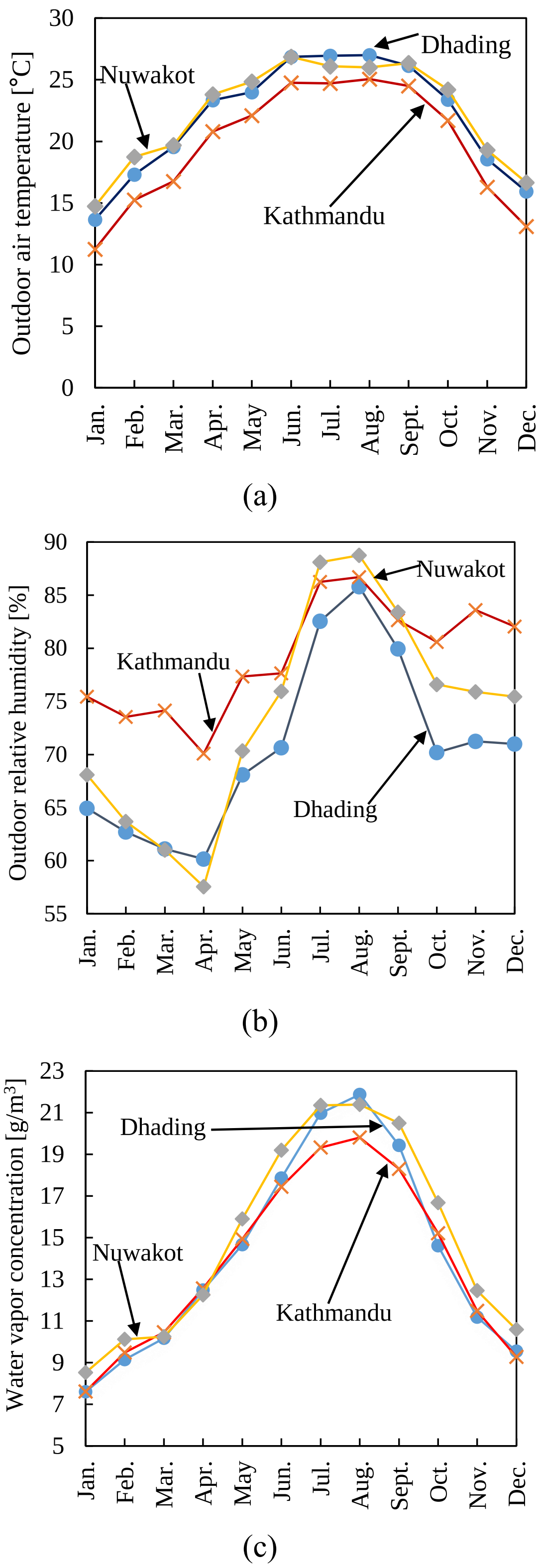


Figure 2.2 Climate data of the study areas: (a) Monthly mean outdoor air temperature, (b) monthly mean relative humidity, and (c) calculated water vapour concentration

2.1.3 Investigated school buildings and description of classrooms

The survey was conducted in 24 classrooms of 8 and 7 classrooms of 3 school buildings under the condition of natural ventilation in 2017 and 2019, respectively. The former field study included two private (198 students) and six public schools (620 students), of which three schools from Kathmandu, four from Dhading, and one from Nuwakot were selected, and latter field visit included one private (33 students) from Kathmandu and two public schools (213 students) from Dhading. With the permission of school administrators, classrooms were selected in each school for investigation. The investigated buildings were in areas that did not restrict window opening and closing operations due to crowded traffic, pollution, or odor. Generally, the participating schools run for six days a week. Fig. 2.3 shows the external and internal views of three general types of schools located in the three different study areas. The structure and size of the classrooms in the investigated buildings were different in most cases. Table 2.1 outlines the characteristics of all the investigated school buildings, participating students, survey time, and the number of votes obtained per topic question. The building structure is a reinforced concrete structure with different façade orientations and either two, three, or four stories. The survey was conducted in classrooms located on the ground, first, or second floor during different periods of regular lessons. The building walls were made of bricks and stones, and the wall surfaces were finished with mortar and plaster. The roofs of some classrooms in schools were made only of thin, 0.26–3 mm-thick zinc sheets. All classrooms have windows of different sizes for natural ventilation and daylighting. In school, S3, there is only one window. In some schools, owing to the absence of shutters and glass sheets, the windows remained open. None of the classrooms were equipped with air-conditioning systems or fans. The number of students in each classroom ranged from 14 to 60, with an average of 33.

Most of the classrooms are located on the ground floor and have windows of different sizes for ventilation and daylighting. Windows and doors were constructed with wood and iron frameworks, provided mostly by wood shutters. However, the construction varies from one school to the next. Windows with a greater number of shutters with a joint vent at the top of them are horizontal rectangular and windows having a single opening with two shutters are usually vertically rectangular shapes, respectively. A few windows were not provided either by shutters or glass sheets.

S2 (Dhading)

S5 (Kathmandu)

S8 (Nuwakot)

S11 (Kathmandu)

Figure 2.3 External (left) and internal (right) views of three schools: S2 (Dhading), S5 (Kathmandu), S8 (Nuwakot), S11 (Kathmandu).

Fig. 2.4 shows a representative plan view of the school buildings S9, S10, and S11 that distinguishes the characteristics of the classrooms, such as their volume, student occupancy, number of windows and doors, structure of windows and doors, and orientations. The average classroom floor area ranges from 9 to 50.2 m^2, while the volume ranges from 27 to 125.4 m^3. The occupancy density ranges from 0.8 to 2.1 student/m^2. The students were all secondary level males and females aged 12~18 years. Although the classrooms could become empty during the 30-minute break time, in reality, only a few students remain in the classrooms. Generally, secondary or primary level students spend their time mostly in one classroom, except for break time. Sometimes, students go outside after each 45-minute lecture to use the restroom.

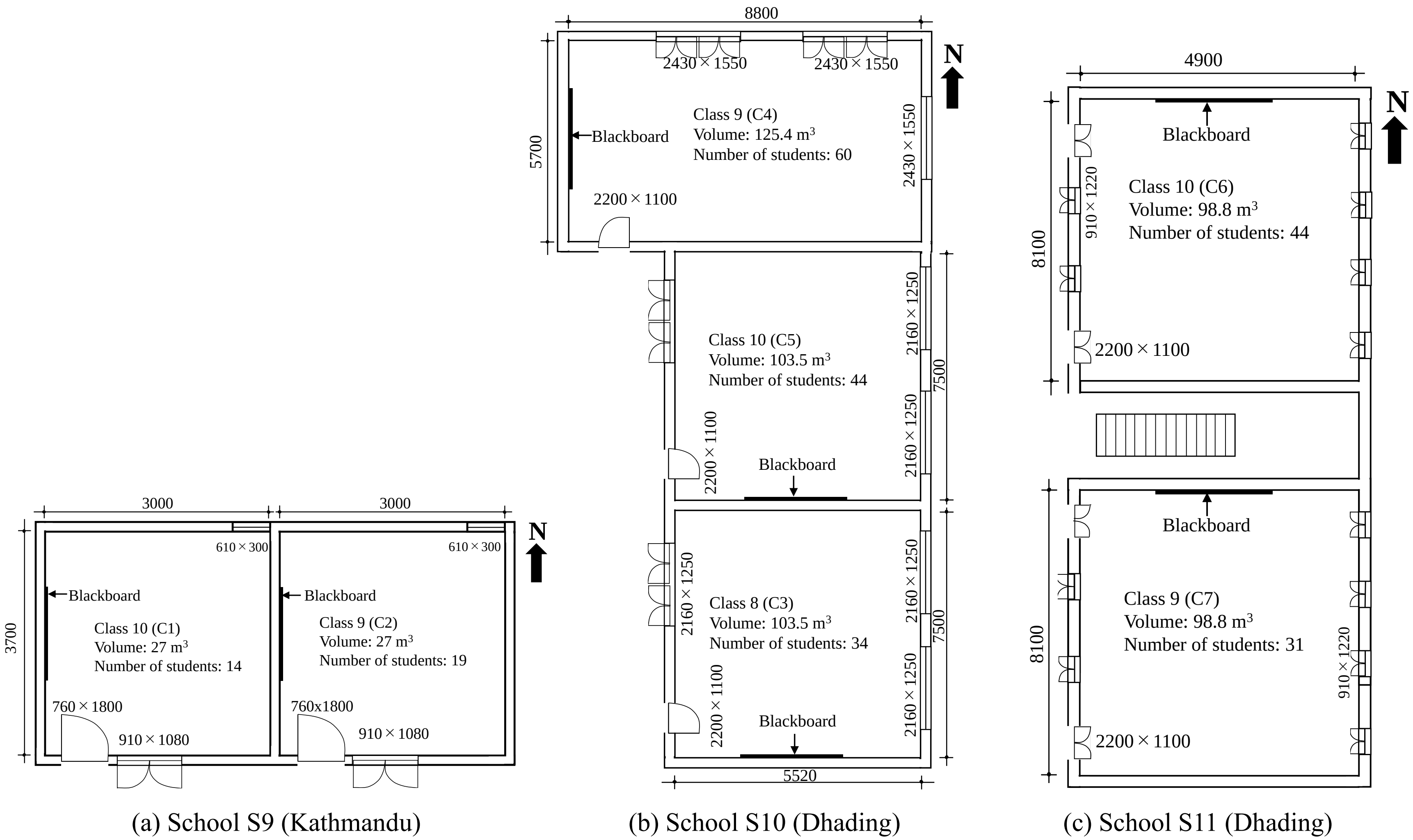


Figure 2.4 Plan view of the investigated school buildings (S9, S10, & S11) and classrooms (C1~C7)

Table 2.1 Characteristics of all the investigated buildings, participating students, survey time, and the number of votes obtained per topic question.

Year	District	Altitude (m)	Code	Name of school	School type	Building structure	Main façade	Surveyed floor	Windows/doors no.	Survey time	Students no.	Grade	Votes no./topic
2017	Dhading	1360	S1	Kewalpur Harihar Bhalkumari School	Public	Two-story,	North	GF	4/1	13:15~14:00	14	8	42
						RC* with brick walls and plaster finish		GF	6/2	11:45~12:30	25	9	75
								GF	6/2	12:30~13:15	27	10	81
		860	S2	Bhuwaneshwori Secondary School	Public	Two-story,	South	GF	4/1	15:00~15:45	38	8	114
						RC with brick walls and plaster finish		GF	4/1	13:00~13:45	46	9	138
								GF	4/1	14:00~14:45	43	10	129
		-	S3	Mahankaleshwori Secondary School	Public	Three-story,	West	GF	2/1	14:15~15:00	48	8	144
						RC with brick walls and plaster finish		GF	1/1	12:45~13:30	37	9B	111
						Zinc roof		1	3/1	12:00~12:45	41	9A	123
								2	4/1	11:15~12:00	52	10	156
		1120	S4	Jyoti Secondary School	Public	Two-story,	West	GF	3/1	14:45~15:30	50	9	150
						RC with brick walls and plaster finish		GF	3/1	15:15~16:00	32	10	96
	Kathmandu	1370	S5	Gramsewa Secondary School	Public	Two-story,	North-west	GF	3/1	14:45~15:30	28	8	84
						RC with brick walls and plaster finish		1	3/1	13:45~14:30	32	9	96
								1	3/1	12:15~13:00	22	10	66
		1310	S6	Pragya Commerce College	Private	4-story	South	1	3/1	15:15~16:00	32	8	96
						RC brick walls & plastered inner walls		1	4/1	13:45~14:30	18	9	54
								2	6/1	14:30~15:15	27	10	81
		1300	S7	Greenland Int'l Secondary School	Private	Two-story,	South-east	1	4/1	11:00~11:45	48	9A	144
						RC with brick walls and plaster finish		1	3/1	11:45~12:30	43	9B	129
						Zinc roof		1	2/1	12:45~13:30	30	8	90
	Nuwakot	1720	S8	Belkot Bhanjyang Secondary school	Public	Single-story, brick wall and plaster finish	East	GF	2/1	11:45~12:15	26	8	78
						Zinc roof, Walls and roofs of a few		GF	2/1	12:15~13:00	25	9	75
						classrooms were made by zinc alone		GF	5/1	10:45~11:30	34	10	102
2019	Kathmandu	-	S9	Ganesh Boarding School	Private	Single-story, brick wall and plaster finish	South	GF	2/1	10:00~15:30	19	9	57
						internally, Zinc roof		GF	2/1	10:00~15:30	14	10	42
	Dhading	1120	S10	Jyoti Secondary School	Public	Two-story,	West	GF	3/1	10:00~15:30	34	8	102
						RC with brick walls and plaster finish		GF	3/1	10:00~15:30	60	9	180
								GF	3/1	10:00~15:30	44	10	132
		1360	S11	Kewalpur Harihar Bhalkumari School	Public	Two-story,	North	GF	6/2	10:00~15:30	31	9	93
						RC with brick walls and plaster finish		GF	6/2	10:00~15:30	44	10	132

2.2 Measurement survey of environmental quantities

The survey was conducted in October 2017 and in May and June 2019. Digital data loggers were used to measure the environmental quantities. Two sets of digital data loggers were prepared to measure the indoor and outdoor environmental quantities. They were air temperature, relative humidity, globe temperature, and air velocity, which were recorded by digital instruments at the time of voting. The surface temperature of the four walls, ceiling, and floor were also measured. For the indoor air quality associated with ventilation, CO_2 concentration was measured during the regular lecture. All the quantities were continuously measured at 10-minute intervals in all classrooms for the whole day periods of regular lessons. Subsequently, the measured indoor CO_2 concentration at a 10-minute interval is recalculated at a 30-second interval for the analysis of natural ventilation (the method is given in Appendix I). The measurement was performed at the centre of each classroom, away from the windows and doors, at a height of approximately 1.1 m, minimizing the influence of the students nearby. Fig. 2.5 shows the general view of the position of the digital data loggers used for the measurement. The index temperatures, mean radiant temperature (*MRT*) and operative temperature (T_{op}), were estimated from measured environmental quantities, which will be discussed in 2.5. Table 2.2 presents the characteristics of the data loggers used. Fig. 2.6 shows the procedure of the data collection during the regular lecture in each classroom in the field survey of 2017 and 2019.

Table 2.2 Characteristics of the data logger used.

Description	CO_2 sensor (TR-76Ui)	Temperature-humidity sensor (TR-74Ui)		Globe thermometer (TR-52i)
Sensor	NDIR	Thermistor	Polymer-resistance	Thermistor
Measurement range	0 to 9,999 ppm	0 to 55 °C	10 to 95%RH	-60 to 155 °C
Accuracy	± (50 ppm + 5%) at 5,000 ppm or less	±0.5 °C	5% RH (at 25 °C, 50% RH)	±0.3 °C
Measurement resolution	Minimum of 1 ppm	0.1 °C	1% RH	0.1 °C
Response time	90%: Approx. 1 min.	90%: Approx. 7 min.	90%: Approx. 7 min.	90%: Approx. 80 sec. in air

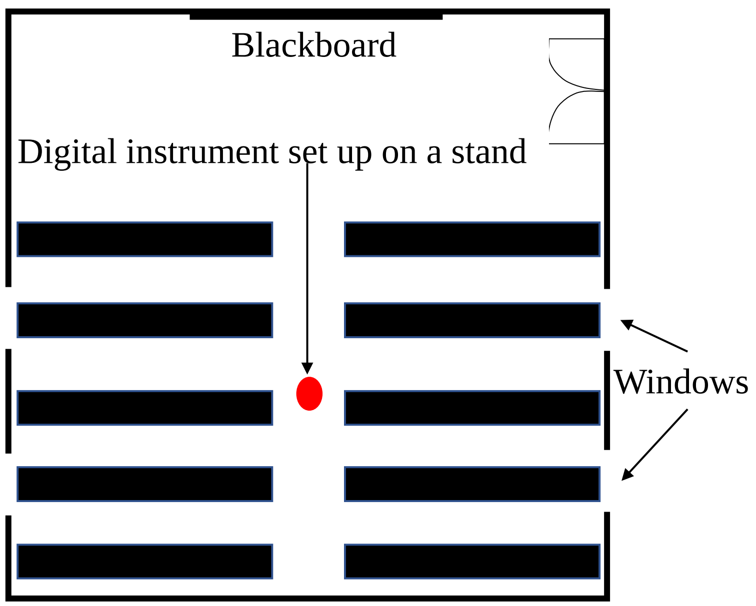
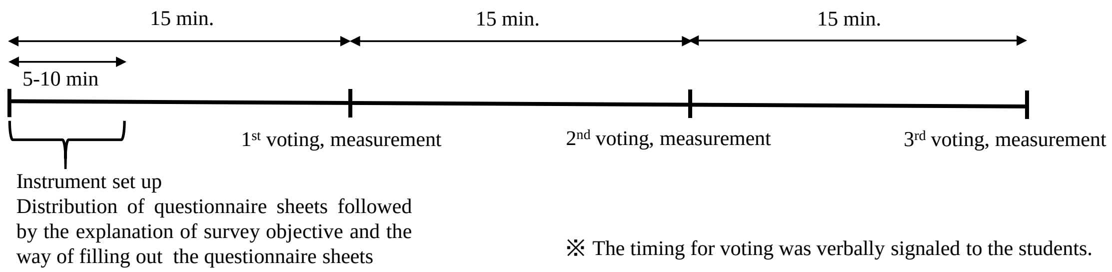
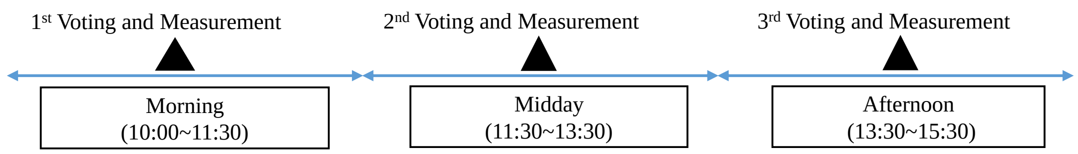


Figure 2.5 General view of the position of the data loggers in classroom



(a)



(b)

Figure 2.6 The procedure of questionnaire survey and environmental measurements: (a) 2017 and (b) 2019

2.3 Questionnaire survey/comfort survey

In conjunction with the measurement of environmental quantities, subjective responses to environmental perception were asked (Fig. 2.7). Altogether, 818 students participated in the questionnaire survey, of which 489 were females (60%) and 329 were males (40%) in 2017 and 246 in 2019, of which 101 (40%) were males and 145 (60%) were females, ranging in age from 12 to 18 years. We questioned the students on their thermal sensation, thermal preference, overall comfort, thermal acceptance, and so on, as shown in Table 2.3. The thermal perception was voted by the students in sedentary conditions without intervening in the regular lesson. This study assumed a constant metabolic rate of the students for thermal sensation as the survey was conducted during regular lectures with no physical activities being performed by the students. The students did not participate in high-energy activities, such as sports or running, between class intervals. A 30-minute break time with a light meal was provided to the students in all the schools during the daytime. During the autumn 2017, the questionnaire sheets were distributed to the students at the beginning of the lesson. First, we took 5-10 minutes to explain the purpose of this survey and the way in which the questionnaire sheets should be filled out. After the first voting, they were asked to vote at every 15-minute interval. Therefore, in one 45-minute lesson, the students would have voted three times, resulting in three sets of measured physical values. We gathered 2454 valid votes: 1359 (Dhading), 840 (Kathmandu), and 255 (Nuwakot). Additionally, 72 sets of measurements of physical quantities were obtained: 36 in Dhading, 27 in Kathmandu, and 9 in Nuwakot.

During the summer 2019 field survey, altogether, 15 questions were asked. They are related to indoor environmental quality conditions such as thermal sensation, overall comfort, IAQ, and so on. The details of the questionnaire are provided in Appendix III. However, we have analysed only the responses to the question, “How do you perceive the air quality of the classroom right now?”. Table 2.3 shows the question and four-point scale used in the survey (Stazi et al. 2012).

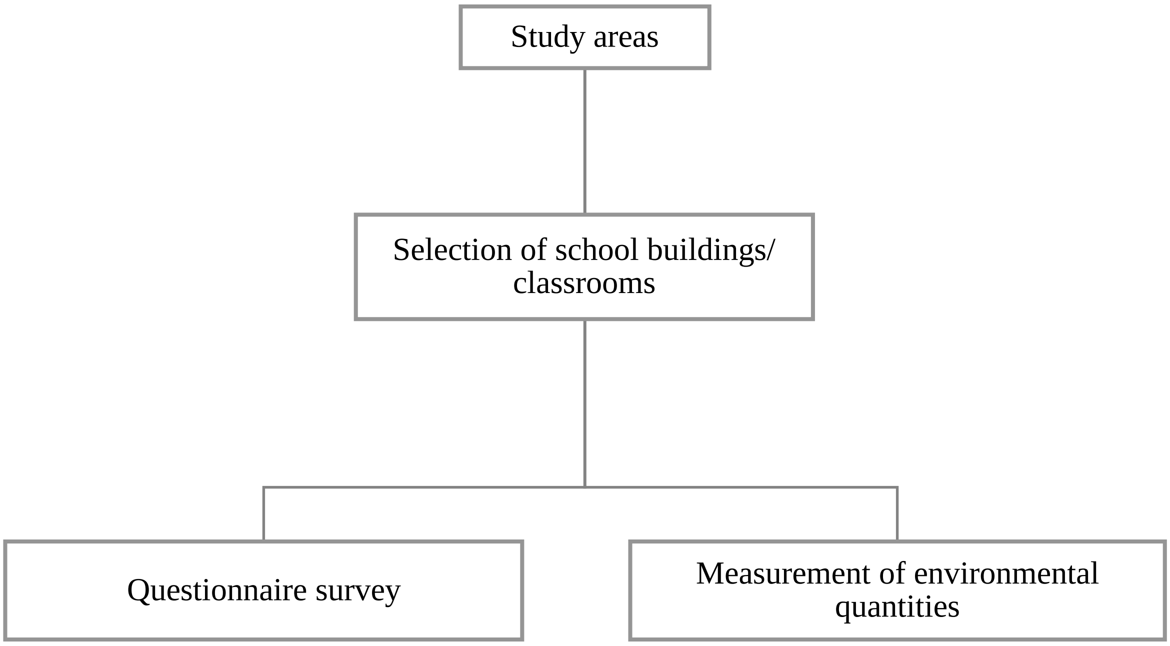


Figure 2.7 Flow chart of thermal comfort survey

Table 2.3 Scales used for thermal comfort survey.

Scale	Thermal sensation	Thermal preference	Overall comfort	Thermal acceptance	Indoor air quality
7	Very hot				
6	Hot		Very uncomfortable		
5	Slightly hot	Much cooler	Moderately uncomfortable		
4	Neutral	A bit cooler	Slightly uncomfortable		Clearly unacceptable
3	Slightly cold	No change	Slightly comfortable		Just unacceptable
2	Cold	A bit Warmer	Moderately Comfortable		Just acceptable
1	Very cold	Much warmer	Very comfortable	Unacceptable	Clearly acceptable
0				Acceptable	

2.4 Estimation of index environmental variables

The comfort index is a value that expresses the relationship between the human body and its surrounding environment (Fabbri 2015). To analyse the thermal environment and comfort, measured environmental quantities alone may not be sufficient. Therefore, we need some index environmental variables to know the actual environmental conditions and this section presents them.

2.4.1 Estimation of mean radiant temperature and operative temperature

Measuring the indoor air temperature or mean radiant temperature is not sufficient to determine the overall thermal environment and comfort level within a space. This is because these factors do not consider other important aspects of the thermal environment, such as heat exchange, conduction, convection, and the effect of air velocity. All these factors can have an impact on thermal comfort and must be considered to accurately evaluate the indoor thermal environment. Consequently, another decisive index, known as operative temperature, is required, which is a function of air temperature and mean radiant temperature (T_{mrt}), and is calculated using the following equations (ISO 7730 2005 & Thorsson et al. 2007).

$$T_{mrt} = [(T_g+273)^4+(1.1\times10^8\times V_a^{0.6}\times \mathcal{E}D^{-0.4})\,(T_g-T_a)]^{0.25}-273 \qquad (2.1)$$

where T_g: globe temperature (°C), T_a: indoor air temperature (°C), V_a: air velocity (m/s), $\mathcal{E}$: emissivity (= 0.95 for a black globe), D: diameter (= 0.075 m for a globe).

Operative temperature, T_{op}, is defined as:

$$T_{op} = \alpha T_{mrt} + (1-\alpha)T_a \qquad (2.2)$$

where T_{mrt} is the mean radiant temperature for the thermal zone. α is the radiative fraction given by

$$\alpha = \frac{h_r}{h_r + h_c}$$

h_c is the convective heat transfer coefficient and h_r is the radiative heat transfer coefficient. If h_c is larger, α decreases i.e. on increasing ACH, h_c becomes larger.

According to ANSI/ASHRAE Standard (2010), operative temperature can be approximated if occupants are engaged in near-sedentary activity, not in direct sunlight, and are not exposed to air velocities greater than 0.10 m/s. Under low air velocities radiative and convective heat transfers may be similar. So,

$$T_{op}=(T_a+T_{mrt})/2 \qquad (2.3)$$

With low air velocity and similar air and radiant temperatures, air temperature alone can be a reasonable indicator of thermal comfort indoors. However, in a thermal environment with heated surfaces due to solar radiation, they may differ greatly, making it necessary to consider radiant temperatures when assessing thermal comfort. Further, if the natural ventilation is high, the convective part may be a little bit large. Therefore, the weighting factors of 0.5 for radiant temperature and 0.5 for air temperature may be different. But during the night, it may be possible due to the low surface temperature.

Moreover, the adaptive comfort model suggests judging the indoor thermal comfort of a naturally ventilated space using operative temperature (Huang et al. 2015). We measured the air velocity only during the voting time, so the operative temperature could not be calculated for the whole-day lesson period. Using the voting time measurements of indoor air temperature, indoor globe temperature, and air velocity on the survey day (28 May) in S1 building, the operative temperature was calculated. Fig. 2.8 shows the correlation between the indoor globe and operative temperature, which indicates that they are equal. Bradshaw (2006) reported that the globe temperature is approximately the same as the operative temperature. Kazkaz and Pavelek (2013) found that the globe temperature is equal to the operative temperature (less than 0.6 K) in the range of air velocities higher than 0.2 m/s and that the difference between the MRT and air temperature is less than 10 K. This implies that globe temperature and operative temperature can be used interchangeably. The differences in MRT and air temperature in the case study classroom at 11:00, 13:00, and 15:00 were 0.2 °C, 2.2 °C, and 0.3 °C, where the five-minute average air velocity was recorded automatically by the data logger as 0.20 m/s, 0.32 m/s, and 0.38 m/s, respectively. Many studies (Gautam et al. 2019 & Zaki et al. 2017) found that the globe and operative temperatures were numerically equal; therefore, we chose the operative temperature for the thermal comfort analysis.

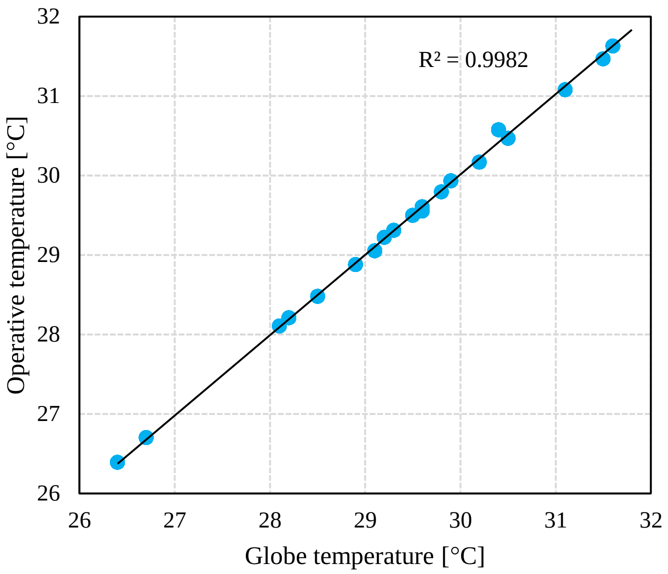


Figure 2.8 Relationship between calculated operative temperature and measured globe temperature.

2.4.2 Water vapour concentration

It is obvious that we are surrounded by moisture while we are outside or inside the buildings. In terms of thermal comfort, we define it using humidity, but humidity alone cannot quantify how much moisture is present around us. Therefore, another index called "water vapour" is needed. The saturated water vapour pressure under the saturation of liquid is given by (Shukuya, 2018)

$$P_{wvs} = e^{25.89-\frac{5319}{(273.15+T_i)}} \tag{2.4}$$

where T_i: air temperature (°C), P_{wvs}: saturated water vapour pressure (Pa)
Relative humidity (φ) is the ratio of the water vapour pressure of the actual air to the saturated water vapour pressure at the same temperature and pressure.

$$p_{wv} = 0.01\varphi\, P_{wvs} = 0.01\varphi e^{25.89-\frac{5319}{(273.15+T_i)}} \tag{2.5}$$

where p_{wv}: water vapour pressure (Pa)
An ideal equation for any gas is given by,

$$PV = nR(273.15+T_i) \tag{2.6}$$

P: pressure (Pa), V: volume (m^3), n: quantity of gas in molar mass (= 0.018 kg for water), R: gas constant (= 8.31 J/mol/m^3)
Using the above equation, we get

$$\text{Water vapour concentration } (C_{wv}) = 2.167\, p_{wv}/(273.15+T_i) \tag{2.7}$$

This equation shows that the concentration of water vapour depends on the air temperature alone, making it a necessary analysis for a thermal comfort study.

2.4.3 Estimation of comfort temperature

This study proposed Griffiths's method to calculate the comfort temperature, even though there is another method called "Linear regression analysis" which is the most common statistical method widely used to predict the trend of mean sensation vote over the range of indoor air temperature. The Griffiths method was developed by Griffiths (1990) to remove the limitations that the linear regression method has. The regression analysis needs a wide and large amount of data for analysis. Furthermore, due to the wide scatteredness of responses of the students obtained from the naturally ventilated buildings, the accuracy would be low. But the Griffiths method can work for a small sample of data and can calculate the individual comfort temperature. This method used a single value of regression coefficient (Griffiths slope or constant) for the linear relationship between thermal sensation vote and indoor temperature (Rijal et al. 2010, Humphreys et al. 2013, Niol & Humphreys 2012, Rijal et al. 2017, & Rupp et al. 2019). The Griffiths constant is the relationship between the thermal sensation vote and the indoor (globe) temperature where no adaptation to temperature takes place. The following relationship shows the Griffiths method of calculating the comfort temperature:

S1, S11

S2

S3

S4, S10

S5

S6

S7

S8

S9

Figure 2.9 Typical school uniforms worn by the students

$T_c = T_g + (4 - TSV)/a$ (2.8)

where T_c: Comfort temperature (°C), T_g: Indoor globe temperature (°C), TSV: Thermal sensation vote, and a: Griffiths constant whose value is 0.5. The constant values of 0.33 (Fanger 1970) obtained from a climate chamber test and 0.25 (Nicol et al. 1994) obtained from field surveys are often used.

2.4.4 Estimation of clothing insulation

Fig. 2.9 show the typical school uniforms that are worn by students. The students were guided to answer the level of dress code they were wearing by referring to the clothing checklist in the questionnaire. Their answers were converted into clothing insulation units according to ISO 7730 (2005) and ASHRAE (2017) for statistical analysis. An expected innerwear clothing value of 0.04 clo was added to the sum of the total clo values of the respective students. The clothing insulation of the students was calculated using the following formula:

$I_{(clo,total)} = \sum I_{(cl,i)}$ (2.9)

where $I_{(clo,total)}$ is the total clothing insulation (clo) and $I_{(cl,i)}$ is the clothing insulation (clo) value of the garment component, i.

2.5 Estimation of CO_2 emission rate and number of air change per hour (ACH)

2.5.1 Estimation of CO_2 emission rate

When students stay indoors for a long period, the amount of CO_2 increases due to their exhalation, and it results in the indoor CO_2 concentration being higher than outdoors. The mass balance of CO_2 for indoor space with respect to the incoming, outgoing, and stored
amounts of CO_2 is used to calculate the ventilation rates of classrooms. Although some studies assume the value of CO_2 emission per student is constant (Asif & Zeehan (2020, Coley & Beisteiner 2002, Cornaro et al.2013 & Hänninen et al. 2017), in this study, we calculated the rate of CO_2 emission from an individual student using the factors such as height, weight, body surface, and metabolic rate. There are a few methods to estimate the CO_2 emission rate (Coley & Beisteiner 2002); the estimation can be made using physical activity, body surface, and individual factors.
The CO_2 emission rate per person is estimated based on the chemical reaction of 1 mol of glucose with O_2 molecules. During the breakdown of food by human body, CO_2, H_2O, and thermal energy are released. The following reaction is assumed for the estimation of the CO_2 emission.

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 + 2808 \text{ kJ} \quad (2.10)$$

Eq. (2.10) represents one mole of glucose that meets with six O_2 molecules and thereby thermal energy of 2808 kJ together with six molecules of H_2O and CO_2 is released. The respiratory quotient, the ratio of the volume of CO_2 to that of O_2, is 1. Since the discharged amount of CO_2 and thermal energy are proportional, the rate of CO_2 to be discharged by metabolism can be estimated provided that the thermal energy emission rate from one person is given. The rate of thermal energy production by one person is equal to the product of metabolic generation rate per body area of one person and the body surface area. This relationship is used to estimate the CO_2 emitted by the students.

$$\frac{Y \times 58.2 \times A_{body}}{2808 \times 10^3} = \frac{x_{CO_2}}{6} \tag{2.11}$$

where *Y*: metabolic energy emission rate measured in metabolic equivalent [met], 58.2 is the rate of thermal energy emission per 1 met [W/m^2], x_{CO_2}: molar rate of CO_2 emission [mol/(s·p)], A_{body}: body surface area [m^2]

To calculate an individual's body surface, A_{body}, the DuBois Height-Weight formula (Du Bois et al. 1916) is used.

$$A_{body} = 0.20247 H^{0.725} W^{0.425} \tag{2.12}$$

where *H*: height [m], and *W*: weight [kg].

Since the molar mass of CO_2 is 44 g/mol, the mass emission rate per person in the unit of g/(s·p) can be calculated from

$$m_{CO_2} = 44 x_{CO_2} \tag{2.13}$$

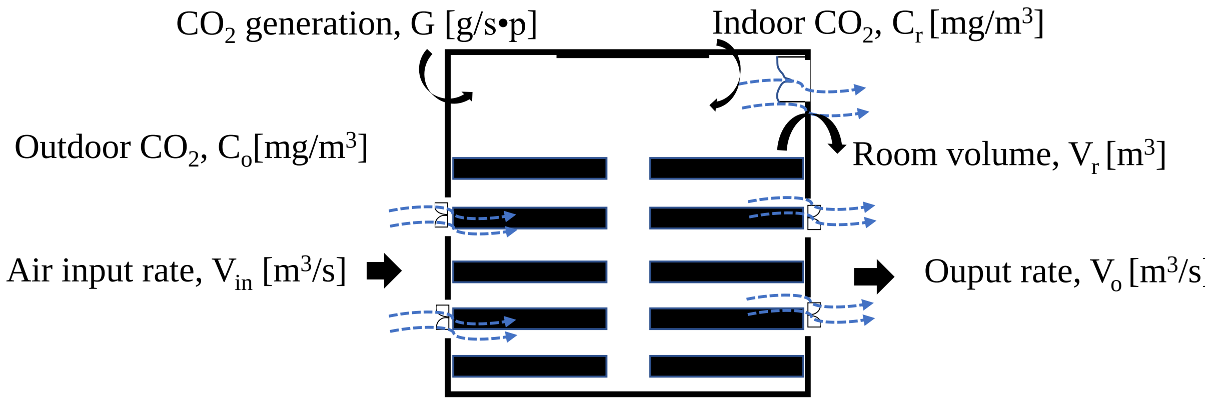
Substituting eqs. (2.12) and (2.13) into eq. (2) yield the following equation,

$$m_{CO_2} = 0.005472 Y A_{body} \tag{2.14}$$

The eq. (2.14) is used to estimate the CO_2 emission rate.

2.5.2 Estimation of the air change rate (ACH) using the CO_2 mass balance model

Since the formulae developed previously are not to estimate the time-variant ventilation, in this paper, a finite differential method of explicit type is applied to the mass balance equation in the classroom space for an infinitely small period, and thereby the formulae to estimate time-variant ACH and indoor CO_2 concentration were developed. The finite differential method of implicit is also derived but not used for analysis (Appendix II). The mass balance equation must satisfy the relationship between the mass of CO_2 coming in, which consists of the inflow by ventilation and the emission being equal to the sum of mass stored and the mass outgoing from the room as presented in Fig 2.10.



$$CO_2\ goint\ in + CO_2\ generated = CO_2 stored + CO_2 going\ out$$

Figure 2.10 Illustration of mass balance of CO_2 equation

For an infinitely small period, the following differential mass balance equation is derived (Shukuya 2019).

$$n_p G\mathrm{dt} + C_o V_{in}\mathrm{dt} = V_r dC_r + C_r V_o dt \quad (2.15)$$

where n_p: number of students, G: CO_2 emission rate by the students [g/(s·p)], C_o: outdoor CO_2 concentration [g/m^3], V_{in}: fresh air input rate [m^3/s], V_r: classroom volume [m^3], C_r: indoor CO_2 concentration [g/m^3], V_o: fresh air output rate [m^3/s], dC_r: infinitesimal change in CO_2 concentration [g/m^3], dt: infinitesimal time interval [s].

Assuming indoor and outdoor air flows are equal $V_o = V_{in}$.

$$n_p G\mathrm{dt} + C_o V_o\mathrm{dt} = V_r dC_r + C_r V_o dt \quad (2.16)$$

The unit of C_o and C_r in eq. (2.16) is g/m^3. They can be converted into ppm using conversion factor 1.865T, where T is the air temperature in Kelvin (Shukuya 2019).

Eq. (2.16) is reduced to the explicit type of finite difference equation denoting dt by Δt and dC_r by ΔC_r. During the time interval from (n-1)Δt to nΔt, the change in indoor CO_2 concentration is $\Delta C_r = C_r(n) - C_r(n-1)$, where $C_r(n)$ and $C_r(n-1)$ denote the CO_2 concentration C_r at the time nΔt and (n-1)Δt, respectively. The same notation is used for n_p, G, C_o, C_r, and V_o. Then, the finite differential equation is given as follows.

$$n_p(n-1)G(n-1)\Delta t + C_o(n-1)V_o(n-1)\Delta t = V_r\{C_r(n) - C_r(n-1)\} + C_r(n-1)V_o(n-1)\Delta t \quad (2.17)$$

Eq. (8) can be rewritten as follows,

$$C_r(n) = C_r(n-1) + \frac{V_o(n-1)}{V_r}\Delta t\{C_o(n-1) - C_r(n-1)\} + \frac{n_p(n-1)G(n-1)}{V_r}\Delta t \quad (2.18)$$

Using the number of air change per hour (ACH) [h^{-1}] denoted by N(n-1), at the time (n-

1)Δt, $N(n-1) = \frac{V_o(n-1)\times 3600}{V_r}$, then eq. (2.17) becomes

$$C_r(n) = (1 - \frac{N(n-1)}{3600}\Delta t)C_r(n-1) + \frac{N(n-1)}{3600}\Delta t C_o(n-1) + \frac{n_p(n-1)G(n-1)\Delta t}{V_r} \quad (2.19)$$

The value within the bracket in front of the first term of eq. (2.18) has to be positive, since the derived equation is based on the explicit type of finite differentiation; that is the constraint required is $\Delta t \leq \frac{3600}{N(n-1)}$ (2.20)

Once $C_r(n)$ is calculated, then the ACH at (n-1)Δt can be calculated from the following equation.

$$N(n-1) = 3600 \times \left(\frac{n_p(n-1)G(n-1)}{V_r\{C_r(n-1)-C_o(n-1)\}} - \frac{C_r(n)-C_r(n-1)}{C_r(n-1)-C_o(n-1)}\cdot\frac{1}{\Delta t}\right) \quad (2.21)$$

Because of the constraints of time required for estimation, eq. (2.20), we used the increment of time, Δt, to be 30 seconds. Therefore, the measured values of CO_2 concentration at 10-minute intervals are interpolated for 30-second interval values.

Using the estimated ACH along with other inputs such as room volume, number of students, outdoor CO_2 concentration, initial CO_2 concentration, metabolic rate and CO_2 emission, the indoor CO_2 concentration is estimated as shown in Fig. 2.11.

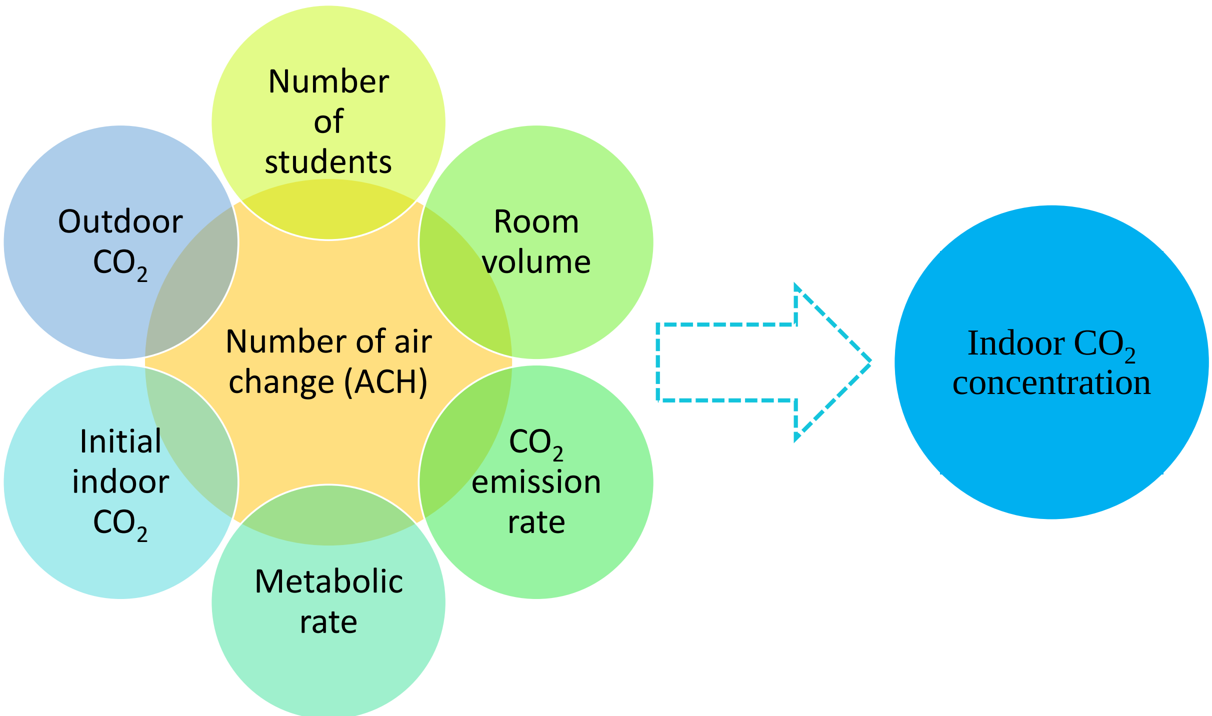


Figure 2.11 Parameters required to estimate indoor CO_2 concentration

2.6 Simulation for passive thermal improvement of classrooms

This section presents the details of the simulation for passive thermal improvements for thermal comfort. A representative school, S11, located in Kathmandu, is selected for the simulation.
The flow chart shows the special study methodology for the improvement study (Fig. 2.12). The methods cover field surveys and building simulation. The field survey collects environmental quantities and the thermal responses of students for the evaluation of thermal conditions as well as building information to develop a base model for simulation purposes. Later, the impact of individual passive design strategies on operative temperature is evaluated. The base model is generated based on case study school S11, which is a representative school found around the Kathmandu valley and other places located in temperate climates in Nepal. The structure, form, and materials used in the case study buildings are also similar to those of other school buildings.

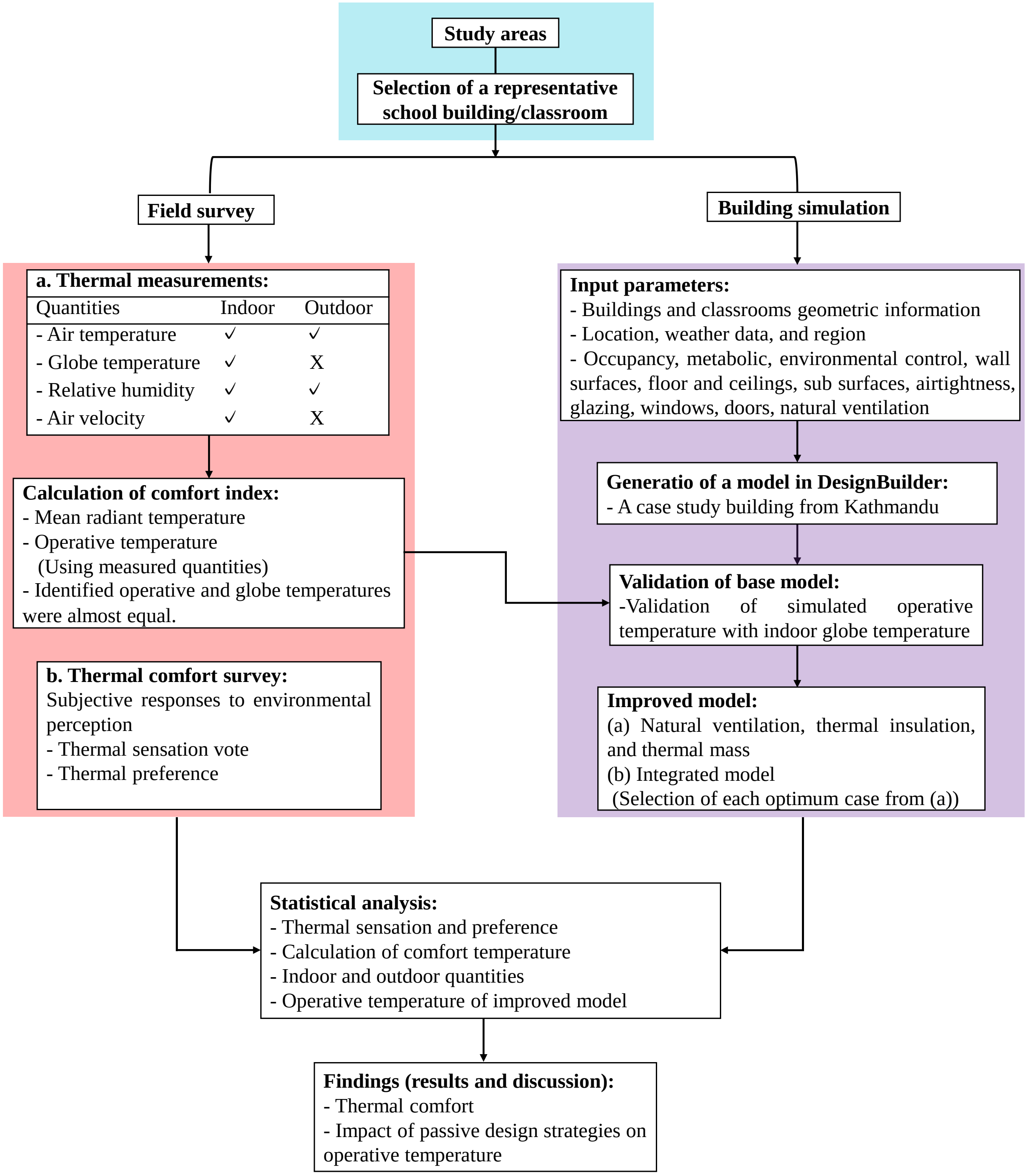


Figure 2.12 Flow chart of the thermal comfort and simulation study

2.6.1 Introduction of simulation software

There are many building simulation software packages. Out of those, this study used Designbuilder in conjunction with EnergyPlus, one of the highly recognised building energy and thermal performance simulation software programs, as environmental analysis software to design buildings and carry out the simulation (Designbuilder). This is a powerful building simulation program that facilitates a 3-dimensional (3-D) graphical interface for EnergyPlus used to model whole building energy use, climate conditions, and thermal loads (Zahiri &Altan 2016 & Al-Absi et al. 2020). But there is a limitation to imputing complex geometry. The input data is inherited from the hierarchy level above it; block data is inherited from the building level, zone data is inherited from block data, and surface data is inherited from zone data (Designbuilder), as shown in Fig. 2.13. This mechanism makes it easy to make any changes to the setting at any level, but not in reverse order. A particular year's weather data cannot better predict future conditions since the weather varies from year to year. Meteorological data from multiple years has been compiled into what is called a "Typical Metrological Year" or TMY, which is used in Designbuilder. The Energy Plus Weather (EPW) data file of Kathmandu (Tribhuvan international airport station) loaded in the software is used for simulation. The case study building is located around 8 km away from the weather station. Fig. 2.14 shows the monthly mean (dry-bulb and dew-point) outdoor temperature, wind speed, and solar radiation of Kathmandu, which were obtained from the weather data file. The maximum airspeed is seen from March to June. The maximum diffuse and direct solar radiations were 95 and 175 kW/m^2, respectively. The simulated data were analysed by exporting them to a spreadsheet. The core of the simulation is a model of the building that is based on the fundamental mass balance of heat, air, or moisture. There are various models used in the software; equation (2.22) shows the model for zone air temperature. According to this model,

$$C_z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} \dot{Q}_i + \sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z) + \sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z) + \dot{m}_{inf} C_p (T_\infty - T_z) + \dot{Q}_{sys} \quad (2.22)$$

Where:

$C_z \frac{dT_z}{dt}$ = Energy stored in the zone air

$\sum_{i=1}^{N_{sl}} \dot{Q}_i$ = Sum of the convective internal loads

$\sum_{i=1}^{N_{surfaces}} h_i A_i (T_{si} - T_z)$ = convective heat transfer from the zone surfaces

$\sum_{i=1}^{N_{zones}} \dot{m}_i C_p (T_{zi} - T_z)$ = heat transfer due to interzone air mixing

$\dot{m}_{inf} C_p (T_\infty - T_z)$ = heat transfer due to infiltration of outside air

$\dot{Q}_{sys}$ = air systems output

$Cz = \rho_{air} C_p C_T$

ρ_{air} = zone air density, Cp = zone air specific heat, CT = sensible heat capacity multiplier

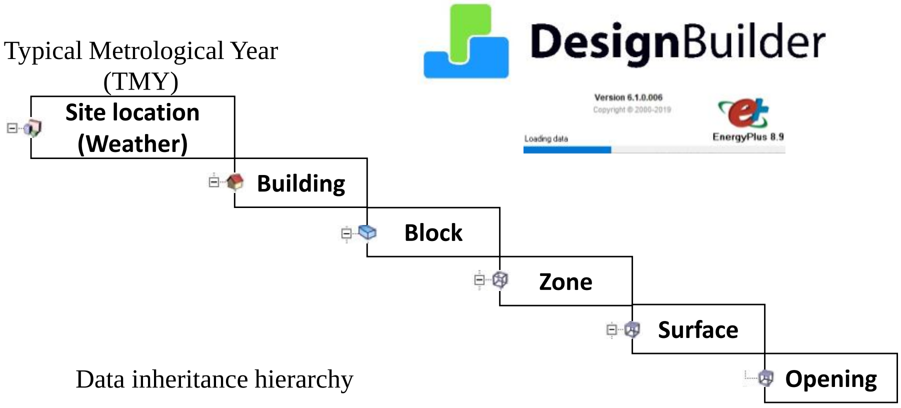
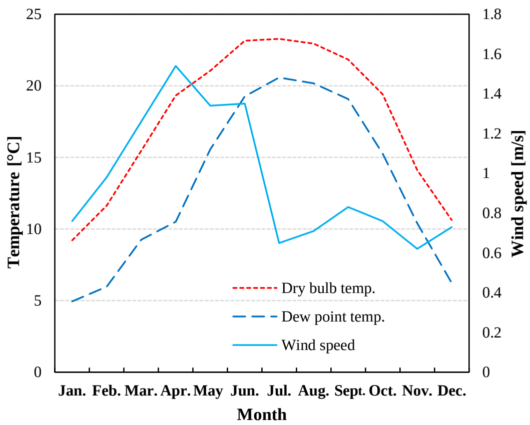
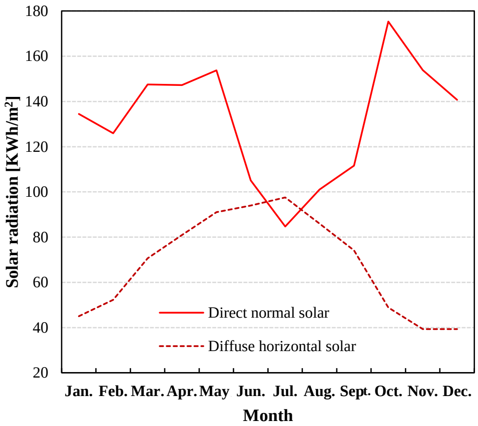


Figure 2.13 Data inheritance hierarchy in Designbuilder



(a)

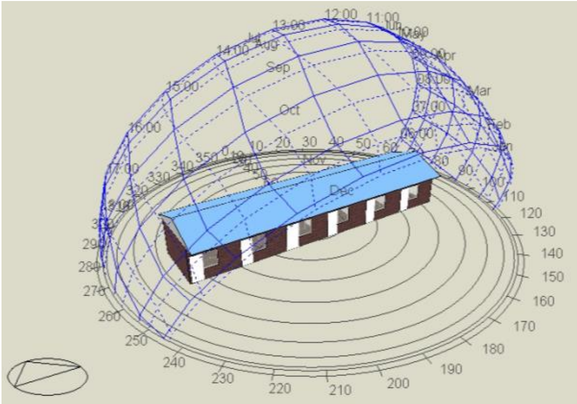


(b)

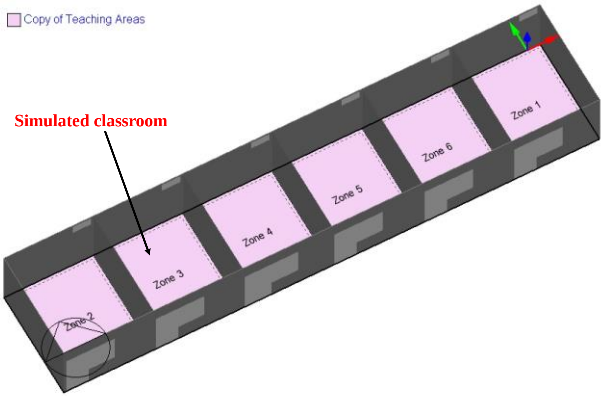
Figure 2.14 Monthly average values of climatic data in Kathmandu: (a) outdoor temperature and wind speed and (b) Direct normal and diffuse horizontal solar radiation.

2.6.2 Base case model

Fig. 2.15 shows the 3D view of the simulated school building (S11) and classroom (zone 3) generated in Designbuilder using the collected information. Fig. 2.15 (a) shows the sun path around the simulated school building, whose main facade is oriented towards the south. Table 2.4 shows the characteristics and thermal properties of the building materials. The wall is made up of two layers: a cement-bonded outermost layer and an innermost layer. The pitched roof (corrugated) is made of zinc sheet whose thickness is set to 3 mm, and the roof is supported by an iron truss. The height of the pitched roof is set to 80 cm from wall level. The ceiling is finished with plywood, whose thickness is around 18 mm. The outermost layer of the floor is cement/plaster/mortar. The partition wall is plastered on both sides. The window wall ratio is kept at 20%, and a single clear glass of 6 mm thickness is selected. No shading options were selected. All the classrooms in this building are the same in dimensions. The description of the simulated classroom is shown in Table 2.5. The minimum fresh air of 8 l/(s･p) is chosen as the recommendation of ASHRAE (2016). For airtightness, the minimum number of air change rates (ACH) of 1 per hour is taken to represent the unintended airflow through cracks. The ventilation is set to 59 ACH, which is the calculated value; however, the time-variant ACH was estimated, and the range of ventilation for the classroom was 47.8–99 ACH in Section 5.3.2. We scheduled the natural ventilation ON for 6 days as the windows and door were open, except Saturday. Lighting is set to 347 lux, as we took the average value of the measurements in the simulated school. Computers, office equipment, mechanical heating-cooling, miscellaneous, general lighting, and domestic hot water (DHW) were set to be turned off. The activity level of reading and sitting was chosen because the survey was conducted during regular lectures with no physical activities being performed by the students, and the CO_2 generation rate was set to its default value. The clothing insulation level of the students was set to 0.5 clo. All the above-mentioned activities, materials, constructions, openings, and so on (Tables 4 & 5) were input into the simulation software to generate the model, and then base model Zone 3 was selected for further analysis.



(a)



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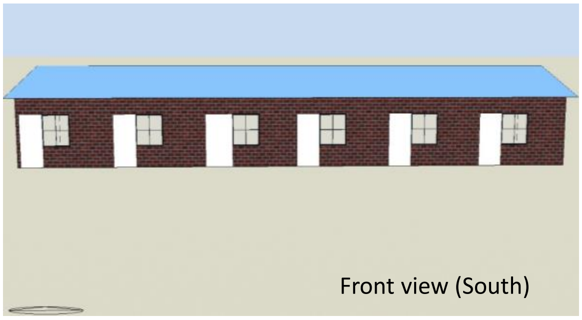


(c)

Figure 2.15 3D view of the simulation school building model (S1): (a) Sun path diagram, (b) Zones, and (c) South view. The latitude and longitude locations of the school building are 27.77348 °N and 85.33081 °E, respectively.

Table 2.4 Building materials and their properties assigned for the model

Component	Description/composition	Thickness (mm)	U-value [W/(m^2•K)]
External walls	Brick + internal cement plaster	87 + 15	3.2
Internal partitions	Cement plaster + brick + cement plaster	15 + 76 + 15	2.3
Floor	Cement/plaster/mortar + brick + soil-earth + common	5 + 60 + 100	2.4
Ceiling	Plywood	18	3.8
Roof	Zinc	3	7.1
Glazing	Clear glass	6	5.7

Table 2.5 Description of the simulated classroom

Classroom description	Input data
Floor area	11.78 m^2 (3.1 m x 3.8 m)
Height	2.4 m
Window 1	0.91 m x 1.08 m (South)
Window 2	0.61 m x 0.30 m (North)
Door	0.76 m x1.8 m (South)
Number of students	14
Occupancy density	1.6 students/m^2
Minimum fresh air	8 l/(s·p)
Airtightness	1 ACH
Natural ventilation (windows, door)	59 ACH, 9:30 to 17:30
Occupied period	Sunday to Friday, 9:30 to 17:30 No occupancy during break time
Activity level	Seated

2.6.3 Validation of base case model

The base model is validated using the measured globe temperature and simulated operative temperature. The accuracy of the model was checked using the root mean square error (RMSE) (Ascione et al. 2019 & Boutet & Hernández 2021). It measures how close the simulated and measured values are. For the reliability of the model, the mean absolute error (MAE) and the standard deviation of mean absolute error (MAESD) were employed. Moreover, the percentage error is also used to check the accuracy.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(T_{si}-T_{mi})^2}{n}} \tag{2.23}$$

$$MAE = \frac{\sum_{i}^{n}|T_{si}-T_{mi}|}{n} \tag{2.24}$$

$$MESD = \sqrt{\frac{\sum_{i}^{n}(|T_{si}-T_{mi}|-MAE)^2}{n-1}} \tag{2.25}$$

Where T_s and T_m are the simulated operative temperature and measured globe temperature at the time i, respectively, and n is the total number of data sets.

Chapter 3: Adaptive thermal comfort of students

3.1 Introduction

This chapter presents the results of the field study on adaptive thermal comfort. As mentioned in Chapter 1, the thermal comfort is quantified using the perceptions of the individuals and measuring the same time thermal environmental conditions, which are discussed in this chapter. Firstly, the actual thermal environmental condition is analysed, and how students perceive those environments is analysed. Furthermore, a comparison is made with the previous studies. Finally, the adaptive behaviours used by the students to adapt to the thermal environment of the classrooms are analysed.

Because there was more data collected during the field survey in 2017, the analysis of the thermal comfort survey is based mainly on that. However, important results are also included in the analysis of the field survey 2019 data.

3.2 The indoor and outdoor thermal environment during voting time

Fig. 3.1(a) shows the relationship between the indoor globe temperature and outdoor air temperature. The values of indoor globe temperature during the voting time ranged from 23 °C to 31 °C. The indoor globe temperature is correlated to the outdoor air temperature, but there are some cases in which the indoor globe temperature is 2 °C to 3 °C higher or lower than the outdoor air temperature. The higher temperatures are linked to the effects of transmitted solar radiation from the windows or absorbed solar radiation by walls or roofs. Alternatively, the lower temperatures occur when the mean radiant temperature is lower than the indoor air temperature, which may be due to the heat capacity effect of building envelopes, which are cooled by nocturnal sky radiation and outdoor air through convection. The variation in the indoor globe temperature was observed by the location of the floors above the ground. The mean indoor globe temperature of the classrooms on the first and second floors of school S6 was 25.9 °C, 26.6 °C, and 26.9 °C, with mean outdoor air temperatures of 25.1 °C, 24.8 °C, and 26.2 °C, respectively; the former being higher than the latter. A similar tendency was observed in school S3, where the mean indoor globe temperature of the classrooms located on the first and second floors was 28.5 °C and 30.5 °C, with mean outdoor air temperatures of 29.8 °C and 28.8 °C, respectively. The second-floor classrooms had a zinc roof whose interior surface is the same as the ceiling surface, which must have been temperature-responsive. The mean indoor globe temperature in classroom 9B at school

S3, which was located on the ground floor and whose ceiling was directly covered by the zinc roof, was 31.4 °C; the corresponding outdoor air temperature was 30.3 °C, owing to the effect of solar radiation as mentioned before. The effect of the difference between the indoor globe and outdoor air temperatures on the thermal perception of students in different classrooms will be discussed in the next section.

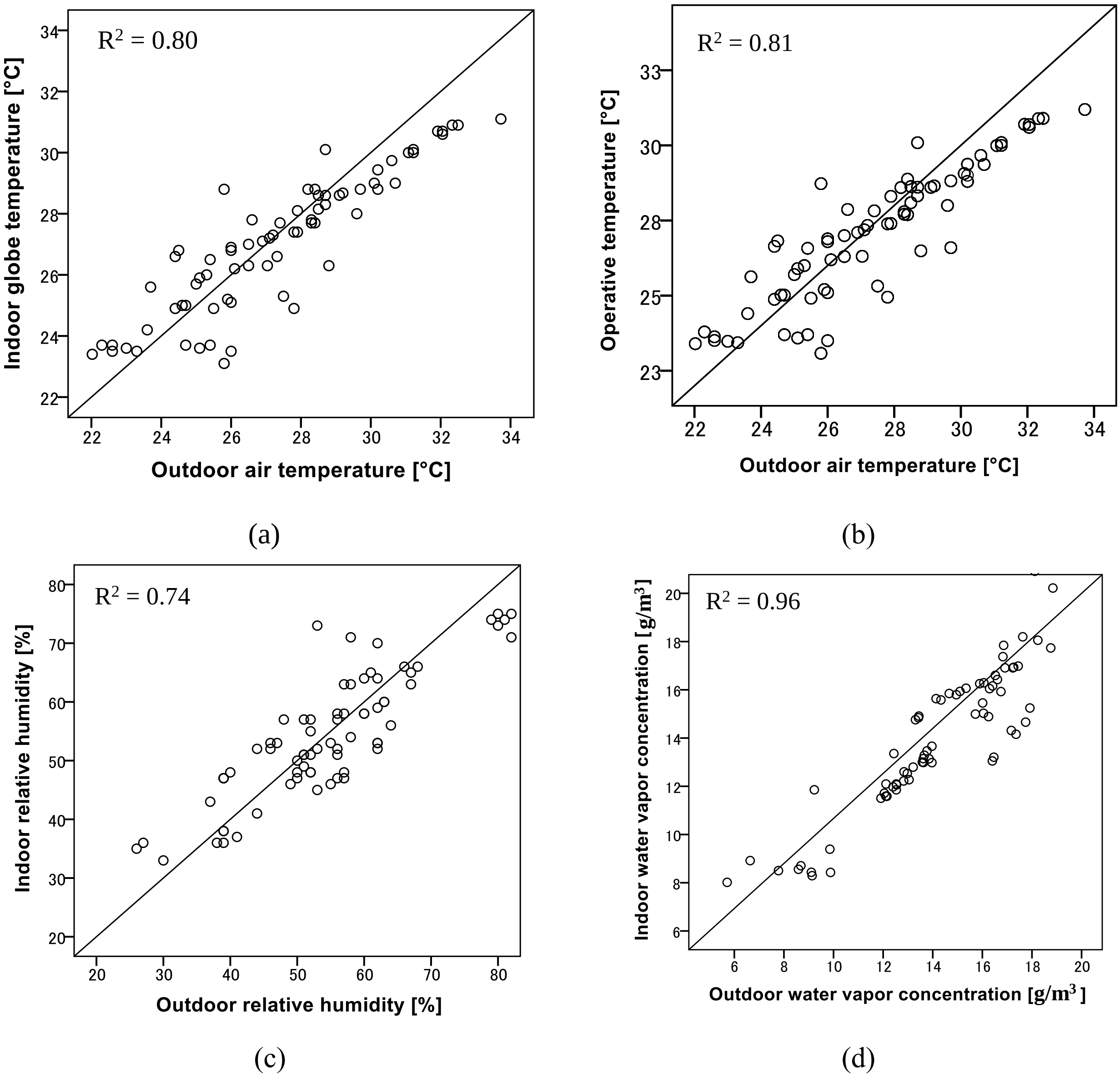


Figure 3.1 Measured environmental quantities: (a) indoor globe temperature and outdoor air temperature, (b) operative temperature and outdoor air temperature, (c) indoor relative humidity and outdoor relative humidity, (d) indoor water vapour concentration and outdoor water vapour concentration

Fig. 3.1 (b) shows the relationship between the operative and outdoor air temperatures, indicating a strong correlation between the two temperatures. Because of the similar correlation between outdoor air temperature and indoor globe and operative temperatures, the indoor globe temperature was used for further analysis.

Fig. 3.1 (c) shows the relationship between the indoor and outdoor relative humidities, while Fig. 3.1 (d) shows the relationship between the indoor and outdoor water vapour concentrations. The indoor and outdoor humidities are correlated with each other; however, they are less correlated than the water vapour concentrations. This is because the relative humidity is a function of not only the water vapour concentration but also the temperature. Therefore, it is better to compare the indoor and outdoor water vapour concentrations. Since the density of the population in all classrooms is high, the emission rate of moisture from the human bodies is also high. Nevertheless, the indoor and outdoor water vapour concentrations are similar to each other. This confirms that natural ventilation performed quite effectively. Although the windows of classrooms were kept open for natural ventilation, the indoor air velocities were exceptionally low, with a mean and standard deviation of 0.10 ± 0.05 m/s.

3.3 Thermal perception of the students

3.3.1 Overall results of thermal responses

Table 3.1 shows the statistical summary of the thermal responses. The mean thermal sensation and thermal preference show that most of the students were neutral and preferred no change. The mean overall comfort indicates that most of the students felt moderate to slightly comfortable. The mean thermal acceptance was 0.11, which indicates high thermal acceptance. The percentages of the three central categories of thermal sensation, thermal preference, and overall comfort are 76%, 87%, and 43%, respectively. The central categories of thermal sensation, “neutral”, and preference, “no change”, in general, are 34% and 36%, respectively. The bottom category of overall comfort, “very comfortable”, was 8%. Evidently from these results, the students accepted the indoor thermal environment with an acceptance percentage of 89%. In what follows, we describe the detailed results based on the analysis using thermal sensation votes.

Fig. 3.2 (a) shows the percentage distribution of all students' votes for thermal sensation, with a total of 2454 in 2017. Approximately three-quarters of the students expressed their thermal perception in the thermal comfort zone (either slightly cold, neutral, or slightly hot).

Fig. 3.2 (b) shows the comparison of thermal sensation between public and private school students. Both private and public-school students responded mainly to the comfort zone, as expected from Fig. 3.2 (a). While no vote on “very hot” was obtained in private schools, quite a few votes on “very hot” were obtained in public schools. The mean response of private school students was 3.6, that is, on the slightly cold side, while that of public school students was 4.3. As will be described later, this is because private school students had considerably higher clothing insulation than public school students.

Fig. 3.2 (c) shows a comparison of thermal sensation in terms of gender. The distributions are similar to each other. Statistically, no significant difference was confirmed between males and females.

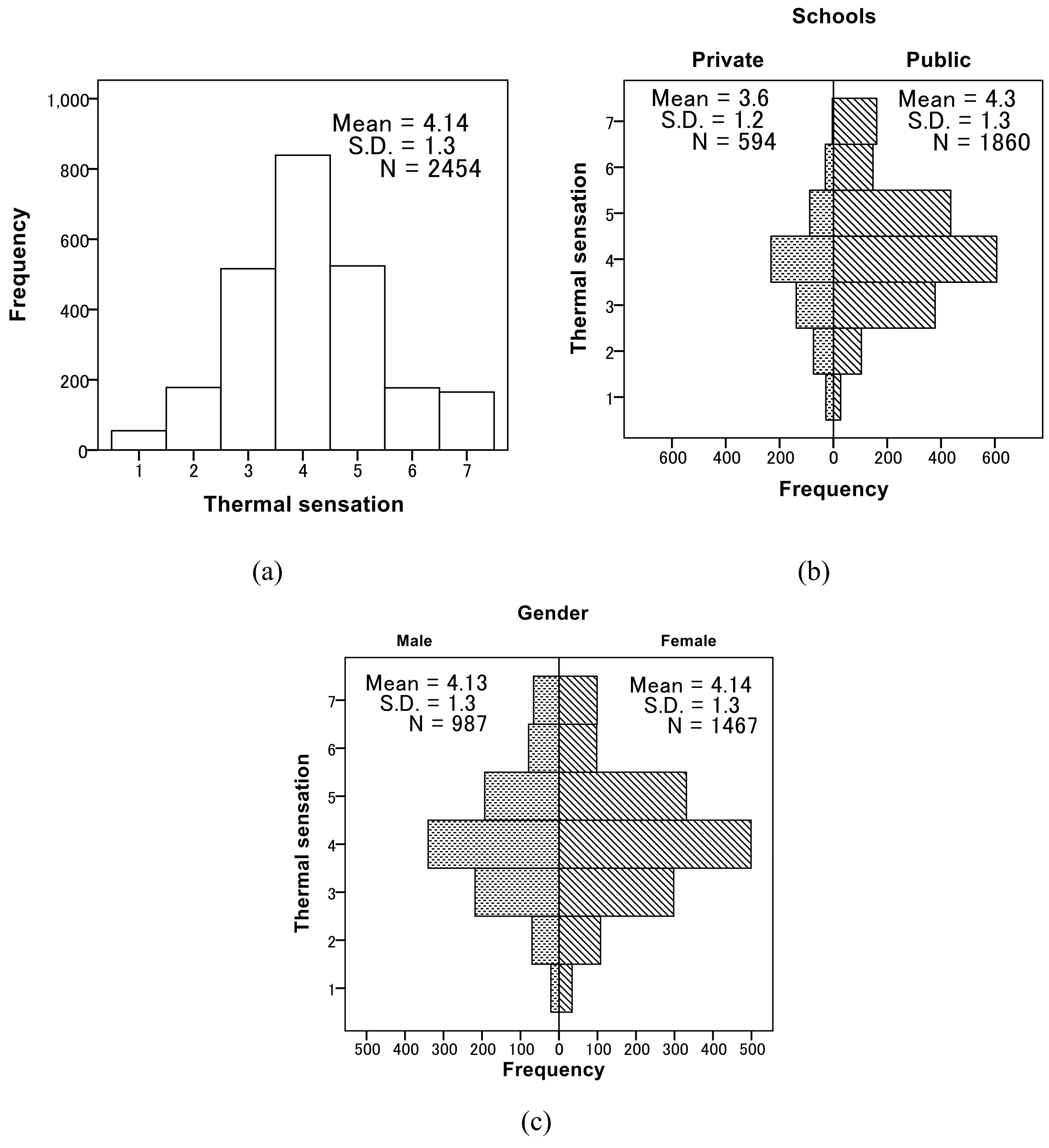


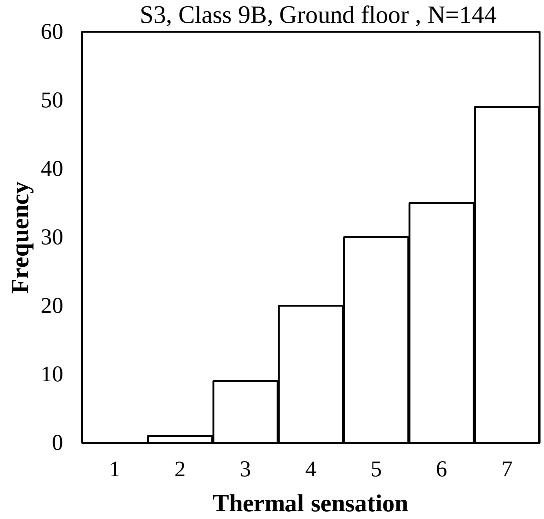
Figure 3.2 Distribution of thermal sensation vote: (a) overall, (b) public and private schools, and (c) gender

The response on the hot side was investigated in the case of students from public school S3. Fig. 3.3 (a) shows the distribution of thermal sensation votes in classroom 9B of school S3. Limited ventilation due to the limited number of windows may be responsible for the hot side responses. There was only one window and door on the east façade for ventilation and daylighting in that classroom. Consequently, ineffective ventilation must have caused an increase in the indoor air temperature, which resulted in the responses being on the hot side. Fig. 3.3 (b) shows the responses of the students in the top-floor classroom of the same building with a zinc roof. Their responses are also shifted towards the hotter side due to the increasing ceiling temperature caused by the zinc roof. This seems consistent with the findings of a previous study, in which architectural design was stated to affect the thermal perception of students (Nico et al. 2015 & Bluyssen et al. 2018).

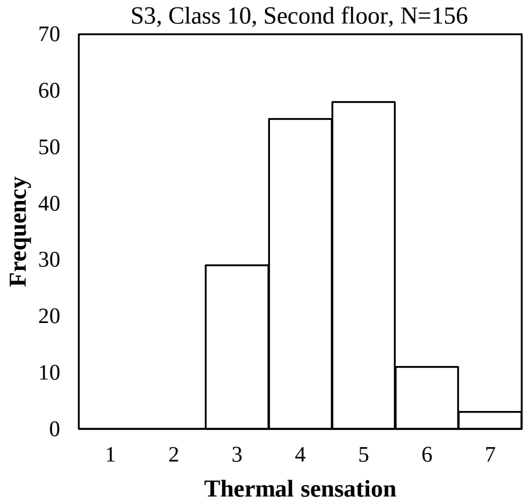
Table 3.1 Descriptive statistics of subjective thermal responses.

Thermal responses	Mean	S.D.	Comfort condition	
			N [%]	CZ [%]
Thermal sensation vote (TSV)	4.1	1.3	34	76
Thermal preference (TP)	3.2	1.0	36	87
Overall comfort (OC)	2.9	1.2	8	74
Thermal acceptance (TA)	0.1	0.3	89	-

S.D.: Standard deviation; N: Percentage of neutral in TSV, no change in TP, very comfortable in OC and acceptance in TA; CZ: Percentage of comfort zone in TSV (Slightly cold, Neutral and Slightly hot), TP (A bit warmer, No change and A bit cooler) and OC (Very comfortable, Moderately comfortable and, Slightly comfortable). The total votes on each sensation scales were 2454.



(a)



(b)

Figure 3.3 Distribution of thermal sensation vote on different floors in a public school S3: (a) ventilation and (b) floor

The metabolic rate of the students due to physical activities is connected to thermal perception. The results presented above confirm that the students have very limited classroom activities due to their regular class schedule. Therefore, we assumed that the effect of metabolic rate on thermal sensation in a sedentary condition in a regular class must be insignificant. Previous studies on naturally ventilated university classrooms estimated an average metabolic rate of 1.2 met under the limited options of activities (de Carvalho et al. 2013 & Talukdar et al. 2020). The metabolic rate quantified for primary and secondary level students is estimated at 1.1 met, which corresponds mostly to reading and writing activities (Yao et al. 2010). However, it could be different under high physical activities. Kumar et al. (2020) estimated that the metallic rate of university students is 2 met under high activities during autumn.

3.3.2 Estimation of comfort temperature

In thermal comfort studies, regression analysis is usually applied to calculate comfort temperature. Due to the adaptive behaviour of students inside the classrooms over a period of time, their thermal perception occasionally becomes different from neutral; however, if the range of indoor temperature is rather narrow, the regression coefficient obtained by applying a simple linear regression method could often bring about odd results for comfort temperature (Rijal et al. 2013, Rijal et al. 2019 & Rijal et al. 2020). This problem is avoided using an alternative method called the Griffiths method (Griffiths 1990, Nicol 1994, Rijal et al. 2010, Humphreys et al. 2013, Niol & Humphreys 2012, Rijal et al. 2017, & Rupp et al. 2019).

Fig. 3.4 (a) shows the distribution of the comfort temperature for all votes regardless of school type and gender. The mean value of comfort temperature turned out to be 26.9 °C. The estimated comfort temperatures are distributed over a wide range, but the values of comfort temperature are mostly between 25 °C and 29 °C. Figs. 3.4 (b) and (c) show the separated distribution of the estimated comfort temperature by school type and gender, respectively. The mean comfort temperature of private school students, at 26.5 °C, is lower than that of public-school students, at 27.1 °C. These values are close to their respective indoor globe temperatures: private (25.8 °C) and public (27.7 °C). Similar results were observed in terms of gender. The mean comfort temperatures for males and females were 26.7 °C and 27.1 °C, respectively.

Fig. 3.5 (a) shows the distribution of comfort temperatures, whose average is 26.9 °C during the summer. They are distributed over a wide range, but the values are mostly between 25 °C and 29 °C.

Fig. 3.5 (b) shows the error bar of comfort temperatures (mean ± 2S.E.). The mean comfort temperatures estimated in the morning, midday, and afternoon are 26.3°C, 26.7°C, and 27.8°C, respectively. An independent sample T-test is applied to compare these estimated mean comfort temperatures. A statistically significant difference in comfort temperature is confirmed for the three-time periods ($p<0.001$). This must be because of the variation in the thermal environmental condition of the classroom due to varying outdoor environmental conditions throughout the day. The comfort temperature increases during the afternoon or day are probably also due to the effect of solar radiation incident on the roof, walls, and so on, as well as transmitted solar radiation. The investigated school buildings were not well insulated, and therefore there is a high chance of heat conduction towards the inner surfaces. In summer, due to the effects of such phenomena, the radiant temperature becomes high. The high indoor temperature increases skin temperature, which then causes an increase in thermal sensation and comfort temperature. Therefore, the role of radiant temperature is probably higher for comfort temperature than air temperature on hotter days.

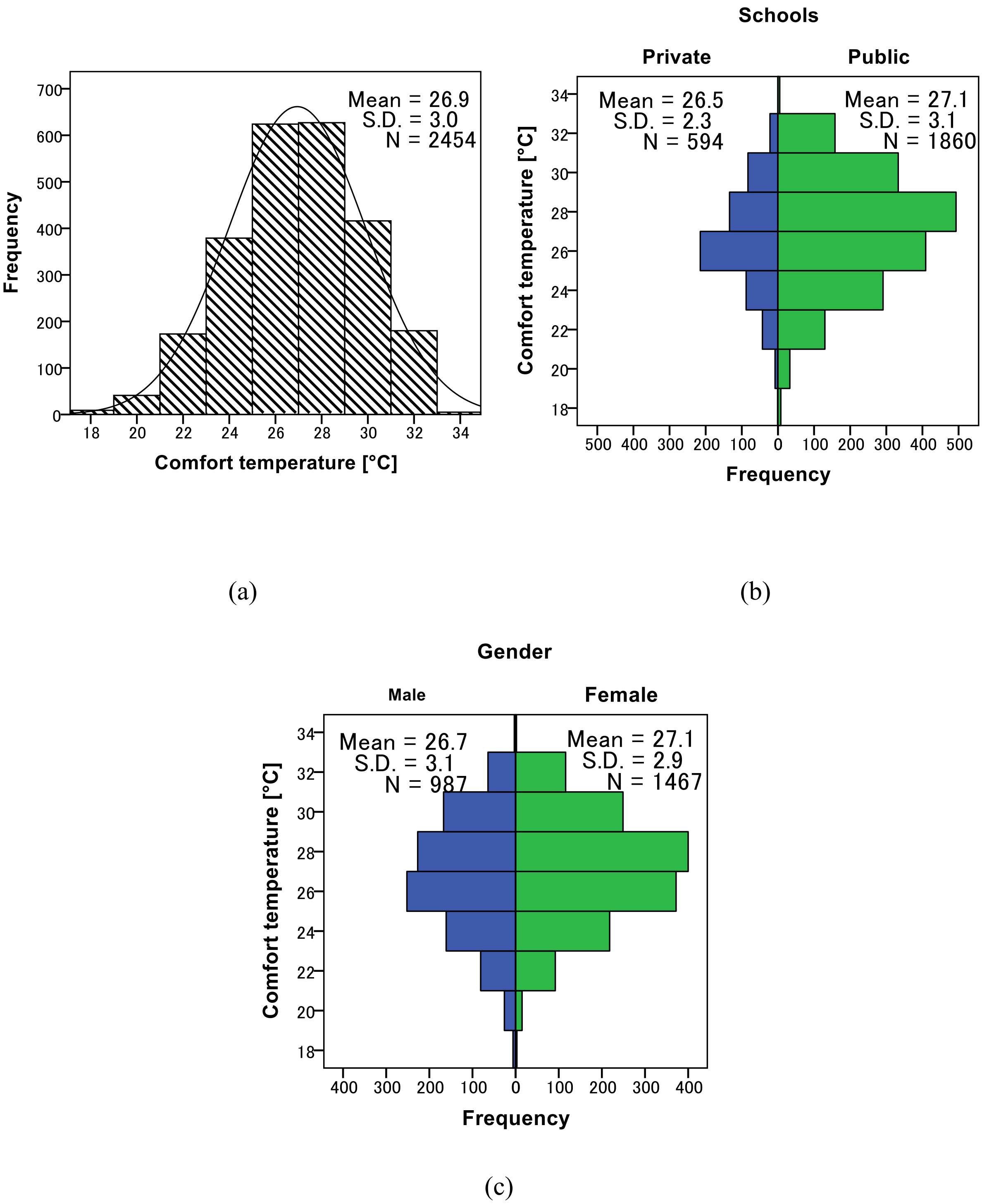


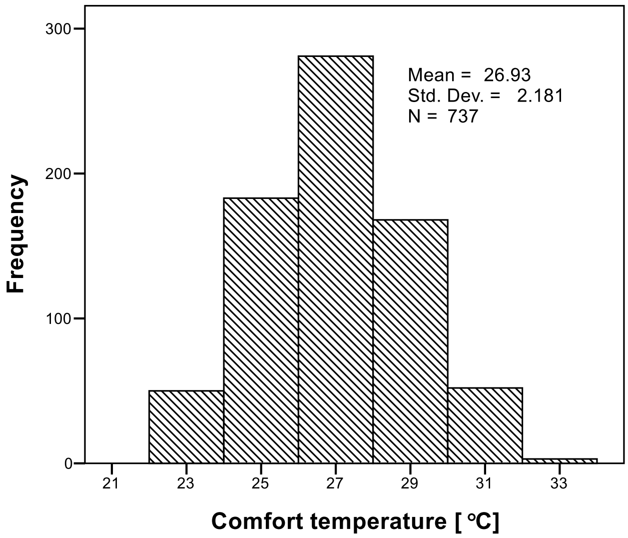
Figure 3.4 Distribution of comfort temperature by Griffiths method: (a) overall analysis, (b) school type, and (c) gender

According to Simon & Parsons (2006), one scale unit change in thermal sensation is equivalent to exposure to around 200 w/m^2 of radiation.

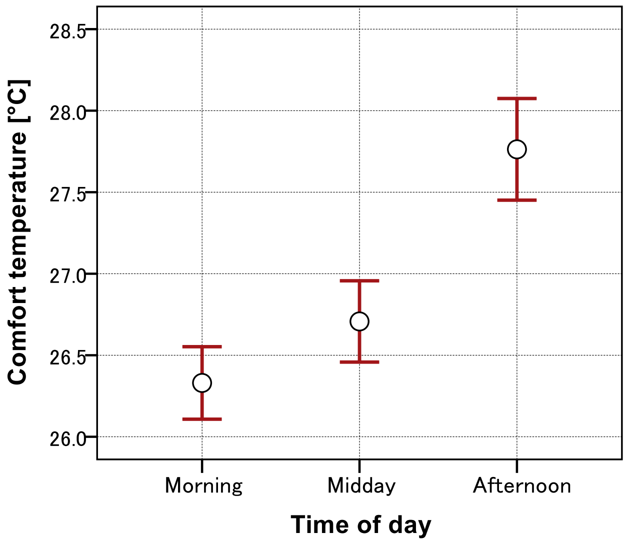
Different comfort temperatures could be a type of short-term adaptation, with different perceptions in the morning, midday, and afternoon. We have two kinds of adaptation: seasonal and short time (within an hour, one day, one week, and so on). In everyday exposures, short-term adaptation influences occupants. The seasonal or long-term adaptation influences occupants who have been living for a long year.

Previous studies have investigated that thermal comfort or discomfort may be due to current and previous conditions, referred to as "thermal history". The evaluations of the thermal environment by students are based on not only the current feelings but also the feelings accumulated over a past period of time (Ji et al. 2017). Sun et al. (2022) found that thermal sensation and preference values were higher in the afternoon than in the morning. They also found that students' thermal sensation was most sensitive to outdoor temperature changes at the beginning of the first class in the morning or afternoon and that their thermal perception was influenced by their pre-class activity state. Brager and de Dear (1998) studied the difference in thermal comfort between air-conditioned and naturally ventilated buildings and found that comfort is influenced by occupants' expectations. Occupants in naturally ventilated buildings were more tolerant of temperature variations and preferred temperatures that matched outdoor conditions, while those in air-conditioned buildings had high expectations for a cool and uniform environment and were sensitive to temperature deviations. These differences likely resulted from past thermal history and perceived control. Fanger et al. (1974) found no significant difference between ambient temperatures preferred by subjects in the morning and the evening, and they concluded that the same thermal comfort conditions could be used from morning to evening, which is contrary to the present study.

The analysis shows that regardless of the autumnal and summer seasons, the comfort temperatures of the students are almost similar.



(a)



(b)

Figure 3.5 (a) Distribution of comfort temperature, (b) Comfort temperature with 95% confidence interval in the morning, midday, and afternoon. These results are based on the data from the field survey of 2019.

3.3.3 Comparison of comfort temperature with previous studies

Table 3.2 shows a comparison of comfort temperature with previous studies. The comfort temperatures obtained in this study were similar to those in previous studies conducted in naturally ventilated classrooms during summer (Liang et al. 2012, Kim & de Dear 2018, Singh et al. 2018, &Kumar et al. 2018). Field studies conducted in the sub-tropical areas show a lower comfort temperature than in the present study because of outdoor climatic conditions (de Dear et al. 2015

& Nakagawa et al. 2020).
Liang et al. (2012) found a students' comfort temperature of 28.2 °C during the autumn season. The comfort temperature was lower than that in the present study during the summer season in the temperate climate of Australia (de Carvalho et al. 2013). Liu et al. (2020) studied the comfort temperature of adults in schools, in China, and found a lower comfort temperature than this study. The comfort temperature of the present study is 2 °C lower than the comfort temperature in a study in schools in Indonesia during autumn (Hamzah et al. 2018). It is also 0.4 °C higher than the comfort temperature calculated for summer in naturally ventilated classrooms in India (Kumar et al. 2018). The comfort temperature of this study is 2.2 °C higher than the study conducted under a high metabolic rate of students during autumn and also found that female students had higher comfort temperatures than males (Kumar et al. 2020). The comfort temperature of the adults in university is estimated at 26.5 °C (Mishra & Ramgopal 2014). In another study in the university classroom of Bangladesh, it was 27.8 °C (Talukdar et al. 2020). These are very close to the comfort temperature of this study.

A few studies conducted in Nepalese residential buildings and temporary shelters in the same study areas of Nepal found a wider range of comfort temperatures (Rijal et al. 2010 & Thapa et al. 2018). Rijal et al. (2010) found that the comfort temperature of the occupants in Nepalese traditional vernacular houses differed by 8.9-10.8 °C from one region to 4.9-13 °C in another region from summer to winter. Another study conducted in a temporary shelter in Nepal found a wider range of comfort temperatures from 15.0 °C to 28.6 °C with a seasonal difference of 13.6 °C (Thapa et al. 2018).

Table 3.2 Comparison of comfort temperature with previous studies conducted in schools and university classrooms

References	Country	Climate	Survey period	Age group	Student sample	Ventilation	T_c [°C]	$T_{c(range)}$ [°C]
This study	Nepal	Temperate	Autumn 2017, summer 2019	12-18	818	NV	27	24-30
Liang et al. 2012	Taiwan	Sub-tropical	Autumn 2005	12-17	1614	NV	28.8	22.4-29.2
Pereira et al. 2014	Portugal	Mediterranean	Mid-season 2013	16-19	45	NV; FR	25.2	22.1-25.2
Hadded et al. 2016	Iran	Hot and dry	2012-2013	10-12	811	NV	23.3	22-25
de Dear et al. 2015	Australia	Sub-tropical	Summer 2013	10-18	NA	NV; AC; EC	22.4	19.5-26.6
Hamzah et al. 2018	Indonesia	Tropical	Autumn 2017	11-18	1594	NV	29	28.2-33.6
Jindal, 2018	India	Composite	Aug. 2015-Feb. 2016	10-18	640	NV	25.9	15.3-33.7
Kim et al. 2018	Australia	Temperate/	Summer 2012-2013	10-15	3545	NV; MM	24.4	-
		Sub-tropical		16-18	1321		24.4	
Mishra et al. 2014	India	Tropical	Jan.-Apr. 2013	19-21	121	NV	26.5	20-31
Jowkar et al. 2020	UK	Mild climate	Autumn 2017, winter 2018	Ave. 22	3000	FR	23	22-25
Singh et al. 2018	India	Composite	Apr.-Jun. 2015	18-26	900	NV	29.8	23-32
Kumar et al. 2020	India	Composite	Autumn, winter 2018-2019	18-21	615	NV	24.8	16.8-35
Liu et al. 2020	China	Cold	Autumn/winter 2015	18-21	900	FR; HS	21-23.26	-
Talukdar et al. 2020	Bangladesh	Tropical	Jul.-Aug. 2017	20-21	579	NV	27.8	27.5-33.8
Guevara et al. 2021	Ecuador	Tropical	Dec. 2017-Jan. 2018	-	429	FR	24.7	21.8-26.9

FR: Free running; NV: Naturally ventilated; AC: Air conditioned; EC: Evaporate cooling; HS: Heating system; MM: Mix mode; T_c: comfort temperature [°C]; $T_{c(range)}$: Range of comfort temperature [°C]

3.3.4 Relationship between comfort temperature and outdoor air temperature

This section explores how the comfort temperature varies with the change in outdoor air temperature and whether the comfort temperature of the students during the autumn season is similar to adaptive temperature limits. Fig. 3.6 shows the comfort temperature and outdoor air temperature during the voting time, together with the ASHRAE adaptive model indicating the upper and lower temperature limits of the comfort zone. The comfort temperature increases as the outdoor air temperature increases. A large number of comfort temperature values are within the upper and lower adaptive temperature limits, although some exceed the limits. This result agrees with recent studies focusing on student well-being in naturally ventilated classrooms with wide ranging comfort temperature (Singh et al. 2018, & Kumar et al. 2020). According to another recent study (de Dear et al. 2020), the thermal comfort state of the students is outside the comfort zone prescribed in the ASHRAE standard. They tend to feel comfortable in a cool indoor thermal environment. When the indoor temperature exceeds the high and low temperature limits, students seek other adaptive behaviours along with clothing behaviour in naturally ventilated schools (Yao et al. 2010). Singh et al. (2019) found that the comfort temperature in naturally ventilated classrooms has a stronger correlation with outdoor temperatures. The ASHRAE model was developed for naturally ventilated building spaces based on a large amount of data from different climatic zones in various countries and the responses obtained from adults. The thermal environmental characteristics of the buildings used and the people's behaviour could be quite different from those in school buildings.

Table 3.3 presents the adaptive thermal comfort equations given by previous studies conducted in naturally ventilated schools and university classrooms. The slope of the adaptive equation in this study is close to that of a study conducted in India during summer (Singh et al. 2018). The slopes of 0.22, 0.47, and 0.30 for primary, secondary, and university classrooms, respectively, found in a previous study (Singh et al. 2019), showed that the slope for the secondary-level students is similar to that in our study. The slope of this study is significantly higher than the slope obtained from students below the age group of 18 years (Teli et al. 2017 & Haddad et al. 2019). The slope is lower than in studies conducted during autumn (Liang et al. 2012 & Trebilcock et al. 2017). These differences could be due to the thermal adaptation in the classrooms and its effect on student perception.

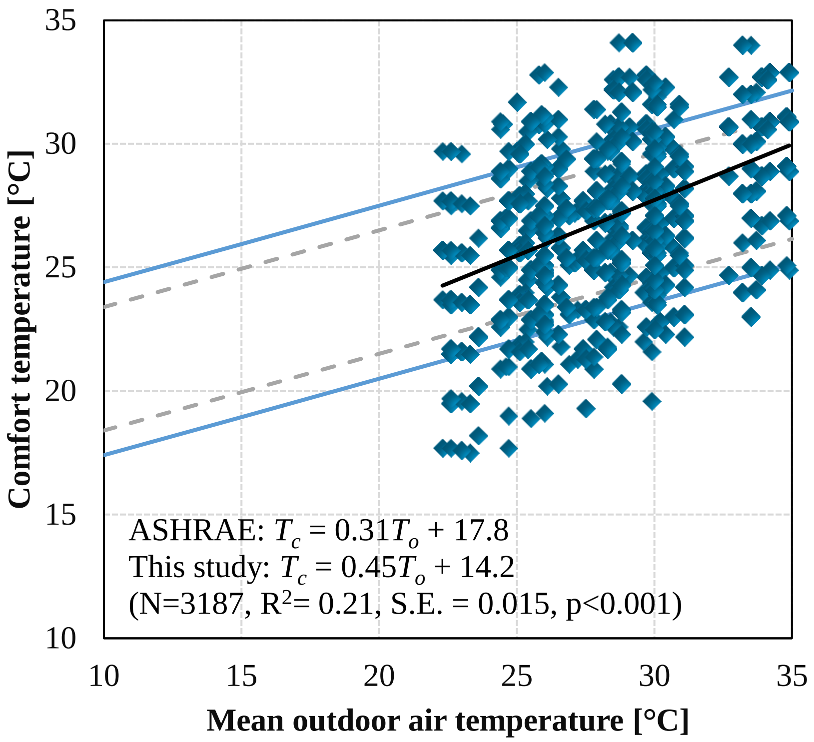


Figure 3.6 Comparison of comfort temperature with ASHRAE 55 adaptive model. Outdoor air temperature in this study is an outdoor temperature during voting time. Each point represents the comfort temperature. They are from the analysis of both autumn and summer data.

Table 3.3 Previous adaptive thermal comfort studies conducted in schools and university classrooms

References	Country	Climate	Survey period	Ventilation type	Adaptive comfort model
This study	Nepal	Temperate	Autumn 2017, summer 2019	NV	T_c = 0.45T_o + 14.2
Liang et al. (2012)	Taiwan	Sub-tropical	Autumn 2005	NV	T_c = 0.62T_{om}-12.1
Hadded et al. (2019)	Iran	Hot and dry	Autumn, win., Spr. 2012-13	NV	T_c = 0.25T_{rm}+19.14
Teli et al. (2017)	UK	Mild climate	2011-2015	NV	T_c = 0.26T_{rm}+18.2
Trebilcock et al. (2017)	Chile	Mediterranean	Autumn, win., 2013-14	NV	T_c = 0.83T_{rm}+7.11
Yao et al. (2010)	China	Sub-tropical	Mar 2005-May 2006	NV	T_c = 0.60T_{om}+9.85
Thapa et al. (2016)	India	Temperate	Jul.-Dec. 2015	NV	T_c = 0.67T_{rm}+9.94
Singh et al. (2018)	India	Composite	Apr.-Jun. 2015	NV	T_c = 0.49T_{rm}+13.8
Kumar et al. (2020)	India	Composite	Autumn, winter 2018-2019	NV	T_c = 0.81T_{rm}+ 6.03
Talukdar et al. (2020)	Bangladesh	Tropical	Jul.-Aug. 2017	NV	T_c = 0.38T_{rm}+16.10

T_c: Comfort temperature [°C], T_o: Outdoor air temperature [°C], T_{om}: Mean monthly outdoor temperature [°C], T_{rm}: Outdoor running mean temperature, NV: Naturally ventilated

3.3.5 Previous adaptive thermal comfort studies in Nepal

Under free-running or natural conditions, the comfort temperature is quite highly correlated with the outdoor air temperature. The comfort temperature at different geographies varies based on their respective climatic conditions. This is because of the acclimatization or adaptation of occupants to those respective climatic conditions. Table 3.6 presents the adaptive thermal comfort equations given by previous field studies conducted in naturally ventilated buildings in different climates in Nepal. The adaptive slopes are mostly different from each other. This could be due to the thermal adaptation in the classrooms and its effect on students' perceptions.

Table 3.6 Summary of adaptive thermal comfort studies in Nepal

References	Climate	Buildings	Survey period	Adaptive comfort model
Rijal et al. 2010	Cold, temperate, & sub-tropical	Traditional	Summer, winter	$T_c = 0.83T_g + 4$ (indoor) $T_c = 0.77T_g + 6.1$ (semi-open)
Gautam et al. 2019	Cold, temperate, & sub-tropical	Traditional	Winter	$T_c = 0.62T_o + 7.6$
Pokharel et al. 2020	Cold, temperate, & sub-tropical	Residential	Winter	$T_i = 0.49T_{om} + 4.8$ (cold) $T_i = 0.45T_{om} + 9.1$ (temperate) $T_i = 0.86T_{om} + 2.8$ (sub-tropical)
Shahi et al. 2021	Cold, temperate, & sub-tropical	Residential	Winter	$T_c = 0.72T_g + 7.7$ (cold) $T_c = 0.69T_g + 7.3$ (temperate) $T_c = 0.53T_{om} + 10.6$ (sub-tropical)
Gautam et al. 2020	Sub-tropical	Residential	Summer	$T_c = 0.46T_o + 14.1$ (local people) $T_c = 0.66T_o + 7.5$ (migrant people)
Thapa et al. 2018	Temperate	Temporary shelter	Autumn, winter, & summer	$T_c = 0.56T_{om} + 10.9$
Rijal, 2021	cold	Traditional	Winter	$T_c = 0.81T_{rm} + 4.4$

T_c: Comfort temperature [°C], T_o: Outdoor air temperature [°C], T_g: mean globe temperature [°C], T_{om}: Mean monthly outdoor temperature [°C], T_{rm}: Outdoor running mean temperature, T_i: indoor air temperature [°C]

3.4 Adaptive behaviours for thermal comfort

Occupants use interactive actions or behaviours to adapt to the environment and such behaviours impact their thermal perception. Students are likely to use adaptive behaviours in naturally ventilated classrooms. This section presents such behaviours used by students to adapt to the thermal environment of classrooms for their comfort. The clothing behaviour and its relation with the outdoor air temperature is analysed in detail.

3.4.1 Adaptive behaviours in the classrooms

In Nepal, approximately 84% of the total energy is used by residential buildings and 2% by commercial and public sectors (Nepal energy sector assessment 2017). There is no quantitative study on energy use patterns in schools in Nepal that would inform how much energy is being used to maintain the thermal environment and the thermal comfort of the students. It is considered that a very limited amount of energy is used to maintain the thermal comfort of students because of the economic situation. Electricity is the primary energy source to run computer labs, lighting, and fans to mitigate harsh indoor temperatures in some public and private schools in urban areas. Schools in rural areas meet energy demand using solar for lighting, operation of basic science equipment, computers, and printing machines, but not primarily to maintain the thermal environment. Consequently, if we prioritize adaptive behaviours, we will have significant energy-saving potential. We are presenting the results from the field investigation that show how students rely on adaptive behaviours to maintain thermal comfort in Nepalese schools.

Students were asked to answer the behaviours they use to adapt or adjust to the indoor thermal environment of the classrooms during the field survey of 2019. They were instructed to specify and write down the other control they used if it was not specified in the questionnaire (Appendix). The responses to a couple of activities were obtained. Fig. 3.7 shows the behaviours used for adaptation in the thermal environment of the classrooms. The maximum responses responded to by the students were obtained for the opening of windows and drinking water.

Rodríguez et al. (2021) investigated that the most frequent adaptive actions taken by the students were opening the door or windows regarding the environmental modifications and taking a cold drink regarding behavioural adaptations, which is very similar to this study. Aparicio-Ruiz et al. (2021) found that students prefer opening the windows and opening the doors as adaptive behaviours to feel comfortable, more than the use of fans, which were mainly turned on in the afternoon. Zaki et al. (2017) found that more adaptive actions were taken by university students under the free-running condition to remain thermally comfortable.

How the clothing adaptive behaviours changes with change in outdoor air temperature will be discussed in the next section.

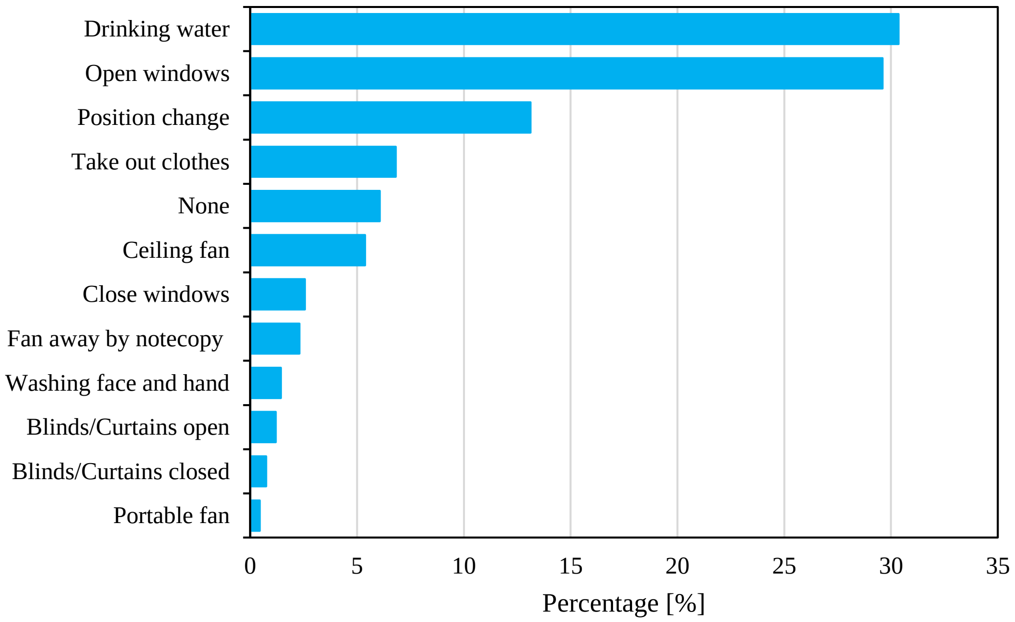


Figure 3.7 Adaptive behaviours used by students to adjust their thermal comfort

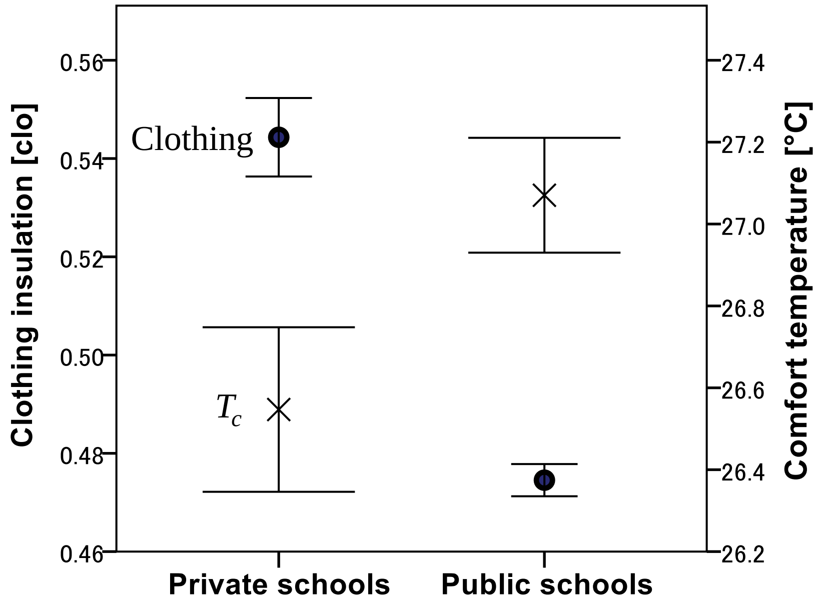
3.4.2 Clothing adjustment in the classrooms and its relation to temperature

The adaptive behaviour of students regarding their clothing and its relation to comfort temperature is discussed in this section. Generally, occupants change clothing, posture, activity levels, and drink more or less water, among other adjustments, to adapt to the indoor thermal environment. In mechanically air-conditioned classrooms, they are less likely to use these non-air-conditioned adaptive options (Kim & de Dear 2018). The students who participated in this survey had a school dress code that had to be followed the entire day. The dress code in private schools may be stricter than in public schools. The clothing worn by the students differed between the public and private schools as well as by gender. As shown in Fig. 2.7, students in public school mostly dressed in the combination of long-sleeved shirts, full pants, skirts, or light trousers, while in private school, the students dressed in the combination of a summer jacket, T-shirt, full shirt, full pants, skirts, or light trousers. Footwear was mostly slippers for public school students and half or full shoes along with half or full socks for private school students.

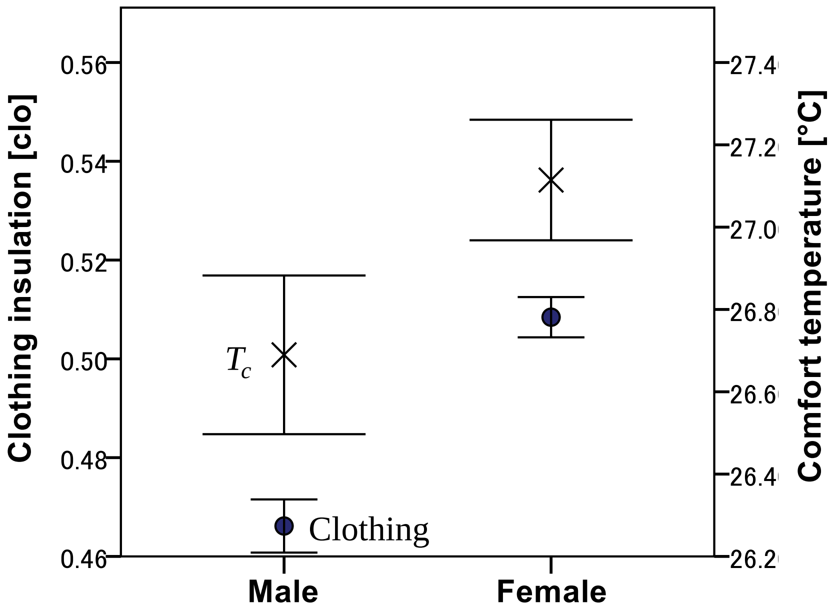
The mean clothing insulation ± standard using all data was 0.48 ± 0.09 clo. Fig. 10 shows the mean values of clothing insulation with 2 standard errors and also the mean values of comfort temperature, where Figs. 3.8 (a) and 3.8 (b) show the comparisons of private versus public schools and males versus females. The mean clothing insulation of private school students (0.54 clo) is significantly higher than that of public school students (0.47 clo). Conversely, the mean comfort temperature of private school students is lower than that of public-school students. The existence of this reciprocal relationship between clothing insulation and comfort temperature is due to the lower indoor globe temperature combined with slightly higher clothing insulation in private school students, compared to public school students. Fig. 3.8 (b) shows that significantly higher clothing insulation was observed in female students (0.50 clo) than male students (0.46 clo); the same tendency was true for the comfort temperature. Higher clothing insulation and comparatively less activity of females, compared to males, might be the factors connected to the process of adaptation to the indoor temperature of the classroom. This result was similar to that of previous studies (Singh et al. 2018, Ngarambe et al. 2019, & Nakagawa et al. 2020). Mors et al. (2011) studied a school in the Netherlands and found the mean clothing insulation changes most during mid-seasons, showing a small difference in clothing value between male and female students. However, another study in university classrooms, where the students were engaged in a high activity level instead of sitting and reading, during autumn noticed no significant difference in clothing insulation (Kumar et al. 2020). A study in Italian classrooms under free-running conditions showed that female students were inclined to wear warmer clothing, preferring a warmer environment. This resulted in a slightly different thermal sensation in females than in male students (Nico et al. 2015). This type of clothing behaviour and its respective clothing insulation are the main factors in the estimation of comfort temperature.

It is known that clothing choices in naturally ventilated classrooms are strongly influenced by outdoor air temperature rather than indoor air temperature during peak seasons (Kumar et al. 2018 & Singh et al. 2019). Accordingly, to investigate the influence of outdoor air temperature on the students' clothing insulation, a regression analysis was conducted. Because of the characteristics of our data, we analysed them together with their average values. All the clothing insulations were first sorted into bins with 2 °C intervals of outdoor air temperature, and then the mean values of clothing within each interval were calculated.

Fig. 3.9 shows the result of the calculation: mean clothing insulation (I_{cl}) versus mean outdoor air temperature (T_o). The mean clothing insulation decreases as the outdoor air temperature increases. As the outdoor air temperature increases, the students seem to adjust their clothing insulation. Among the six plots, four were quite close to 0.50 clo, while the other two plots, corresponding to 31 °C and 32 °C, were much lower than the former four plots. This tendency may be because they follow the dress code up to the threshold value of the mean outdoor air temperature, which is around 30 °C. This tendency demonstrates that the students adapt to the thermal environment in classrooms by altering their clothing when the mean outdoor air temperature exceeds 30 °C. This means that the decision was made on their own, according to their state of thermal comfort, rather than merely complying with the dress code. This occurs when the indoor thermal environment is harsher than that which can be endured by complying with the dress code.



(a)



(b)

Figure 3.8 Mean clothing insulation and mean comfort temperature with 95% confidence interval (mean ± 2S.E.): (a) school type and (b) gender

According to previous studies in naturally ventilated office and residential buildings (De Carli et al. 2007, Rijal 2018, Gautam et al. 2019 & Thapa et al. 2018), the change in clothing insulation of occupants is highly dependent on outdoor air temperature. A study by Corgnati et al. (2009) in an Italian free-running school found that students wore less clothing when outdoor air temperature increased during autumn. Similar results were found by Nakagawa et al. (2020) for both male and female Japanese high school students and by Teli et al. (2013) for primary school students in the UK. A study by Kim et al. (2018) in an Australian secondary school is consistent with the results that the clothing insulation remained weakly responsive at lower outdoor temperatures during summer seasons. A study in university classrooms showed that outdoor temperature has stronger associations with clothing than indoor air temperature (Yao et al. 2010).

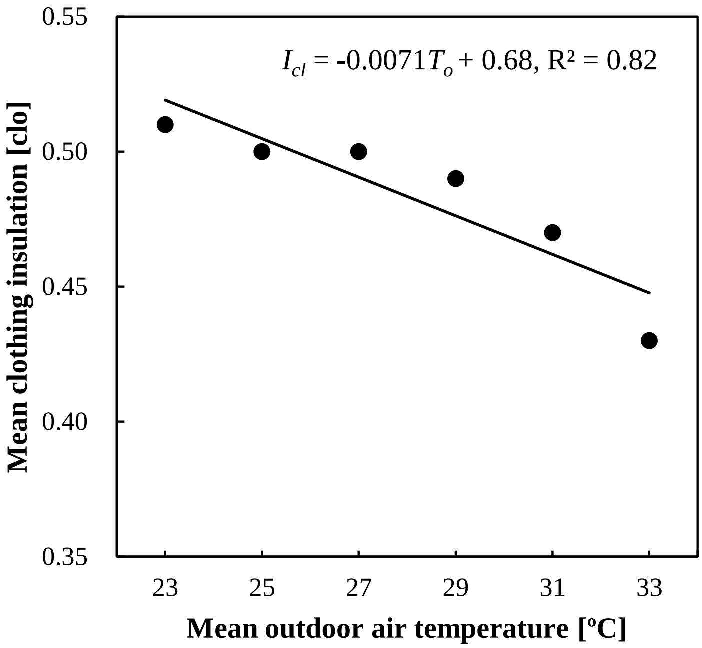


Figure 3.9 Variation in mean clothing insulation with mean outdoor air temperature

3.5 Conclusions

This chapter presents the following major conclusions.

1. According to the comparison of the indoor globe and operative temperatures with the outdoor air temperature, as well as the indoor and outdoor water vapour concentrations, natural ventilation of the classroom performed relatively well.
2. Approximately three-quarters of the students participating in the survey were comfortable under similar indoor and outdoor thermal environments; this is probably because of natural ventilation. The discomfort was due to the higher temperature caused by the thermally poor characteristics of the building envelopes, such as zinc roofs or walls.
3. The mean comfort temperature estimated from all the data was 26.9 °C, which is the same for both autumn and summer. The estimated comfort temperatures are distributed over a wide range, but the values of comfort temperature are mostly between 25 °C and 29 °C. The comfort temperature of the students in private schools was lower than that in public schools, and female students had higher comfort temperatures than male students. The students with comfort temperatures beyond the temperature limits prescribed by ASHRAE showed a tendency to adapt to their indoor thermal environment.
4. Differences in clothing insulation and comfort temperature in terms of gender and school type were observed. The clothing adaptive behaviour was weak up to 30 °C and more responsive at outdoor air temperatures above 30 °C.

This chapter presented that most of the students adapted and felt comfortable under the condition of natural ventilation in the thermal environment in schools. The comfort temperature for male and female students is different in public and private schools by owing to clothing insulation.

Chapter 4: Natural ventilation and CO_2 concentration in classrooms

4.1 Introduction

This chapter presents the evaluation of indoor air quality as represented by natural ventilation and CO_2 concentration based on a field study and modelling of the CO_2 mass balance. Even though there are many factors that define indoor air quality, this study is focusing only on natural ventilation and CO_2 concentration conditions. Since ventilation directly affects thermal comfort, it is also necessary to study this topic carefully. The ventilation rate is estimated in terms of the number of air changes (ACH), and the CO_2 concentration is estimated using the developed model. An attempt to analyse the effect of ACH on indoor CO_2 concentration is made at different ACH values using the developed base model. As a representative, this chapter presents the analysis based on the three school buildings (S9, S10, and S11) investigated during the summer of 2019.

4.2 Evaluation of IAQ based on field study

4.2.1 Thermal environment during the field measurement

The thermal environment condition of the classrooms is first presented here in this section in order to know the basic relationship between the indoor and outdoor environments. The indoor air and globe temperatures were very close, as shown in Fig. 4.1. Therefore, only the indoor globe temperature is presented for analysis. Fig. 4.2 shows the outdoor air temperature and indoor globe temperature measured in seven classrooms in three schools. The fluctuating range of temperatures is different in the three schools. Overall, the indoor globe temperature varied from 23 °C at the beginning of regular classes in the morning to 29 °C during the day time, while the outdoor air temperature ranged from 25 to 32 °C. The fluctuations in outdoor temperature are a little bit sharp, but the globe temperatures are smooth and quite slow. This is probably because of the heat capacity of the walls surrounding the room space. Such effect is small in schools S9 than in S10 and S11. The heat is continuously discharged from the bodies of students into the room space by long-wavelength radiation, convection, and evaporation. Adequate ventilation is necessary to remove all the heat generated by the human bodies and by the solar radiation entering through the windows or doors. Overall, the outdoor relative humidity ranged from 24 to 72% and indoors from 24 to 75%. The measured average air velocity ranged from 0.19 to 0.37 m/s, with an overall average of 0.28 m/s.

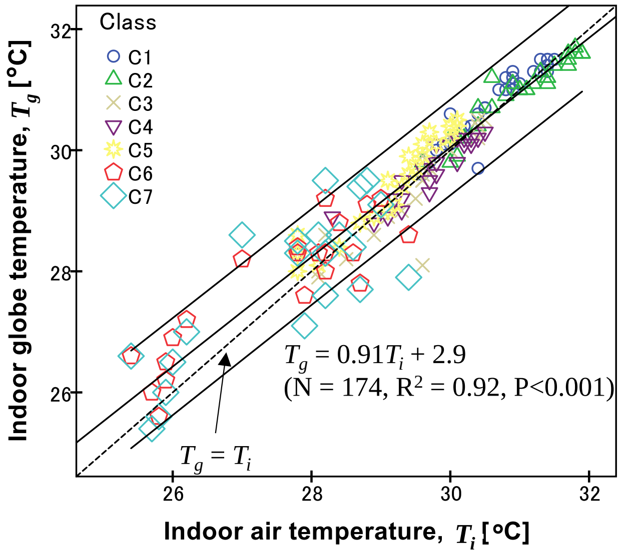


Figure 4.1 Relationship between the indoor globe temperature and indoor air temperature with 95% confidence interval of data analysis. The classrooms C1 to C7 are as shown in the plan view in Fig. 2.4

4.2.2 CO_2 concentration based on the measurement

This section provides a summary of measured indoor CO_2 concentrations and their comparison with those in previous studies. Fig. 4.3 shows the measured indoor CO_2 concentration versus time in seven classrooms in three schools. The overall indoor CO_2 concentrations are between 457 and 744 ppm. The threshold value specified by the ASHRAE (2016) guideline in schools is 1000 ppm and thus indoor CO_2 concentration is lower than the acceptable limit value. This is considered due to large ventilation rates, as will be discussed later, caused by windows being kept open. The fluctuation of indoor CO_2 concentration is considered to be caused by the variation of outdoor wind while lectures are given, as well as the students and teachers leaving or entering the classrooms.

The indoor CO_2 concentration decreased during break time and again started to increase after break time, around 13:00 or 14:00. Before or after each lesson, some students go outside to drink water or use the restroom; this causes irregular occupancy patterns. It can be said that the dilution of indoor CO_2 concentrations is higher in all classrooms. The average outdoor CO_2 concentration measured outside the school building S3 is 422 ppm.

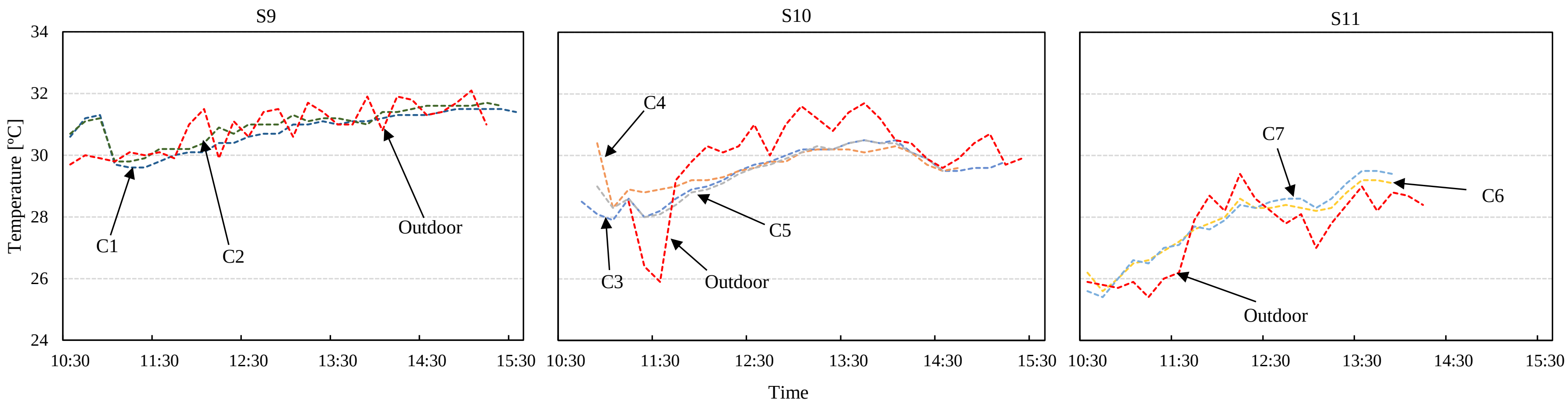


Figure 4.2 Measured outdoor air temperature and indoor globe temperature

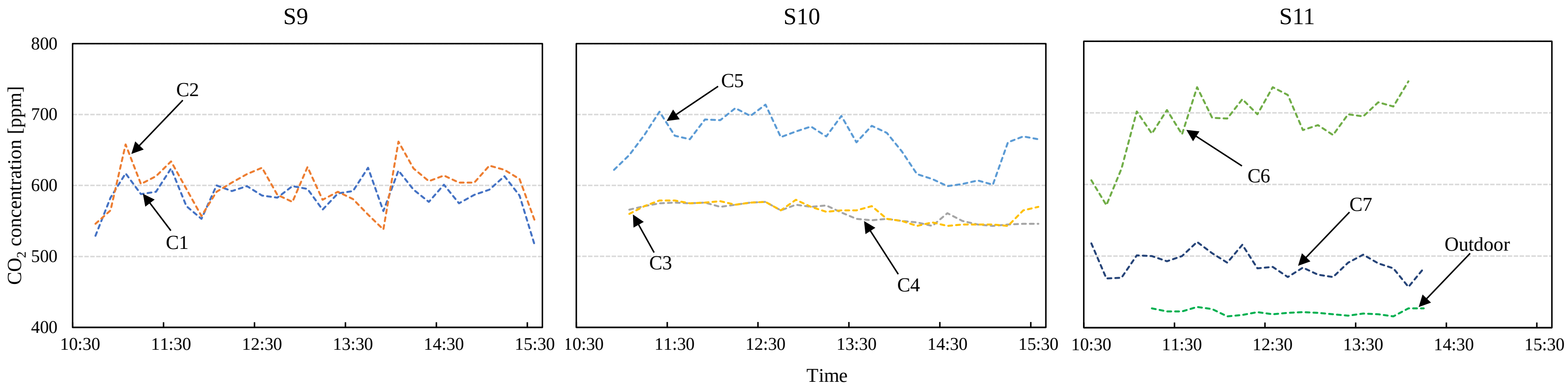


Figure 4.3 Continuous measurement of indoor CO_2 concentration

Nepal currently does not have applicable guidelines or standards regarding IEQ associated with thermal comfort, air quality, and the thermal environment of school buildings. There are structural guidelines, but no consideration has been given to the environment. Currently, the government of Nepal, Ministry of Education, has published a notice regarding the school building architectural drawing design model (Exam Sanjal 2021), but no consideration has been made regarding the indoor environmental quality such as CO_2, temperature, and so on. The structural design based on WWR and student density according to floor areas is still lacking. However, in reality, large size windows with no shutters are common in the study area, which causes effective cross ventilation in classrooms. Because of open windows, CO_2 is quite low. The CO_2 levels due to such a design should be studied in the future. However, this study cannot clearly show what kind of environment those buildings could create after they are built.

4.2.3 Comparison of indoor CO_2 concentration with previous studies

Table 4.1 shows a comparison of measured indoor CO_2 concentration with previous field studies conducted in primary to higher school students aged 3~18 years. The indoor CO_2 concentrations in this study are relatively lower than in previous studies. The range of measured values in this study is also quite small in comparison to other studies. The CO_2 concentrations are related to the number of students, opening size, outdoor wind condition, and so on, even though they are naturally ventilated classrooms. Due to these reasons, studies (Santamouris et al. 2008, Toftum et al. 2015, Korsavi et al. 2020, & Asif & Zeeshan 2020,) showed higher indoor CO_2 concentrations than this study under naturally ventilated conditions during summer.

Table 4.1 Comparison of indoor CO_2 concentration with previous studies conducted in school buildings

References	Country	Education level	School (S) / Classroom (C)	Density [person/m^2]	Condition	Season	Indoor CO_2 concentration [ppm]	
							Mean	Range
This study	Nepal	Secondary	3 S/7 C	0.8~2.1	NV	Summer	602	457~744
Asif & Zeehan (2020)	Pakistan	Primary*	1 S/11 C	0.7~1.2	NV	Summer	-	426~5000
Rashidi et al. (2012)	Kuwait	Elementary	3 S/10 C	0.5[a]	NV, MV	Summer	721	491~1215
Cornaro et al. (2013)	Italy	Middle school	1 S/8 C	-	NV	Winter & summer	-	400~2500 ***
Stabile et al. (2016)	Italy	Primary	7 S/ 16 C	-	NV	Winter & summer	908	501~1423
Vilcekova et al. (2017)	Slovak Republic	Primary	1 S/5 C	-	NV	Autumn	1164	577~1787
Dorizas et al. (2015)	Greece	Primary	9 S/ 9 C	-	NV	Spring	-	893~2082
Santamouris et al. (2008)	Greece	-	27 S/ 62 C	-	NV, MV	Autumn & spring	1410 NV, 910[b] MV	400~3000
Korsavi et al. (2020)	UK	Primary	8 S/29 C	-	NV	Summer	1050	475~3430
Toftum et al. (2015)	Denmark	Elementary to high	389S/ 820 C	-	NV, MV	Autumn	1261, 2479[2]	400~4597
Simanic et al. (2019)	Sweden	Elementary	7 S/145 C	0.05~0.07	MV	Summer & winter	-	<1000**
Deng & Lau (2019)	USA	Elementary to high	220 C		MV	Fall, winter & spring	1171	541~2369
Majd et al. (2019)	USA	Primary, lower secondary	16 S		NV, MV	Fall, winter & spring	851, 998, 845	554~2318
Haddad et al. (2021)	Australia	Secondary	1 S/2 C		NV, MV	Mid-season	744	442~1510

NV: Natural ventilation, MV: Mechanical ventilation, *Students from the age group of 3 to 11 years, **Low-energy school, ***Approximated value from figure, a: Guideline, b: Median

4.2.4 Responses of the students on IAQ

As described in 4.2.1, the indoor and outdoor thermal environments were close, and as mentioned in 4.2.2, the CO_2 concentration was below 1000 ppm. This section discusses how students perceive air quality under such conditions. Fig. 4.4 shows the occurrence of perceived air quality. IAQ depends on numerous indoor physical and chemical parameters, and CO_2 itself is a kind of their indicator. More students are saying acceptable but still unacceptable is not small. The unacceptable responses of the students are probably from those who are not surrounded by some flow of air and feel some stuffiness, even if the IAQ itself is acceptable. Probably, no uniform distribution of air flow occurred in the classrooms. Bogdanovica et al. (2020) found from a subjective assessment that the perception of students feeling tired and having headaches increases with the increase in indoor CO_2 concentration. Vilcekova et al. (2017) found that those perceptions of the students on IAQ were 53% for acceptable and 72% for stuffy feelings and these perceptions were consistent with the high indoor CO_2 concentrations.

The responses are further analysed with the indoor CO_2 concentration measured during voting time, as shown in Fig. 4.5. A weak correlation of increasing unacceptability responses was observed with the increase in the indoor CO_2 concentration ($r = 0.12$, $N = 736$, $p = 0.001$). It may be due to the narrow range of CO_2 concentrations in the classrooms. Bogdanovica et al. (2020) investigated the potential effect of CO_2 concentration on the well-being of students, with the findings that there was a moderate correlation ($r = -0.49$; scale: 1. Unacceptable and 5. Unacceptable) between the perceived IAQ associated with microclimate and indoor CO_2 concentration. Korsavi et al. (2021) employed a regression analysis of perceived IAQ associated with air freshness and found a weak correlation ($r = 0.17$) to indoor CO_2 concentration. The perception was towards stuffy when CO_2 concentrations were more than 1450 ppm.

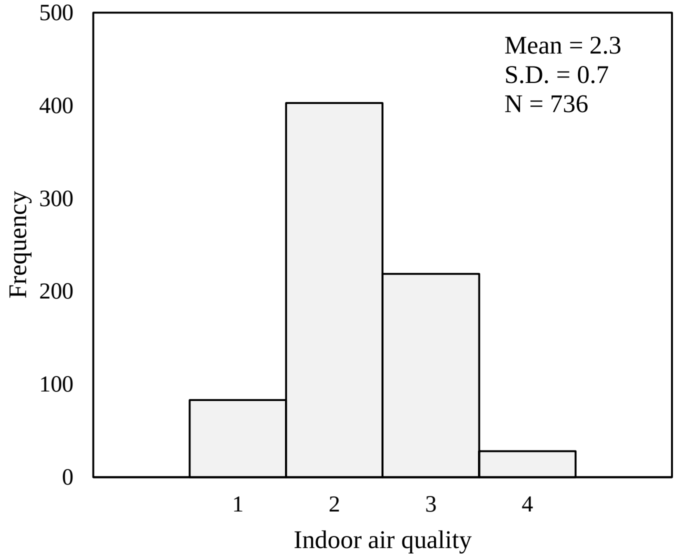


Figure 4.4 Distribution of indoor air quality (IAQ) responses

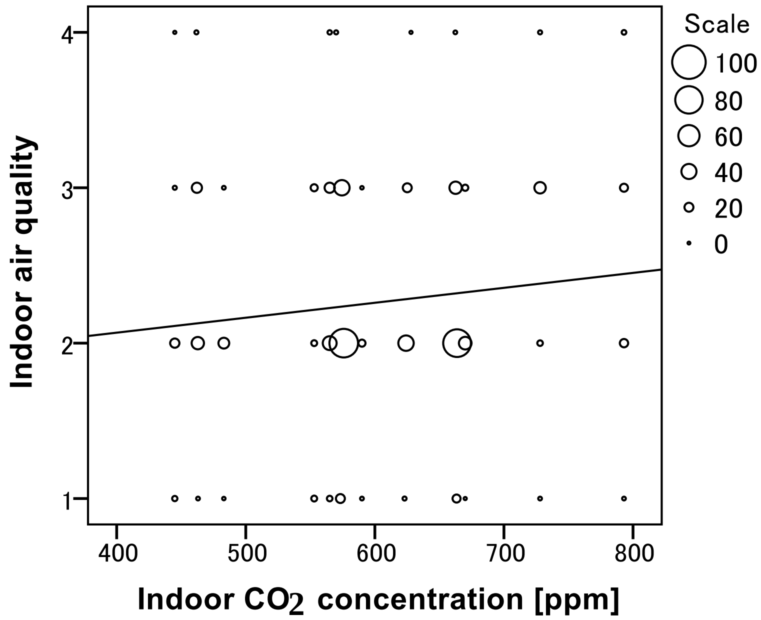


Figure 4.5 Relationship between the indoor air quality responses and indoor CO_2 concentration

4.3 Evaluation of ventilation rate and CO_2 concentration based on estimation

This section presents the quantitative results and their discussion based on the model developed in section 2.5. The estimated indoor CO_2 concentration was validated by comparing it with the measured indoor CO_2 concentration. Finally, we have estimated the indoor CO_2 concentration for reduced ACHs at 50% and 25%.

4.3.1 CO_2 emission rate of the students

The amount of CO_2 discharged in a confined space is dependent on the number of students and their metabolic rate. In this study, the metabolic rate was assumed to be 1.2 met for the sedentary reading and writing conditions. With this assumption, the average maximum CO_2 emission rate was estimated to be 9.3 mg/(s·p) in classroom C1 and a minimum of 8.2 mg/(s·p) in classroom C3. The overall range was from 6.4 to 10.9 mg/(s·p). Using the atmospheric pressure of 101 kPa and the measured average indoor air temperature in Kelvin, and the universal gas constant of 8.314 J/(mol·K), the range of emission rate is 3.6 to 6.1 ml/(s·p). These values agree with those given in previous studies (Batterman 2017, Kabirikopaei & Lau 2020, Bartlett et al. 2004, & Kapalo & Siroczki 2014). Even at the same type of physical activity, the CO_2 emission rate is different because of age group and body surface (Batterman 2017). How the body surface area is related to the CO_2 emission rate is presented in Fig. 4.6. Persily & de Jonge (2017) found through the pieces of literature that for an adult with a 1.8 m^2 body surface engaging in office work at 1.2 met, the corresponding CO_2 emission rate is 5.2 ml/(s·p). For a child of 1 m^2 body surface area at the same activity level, the corresponding emission rate is 2.9 ml/(s·p). When the students perform some heavy activities inside or outside the classrooms and return to the classrooms, they emit more CO_2 and heat. Kapalo et al. (2019) investigated that the highest increase in CO_2 emission was recorded during hard physical activities. In this study, there is no significant difference in emission rate between male (4.1 ml/(s·p)) and female (3.9 ml/(s·p)) students, which is similar to previous studies (Persily & de Jonge (2017). But a climate-controlled chamber study with university students and staff members of the university in China found that women emit CO_2 less than men (Yang et al. 2020).

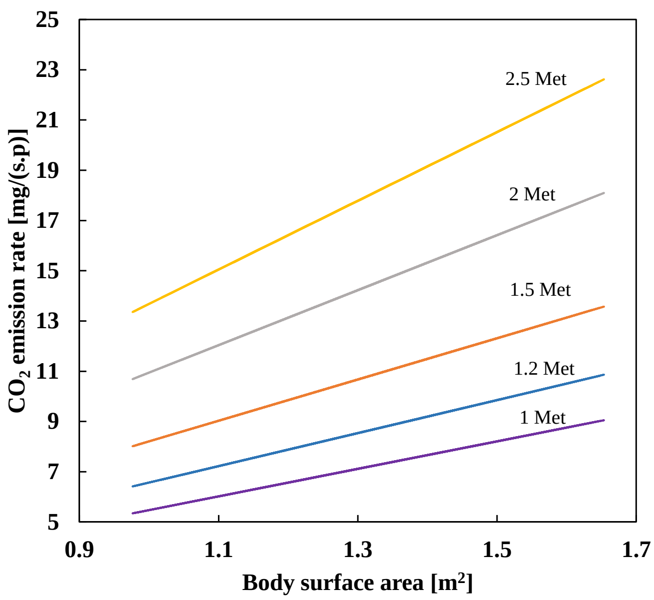


Figure 4.6 Relationship between the body surface area and CO_2 emission rate

4.3.2 Estimation of ventilation rate and CO_2 concentration of classrooms

Using the number of students together with the CO_2 emission rate described before, measured indoor CO_2 concentration, and outdoor CO_2 concentration, the time-variant ACH was estimated from eq. (12) for every 30-second interval, and then using the results of the calculation, the average ACHs for 10-minute, 20-minute, and 1-hour intervals were estimated. Using the averaged ACHs for every period of 10-minute, the indoor CO_2 concentration was estimated, and the fitting of the estimated CO_2 concentration to the measured CO_2 concentration was close. Fig. 4.7 shows the relationship between the measured and estimated indoor CO_2 concentration, verifying that the developed model is working well ($R^2 = 0.98$) and can be used to estimate the indoor CO_2 concentration and ventilation analysis.

The error of the developed model was examined using the following relation between measured and estimated CO_2 concentrations.

$$Percent\ error = \frac{|Measured\ CO_2 value - Estimated\ CO_2\ value|}{Measured\ CO_2\ value} \times 100\% \qquad (4.1)$$

Table 4.2 Percent of maximum and mean error of the developed model

Schools	Classrooms	Error [%]	
		Maximum	Mean
S9	C1	6.6	1.1
	C2	10.2	1.2
S10	C3	1.6	0.2
	C4	1.9	0.2
	C5	4.9	0.7
S11	C6	6.2	1.2
	C7	4.3	0.9
All		5.1	0.8

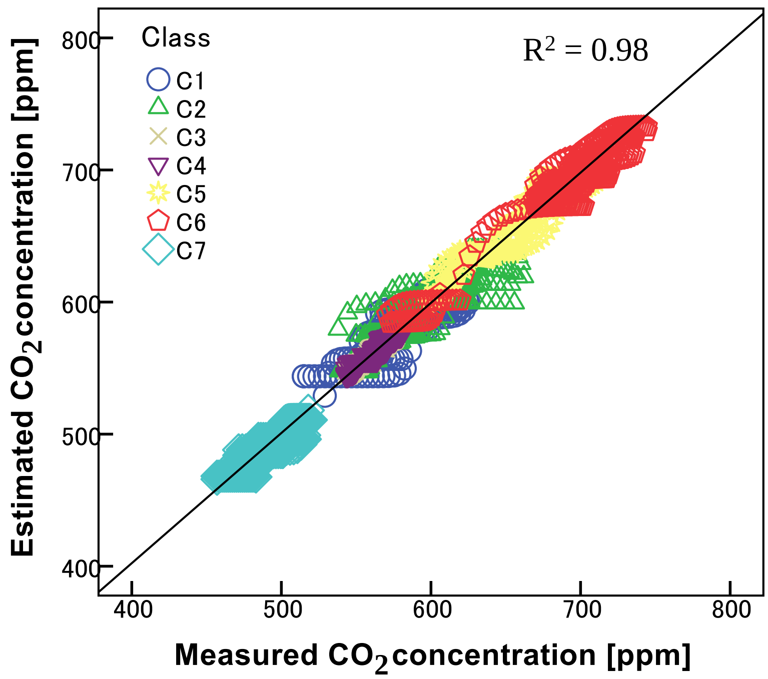


Figure 4.7 Relationship between the estimated and measured indoor CO_2 concentrations

Fig. 4.8 shows the ACH in all classrooms. The reciprocal relationship between the measured indoor CO_2 concentration and estimated ACH can be seen for the whole day periods of lessons, as shown in Figs. 4.3 and 4.8. For example, CO_2 concentration at 658 ppm corresponds to ACH of 55 h^{-1}, and CO_2 concentration at 538 ppm corresponds to ACH of 105 h^{-1}. ACHs in all classrooms are more than 25 h^{-1}, which resulted in the large rate of ventilation in these classrooms. This implies that natural ventilation performed very well; it is suitable for air quality and summer thermal comfort.

Behind such a condition of well-performed ventilation, factors such as window/door opening areas, their orientation, wind speed, and direction must be associated. On the windward side of the building walls, high pressure is exerted while on the leeward side low pressure is exerted, and thereby cross ventilation through the classrooms is made. Outdoor wind speed increases ventilation rates as the windows fully opened are oriented towards the wind direction (Korsavi et al. 2020). As shown in the plan view of the classrooms in Fig. 2.4, the orientation of the walls having windows influences wind flow. In general, as a characteristic of the investigated school buildings in the local areas, the wind flow rate would be high in the east or west direction if the opening was in that direction, resulting in cross ventilation. However, if the windows are facing north or south, it may not work properly. For example, in classroom C5, the air flow is dominant from west to east or vice-versa because of the orientation of the windows. The ventilation in classrooms C3 and C5 confirmed that having windows facing both east and west sides provide almost constant by performed ventilation. Therefore, proper orientation and position of windows or doors are necessary to make the ventilation

of classrooms efficient.
The students are emitting heat so that there is a buoyancy effect in addition to the wind effect. The air heated by the bodies of students flows upwards gradually and goes out from the upper window. Such an effect must have induced a large amount of outdoor air from the window on the opposite side for the effective cross ventilation (high ACH) in C1 and C2. A study (Gratia et al. 2004) examined various efficiencies of ventilation in different positions of windows through simulation and found higher ACH at different heights

of windows for ventilation by buoyancy effect. For example, 45% opening on one side and 100% opening on another at a different height have higher ACH. This case is similar to those in classrooms C1 and C2. Possibly, the running wall fan on the back side of classroom may also help affect a higher ACH. In school S9, the student density is higher in classrooms C6 than C7 and its influence has resulted in different ventilation rates even if the size and orientation of the classrooms are the same as each other. The occupant density of 0.8–2.1 persons/m^2 in this study, under the condition of natural ventilation by windows and doors, provided sufficient ACH as shown in Fig. 10, which could be obtained during regular lessons. Because of such a high ACH, even with high occupancy, the indoor CO_2 concentration is low. A significant relationship between ACH and occupant density was not observed in this study, and therefore, further examination is conducted with occupancy. The average ACH of each classroom is negatively correlated (r = -0.38) with the respective number of students. It shows that the ACHs decrease when occupancy increases. This is due to more CO_2 emission or some obstacles due to occupancy caused to lessen the flow of internal wind.

A study conducted in Nepalese traditional houses for winter thermal improvement associated with ventilation found ACH of 42 to 73 h^{-1} during day time (Rijal & Yoshida 2005). According to an internationally recognised BREEAM rating scheme, a room with openable window area with 5% window to floor area provide adequate natural ventilation and ventilation rates (CIBSE 2016). In the present study, window area to floor area ratios in the investigated classrooms are higher than 13%. This criterion can be obtained if the cross ventilation is available to openable windows. A study in multi-story hospital in China (Jin et al. 2015) found that ACH of 30-160 h^{-1} for cross ventilation and 0.5-7 h^{-1} for single sided ventilation.

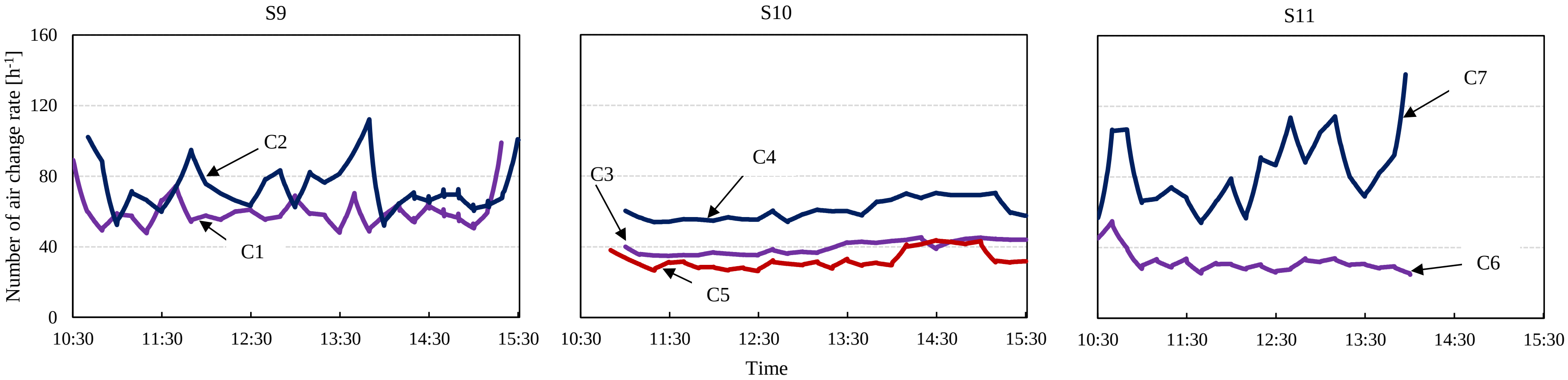


Figure 4.8 The estimated number of air change (ACH) in the investigated schools

4.3.3 Comparison of ACH and indoor CO_2 concentration with previous studies

Table 4.3 shows the ACH estimated mostly through analytical methods under the condition of NV or mechanical ventilation in different seasonal field studies at different educational levels in various countries. It is difficult to make a precise comparison of the results obtained in this study with those in previous studies since the method used, building structures, their locations are different, but a rough comparison must be meaningful to know their overall relationships. Fig. 4.9 shows the plot of indoor CO_2 concentration range against the corresponding ACH range, taking the values shown in Table 4.3. It shows that there is a clear tendency that as ACH increases, indoor CO_2 concentration decreases. It is seen that most classrooms are performing ventilation within the range of 1 to 10 h^{-1} to maintain the CO_2 concentration below 5000 ppm. The ACHs found in this study are very large and resulted in low values of indoor CO_2 concentrations if compared with the results of previous studies.

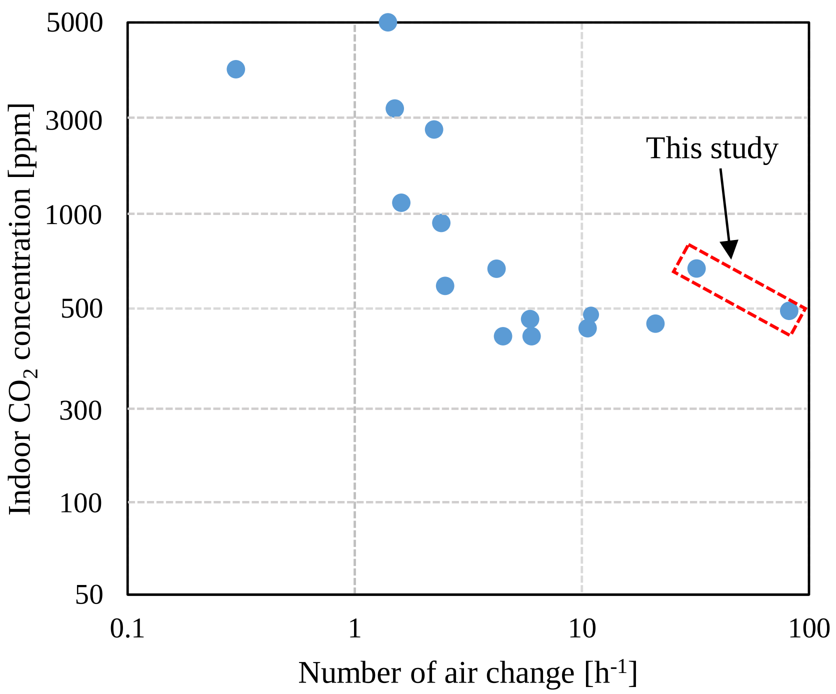


Figure 4.9 Relation between the indoor CO_2 concentrations and number of air changes in this study and previous studies (The logarithmic scales on both axes are used to display small to large values of ACH and indoor CO_2 concentrations.)

Table 4.3 Comparison of ACH and indoor CO_2 concentration with previous studies conducted in school buildings

References	Country	Education level	School (S) / Classroom (C)	Condition	Season	ACH [h^{-1}]	CO_2 concentration [ppm]
This study	Nepal	Secondary	3 S/7 C	NV	Summer	25~138	457~744
Asif & Zeeshan (2020)	Pakistan	Primary	1 S/11 C	NV	Summer	1.4~10.6	426~5000
Park et al. (2019)	Korea	Elementary	1 S/3 C	NV, MV	Summer	0.30~22.6, 2.1~3.7 (SS)	-
Cornaro et al. (2013)	Italy	Middle school	1 S/8 C	NV	Winter & summer	1.5~6*	400~2500
Stabile et al. (2016)	Italy	Primary	7 S/ 16 C	NV	Winter & summer	0.12	501~1423
Krawczyk et al. (2016)	Spain & Poland	University	2 S/ 8 C	NV	September	2.5~4.5	400~600**
Almeida et al. (2017)	Portugal	K-higher	8 S/32 C	NV, MV	Spring, summer& autumn	2~6.4	-
Korsavi et al. (2020)	UK	Primary	8 S/29 C	NV	Summer	0.3~11	475~3430
Abhijith et al. (2022)	UK	Primary	3 S/6 C	NV	Spring, summer	0.08~9.38	546.2~1262.6 ppm
Johnson et al. (2018)	USA	Elementary	12 S	MV	Cold & mild	1.6~5.9, 2.4	459~1169, 994
Haddad et al. (2021)	Australia	Secondary	1 S/2 C	NV, MV	Mid-season	2.23~21.1	442~1510

NV: Natural ventilation, MV: Mechanical ventilation, *Natural trickle ventilation, **Recommended range, SS: Single side ventilation, K: Kindergarten

4.3.4 Prediction of indoor CO_2 concentration under reduced ACH

As mentioned earlier, glass windows are rarely used in Nepalese school classrooms. If we replace those wooden shutter windows with glass windows in the future, the closing of windows behaviours could become dominant. That could decrease the opportunities for natural ventilation and thereby result in an increase in the indoor CO_2 concentration, which would be problematic. Considering such a situation and being aware of the negative effect of low ventilation, an attempt of observing the effect of ACH on indoor CO_2 concentration is made at different ACH using the developed base model. Fig. 4.10 shows the variation of indoor CO_2 concentration under two cases of reduced ACH: 50% and 25%. The manner of indoor CO_2 concentration fluctuating with the reduced ACHs looks proportional to the base case of the fluctuations of indoor CO_2 concentration.

The indoor CO_2 concentration in the case of 50% ACH is lower than that in the case of 25% ACH. It is rational because the ACH and indoor CO_2 concentrations are reciprocally proportional. The measured indoor CO_2 concentration in the present study is below 800 ppm. If the ventilation is reduced by 50% or 25%, the indoor CO_2 concentration is still approximately below 1600 ppm in all seven classrooms; 50% or 25% reduction of ACH does not cause any problematic CO_2 concentration. Asif & Zeehan (2020) simulated indoor CO_2 concentrations in naturally ventilated classrooms for three ventilation scenarios; 3, 8, and 20 l/(s·p) using their own analytical method. The trend of indoor CO_2 concentrations was approximately below 2000 ppm, 1000 ppm, and 700 ppm, respectively. It is consistent with what was obtained in this study.

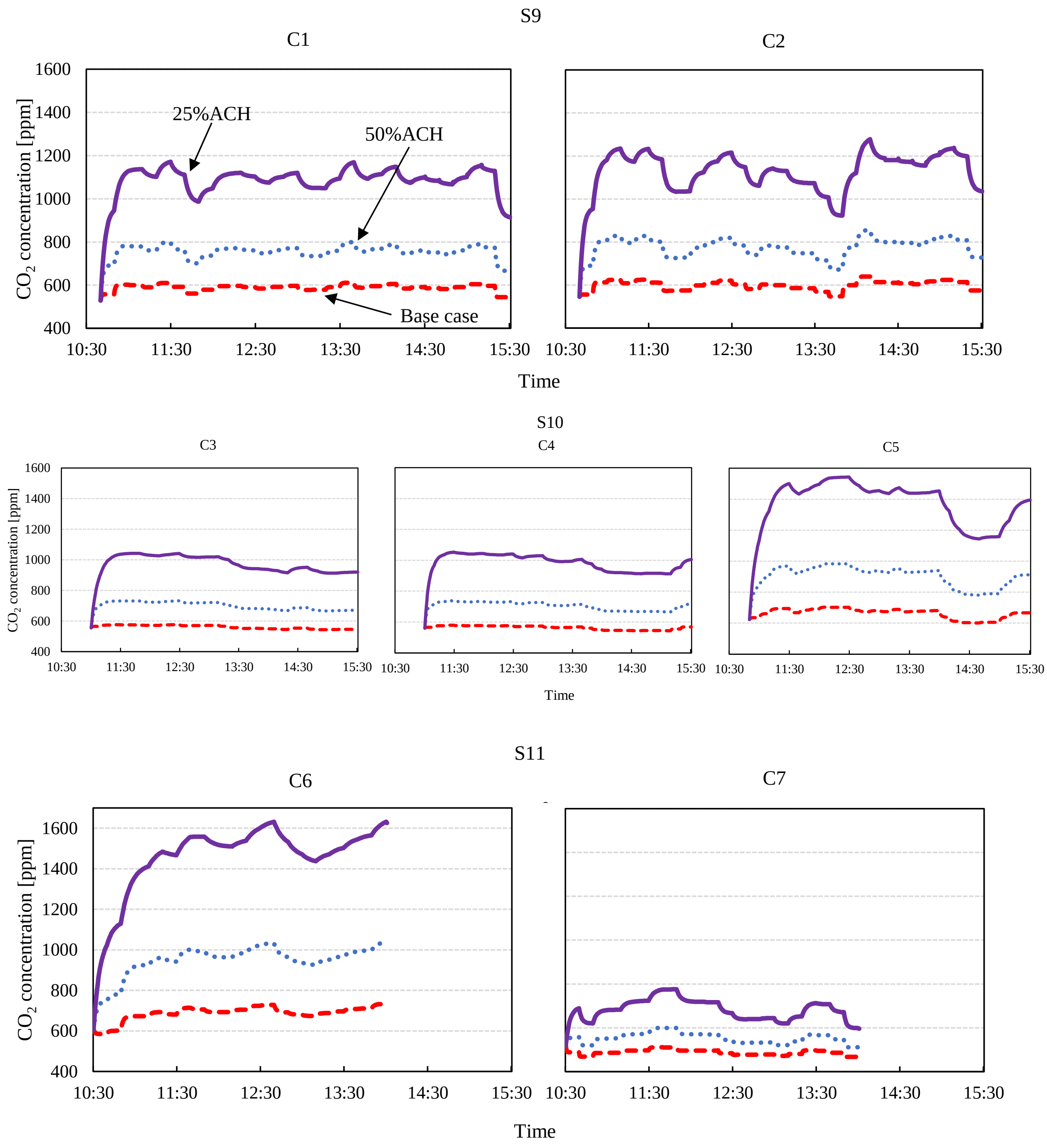


Figure 4.10 Indoor CO_2 concentration under reduced number of air change (ACH)

4.4 Conclusions

The major findings are as follows.

1. The measurement showed that the indoor CO_2 concentrations were much lower than the acceptable limit, and most students accepted the indoor air quality.
2. The estimated indoor CO_2 concentrations matched well with the measured CO_2 concentrations. This confirmed that the estimating method developed is highly accurate and can be used to estimate indoor CO_2 concentration.
3. Using the measured results along with the CO_2 emission rate, the time-variant number of air change was estimated. It was found that the ventilation was performed sufficiently.
4. The indoor CO_2 concentration was estimated at two scenarios: 50% and 25% reductions in ACH to demonstrate the future condition if some renovation is done or if wooden window shutters are replaced by glass sheets. The results showed that the indoor CO_2 concentrations were still lower than the acceptable limit. It is an important point for the improvement because the glass windows, which are a high priority, effect on natural ventilation performance.

The developed model and the findings of this study should be useful for the evaluation of school buildings if they are to be improved or renovated in the future. In terms of indoor air quality, they are so much better than that in some of the developed countries. This is good for all of us to rethink the role of natural ventilation for rational indoor air quality from the perspective of global environmental issues in association with energy use. Further, in order to make the classrooms safe from the infections of airborne diseases, natural ventilation could be an on-site sustainable mitigation strategy.

Chapter:5
Passive thermal improvement of classrooms

5.1 Introduction

This chapter mainly focuses on improving the thermal environment using passive design strategies after evaluating the subjective perceptions of the students. The purpose of this chapter is to analyse and compare the impact of various passive design strategies, such as natural ventilation, insulation, and thermal mass, on the indoor thermal environment through a case study of a school building. The first section of this chapter presents the thermal comfort evaluation based on the field survey, while the second section presents the improvement of the thermal environment for thermal comfort based on building simulation techniques.

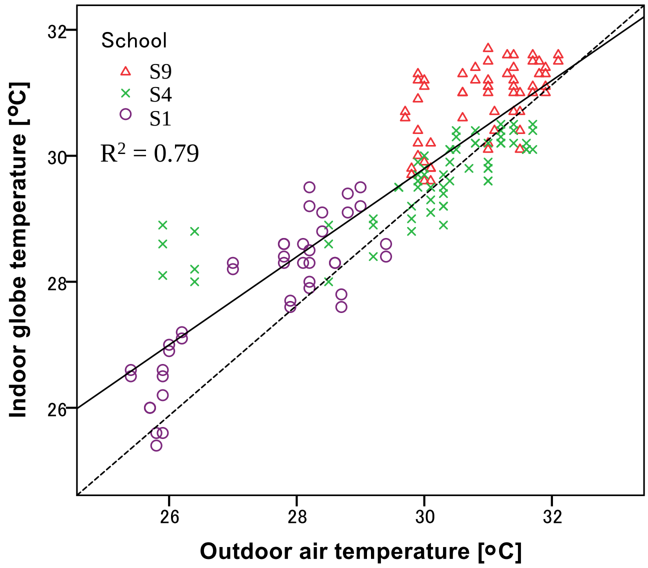
The measured data used in Chapters 4 and 5 is the same, but for different purposes. Chapter 4 is based on field measurement and modelling, and focuses on CO_2 and ventilation estimation. In Chapter 5, the estimated ventilation, such as an average of 59 ACH, is used for simulation. So far, Chapters 3 and 4 are based on field measurements and a questionnaire survey. With field measurements and a questionnaire survey, we cannot do everything. Hence, this chapter aims to investigate the impact of various passive design strategies, such as natural ventilation, insulation, and thermal mass, using simulation.

5.2 Thermal comfort of students

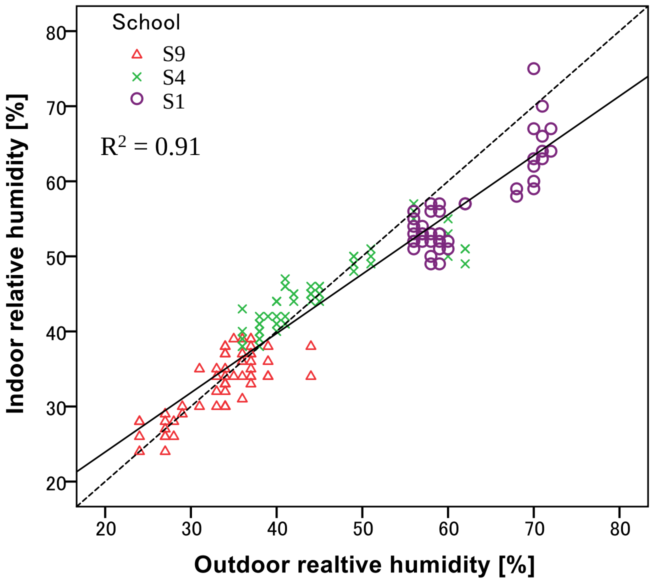
5.2.1 Thermal environment during the voting time

Environmental quantities such as temperature and relative humidity were measured in order to observe their trend. We measured the globe temperature, as it represents the combined effect of radiation from indoor surfaces and the convection of space air. The measured indoor air and globe temperatures were quite close and did not vary much. Fig. 5.1 (a) shows the regression relationship between the continuously measured indoor globe temperature and the outdoor air temperature during the voting time in each school building. The indoor globe temperature in S9 lies between 29.6 and 31.5 °C while the outdoor air temperature is between 29.7 °C and 32.1 °C, which is higher than any of the investigated buildings. Both indoor globe and outdoor temperatures displayed a similar pattern of variation. The indoor and outdoor temperatures differed among buildings due to their architectural characteristics, orientation, geography, climatic conditions, and so on.

Fig. 5.2 (b) shows the variation of measured indoor and outdoor relative humidities in each school building. The indoor relative humidity follows the outdoor relative humidity. Among all school buildings, S9 and S1 have the lowest and highest relative humidity, respectively. The outdoor relative humidity lies between 24 and 44% and indoors between 27 and 39% during regular lessons during the survey time in S9. They are correlated and similar to each other. This confirmed that the natural ventilation performed quite effectively.



(a)



(b)

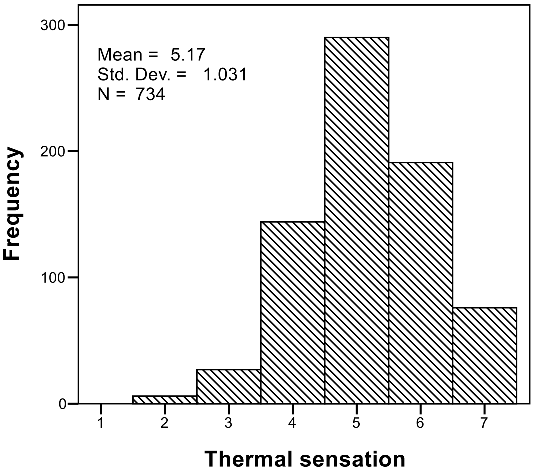
Figure 5.1 Measured environmental quantities during the voting time in S1, S4, & S9 buildings: (a) indoor globe temperature and outdoor air temperature and (b) indoor and outdoor relative humidity.

5.2.2 Thermal sensation, preference, and comfort temperature

This section examines students' perceptions of the thermal environment mentioned in the previous section. Fig. 5.2 (a, b) shows the overall distribution of thermal sensation and preference of the students in all three investigated school buildings. It shows that 75.9% of the responses were towards the hotter side (responses for 5, 6, & 7), with most preferring a cooler environment. At neutral, there were few responses. The results showed that 63.6% of the student's responses were within the central three categories (responses for 3, 4, and 5), which are representative of satisfaction and acceptance. The responses of the students in the simulated school building showed that 88.7% of them were obtained towards the hotter side. 54.5% of the student's responses were within the central three categories, preferring the cooler environment as shown in Fig. 5 (c, d). The preference for "3. No change" was 15.2%. The responses of 61.6% and 23.2% were obtained at "4. A bit cooler" "5. Much cooler". Overall, the preference for "3. No change" was 21.8%. The responses of 75.8% were obtained towards the preference for cooler. In the simulated school building, 84.8% of students responded to a preference for cooler, with 15.2% for "3. No change". The significant number of responses on the hotter side are the issues of thermal environment and comfort in the school buildings. The reduction of the indoor temperature should be necessary to change the responses of the students toward the comfort side.

The average comfort temperature of the students, based on their thermal sensation and measured indoor globe temperature, was estimated using the Griffiths method.

Fig. 5.2 (c) shows the distribution of comfort temperatures, whose average is 26.9 °C. S9 school in Kathmandu has a higher average comfort temperature than S4 and S3 schools: 28 °C, 27.5 °C, and 25.5 °C, respectively. The S1 school is significantly lower than the remaining ones. Overall, the comfort temperatures are distributed over a wide range, but the values are mostly between 25 °C and 29 °C. These values are close to the findings of the studies conducted in naturally ventilated schools during the hot seasons (Liang et al. 2012, Talukdar et al. 2020, & Heracleous & Michael 2020). The comfort temperature perceived by the students is higher, which must be because of their greater status of adaptation and tolerance to the indoor thermal environment.



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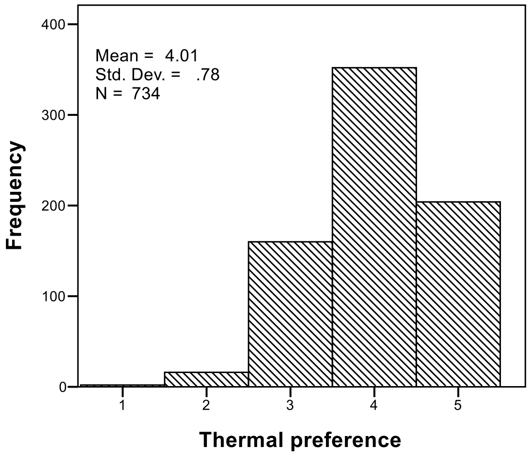

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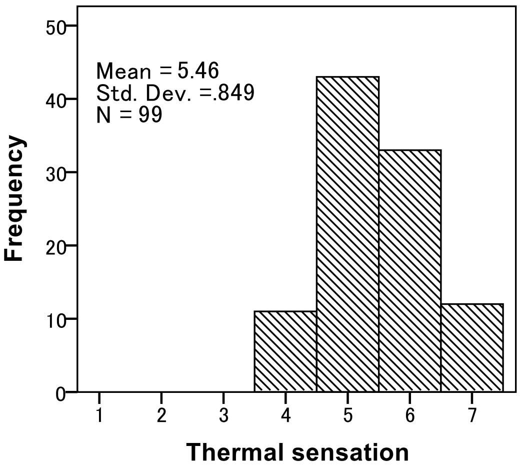
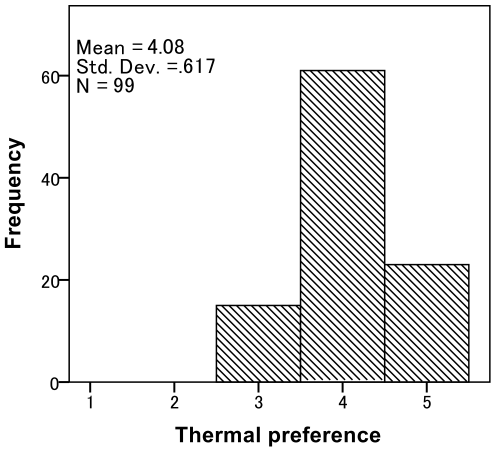


(c)



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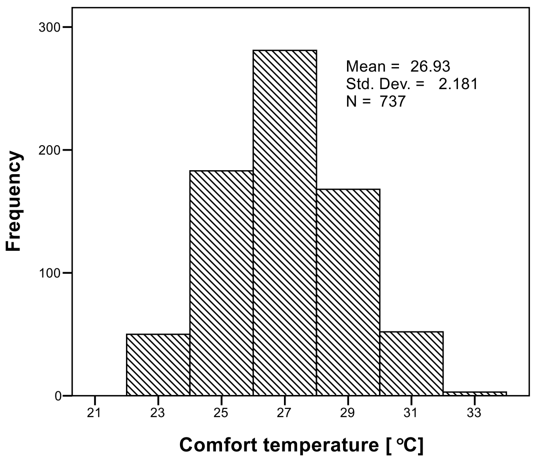


(e)

Figure 5.2 Distribution of (a) overall thermal sensation, (b) overall thermal preference, (c) thermal sensation in the simulated building, (d) thermal preference in the simulated building, and (e) estimated overall comfort temperature.

5.3 Thermal improvement of the classroom based on simulation

5.3.1 Daily variation of the indoor and outdoor air temperature

Fig. 5.3 shows the continuously measured indoor air, globe, and outdoor air temperature variations of the investigated classroom (zone 3) for seven days. The indoor air and globe temperatures did not differ significantly and were quite close on all seven days. But, the variations in outdoor air temperature were a little bit sharp relative to the corresponding indoor air and globe temperature. Both indoor and outdoor temperatures displayed a similar pattern of fluctuation, with the highest temperature peaks occurring during the day. Indoors is probably because there is not much effective thermal capacity of building materials or ventilation effect. Fig. 5.3 confirms that the maximum indoor temperatures that follow the outdoor air temperature start to occur after 12:30, which is around 30 °C, and after a certain time, the temperature decreases. At the same time, the outdoor air temperature amplitude during the day reaches a maximum of more than 35 °C, while it reaches a minimum of less than 20 °C at night. There are cases where the differences between the indoor globe temperature and the outdoor air temperature are 5.4 °C during the daytime.

The horizontal line represents the comfort temperature as found in Section 3.2. The average comfort temperature appears to be close to both the average school-hour (10:00–16:00) indoor air temperature (28.0 °C) and the globe temperature (28.1 °C). However, the indoor globe temperatures are higher than 28.0 °C, and improvement is needed to reduce them.

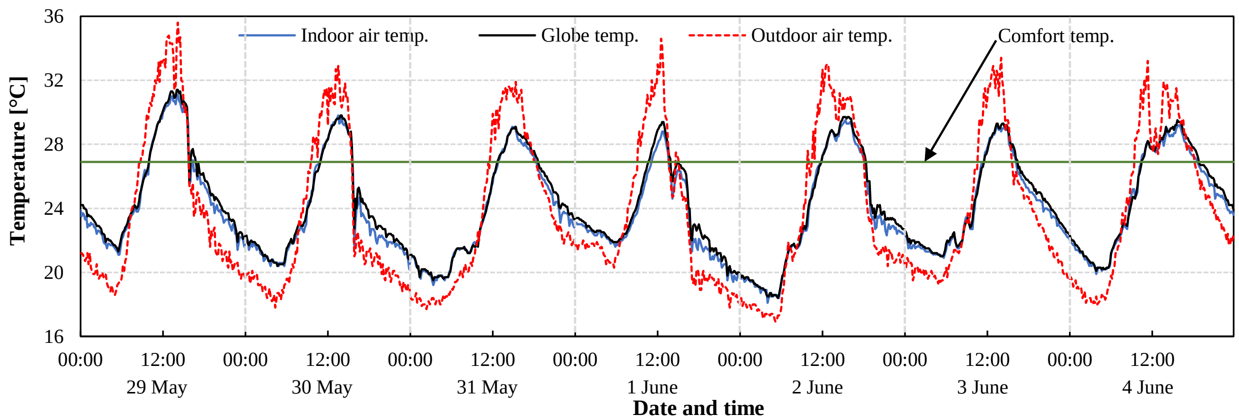
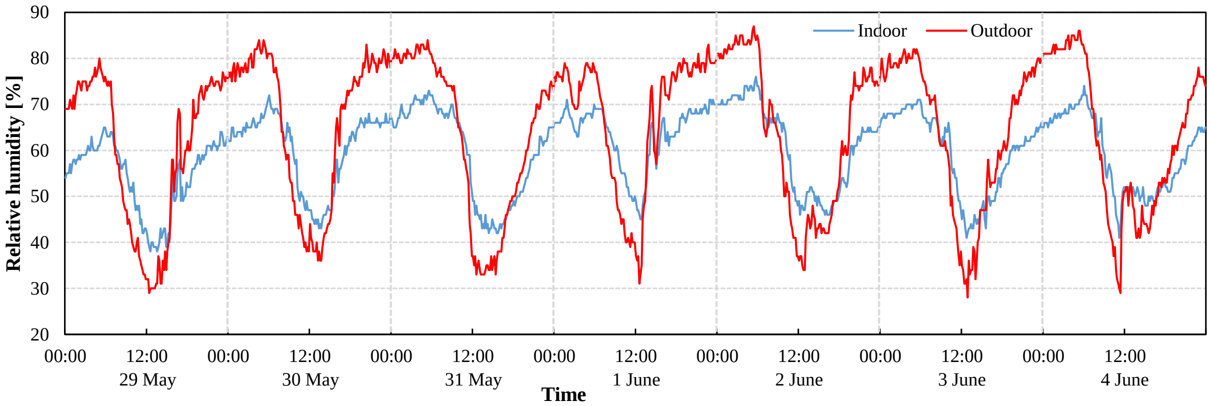


Figure 5.3 Variation of indoor and outdoor temperatures in zone 3 of the S1 school building over a week (2019)

5.3.2 Daily variation of the indoor and outdoor water vapour concentration

Fig. 5.4 (a) shows the variation of measured indoor and outdoor relative humidities. The indoor relative humidity follows the outdoor relative humidity, but the amplitude of the outdoor relative humidity is high and that of the indoors is low, especially during the day. According to ASHRAE, relative humidity higher than 60% is not good for thermal comfort. The outdoor relative humidity ranged from 24 to 44% and indoors from 27 to 39% during regular lessons on the survey day, where the maximum relative humidity was observed around 12:00 and the minimum around 15:00. The indoor relative humidity ranges from 38 to 76% and that of the outdoors from 28 to 87%. The students are exposed to the range of indoor relative humidity of 38 to 66% from 10:00 to 16:00. This demonstrates that the indoor relative humidity under natural conditions is not specified.



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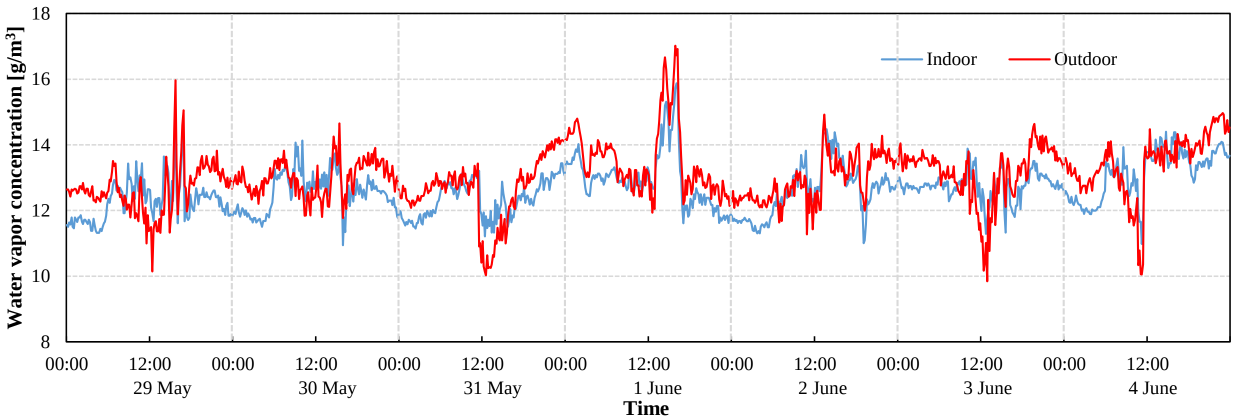


(b)

Figure 5.4 Variation of daily indoor and outdoor (a) relative humidity and (b) water vapour concentration. The graph presents a one-week (2019/5/29 to 2019/6/4) measurement even though we have measured for more than one month.

Relative humidity alone cannot analyse the moisture level for comfort and indoor air quality. Therefore, using the continuously measured air temperature and relative humidity, indoor and outdoor water vapour concentrations were calculated (Shukuya 2019). Fig. 5.4 (b) shows the relationship between the indoor and outdoor water vapour concentrations, indicating that they show a similar trend of variation. They fluctuated mostly between 12 and 14 g/m^3. The mean indoor and outdoor water vapour concentrations are 12.7 and 13 g/m^3, respectively, and the indoors are higher by an average of 0.4 than the outdoors. The indoors is lower around 00:00 to 8:00 and 17:00 to 00:00, while it is higher during the day time. This is because of the activities of the students and the moisture generated by respiration during the day. The higher the indoor air temperature, the more water vapour that the air can hold.

5.3.3 Validation of the base model

The base model is validated using the measured globe and simulated operative temperatures using the simulation results for Zone 3. Fig. 5.5 shows the variation and relationship between them for a day. Based on the analysis, good agreement has been found between the measured globe temperature and the simulated operative temperature, with a correlation coefficient of 0.96. The RMSE value was found to be 0.074. The mean absolute error (MAE) of 0.70 °C with a standard deviation of MAE 0.55°C was found, which shows the reliability of the simulated operative temperatures. Further, the good agreement, with an average percentage error of 4.4%, is comparable to previous studies (Liu et al. 2018 & Al-Absi et al. 2020). It confirms that the base model can be used to predict the operative temperature according to the passive design applied.

As discussed in the previous sections, the students are thermally discomfort with high temperatures. The next sections, therefore, analyse the reduction of such high temperatures by employing the passive design strategies, using the simulation result of zone 3 in the S9 school building in Kathmandu. The strategies employed, such as natural ventilation, thermal insulation, and thermal mass, can be used as a retrofit in practical situations or before construction. Individually, each strategy is investigated separately, keeping other components unchanged. Then, their impacts on operative temperature were analysed to identify the optimum case of each strategy. The strategies were applied at the whole building level, but we here analyse the simulated classroom (Zone 3) only. We have selected affordable passive refurbishment expanded polystyrene (EPS), glass wool (GW) as an insulating material, and cast concrete as a thermal mass for improvement, considering that they are found at the local level. The simulation was run at 10-minute intervals.

Fig. 5.5 (c) shows the simulated operative, air, and radiant temperatures of the base model for reference on how these three temperatures fluctuate during simulation. As mentioned in 2.4.1, the improvement of radiant temperature or air temperature alone cannot say much about the improvement of average room temperature. Therefore, the operative temperature was selected for analysis and improvement, which represents both air and radiant temperatures.

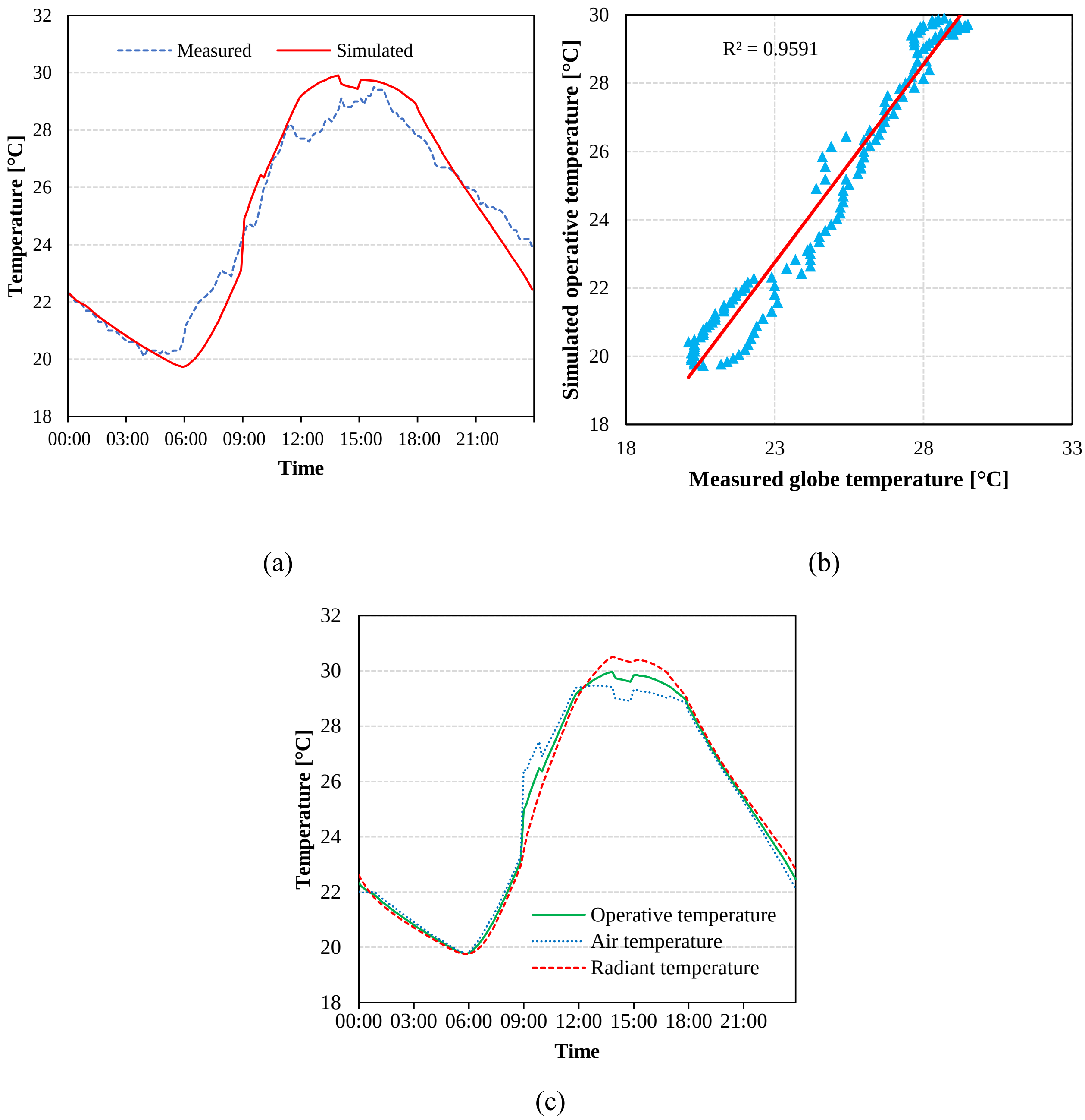


Figure 5.5 Validation of the base model: (a) variation, (b) relationship between the measured globe and simulated operative temperatures, and (c) variation of simulated operative, air, and radiant temperatures on June 4, 2019. A few other studies (Camacho-Montano et al. 2020 & Khaksar et al. 2021) used measured indoor air temperature and simulated operative temperature to validate models.

5.3.4 Site orientation

In addition to the abovementioned strategy, site orientation is the most important strategy that should be considered while selecting a site before building construction. Therefore, the purpose of this section is to provide a more fundamental understanding of the fluctuation of operative temperature caused by orientation. The orientation of 180° (south) is used in the case study building. The four primary orientations of 0°, 180°, 270°, and 360° are commonly taken into consideration to investigate the impact of orientation on temperature inside buildings. Fig. 5.6 shows the effects of different site orientations on the operative temperature of the classroom for the month of June.

It showed that the operative temperature range was highest when the orientation was east (90°) or west (270°) and lowest when facing north (0° or 360°) or south (180°). The lowest temperature profile on the north or south face is due to the minimum solar radiation received from windows and doors compared to other orientations. Fig. 5.6 shows that east and west orientation caused the maximum operative temperature and the minimum when the classroom faced north and south. This must be due to symmetry in the shape and openings, as the solar exposure in both cases becomes identical. When compared to the other directions, Zahiri and Altan (2016) found that classrooms facing west have the highest indoor air temperature and classrooms facing north have the lowest.

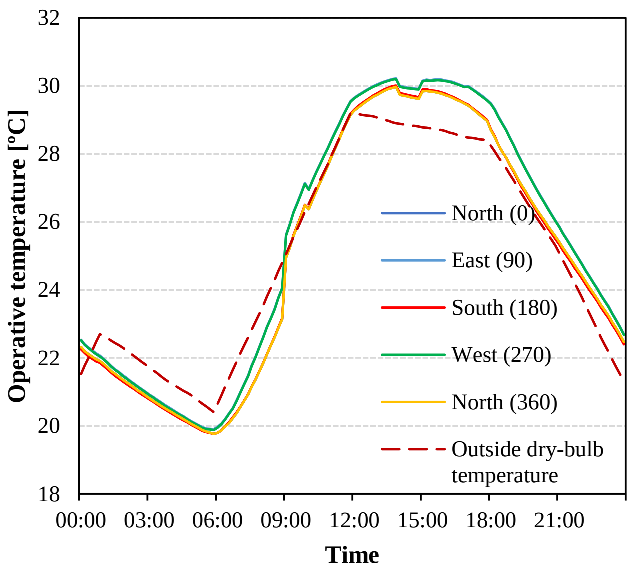


Figure 5.6 Operative temperature for four primary site orientation

5.3.5 Natural ventilation in terms of the number of air change rate

The only way to keep an indoor environment cool in the absence of temperature or humidity control and prevent overheating is by providing natural ventilation (Pohl 2011). Sufficient airflow can ensure good ventilation in indoor spaces like classrooms, depending on the orientation of a building and the position of its windows. It makes the students feel more comfortable and maintains indoor air quality by increasing wind speed during school hours (Heracleous & Michael 2022). In the base model, 59 ACH was used for natural ventilation, which is the estimated average ACH value for the classroom; however, the time-variant ACH was estimated, and the range of ventilation for the classroom was 47.8–99 ACH. Such high ventilation is probably due to the buoyancy effect and the room's size. The heat generated inside the classroom is not only due to solar radiation but also from the students, and this results in a temperature difference inside the classroom, so there is a buoyancy effect in addition to cross ventilation. The air heated by the bodies of students, which is less dense and creates low pressure, rises gradually and escapes out of the upper window. The cooler air gets sucked in from the opening below or the window on the opposite side from outside. Such an effect must have led to a high ACH. According to a study (Al-Absi et al. 2020), different heights of windows at different positions create a significant buoyancy effect for ventilation, resulting in higher ventilation. They found that 45% opening on one side and 100% opening on the other at a different height had a higher ACH.

As mentioned in Table 2.5, the width of the case study classroom is just 3.8 m, and the classroom has a small volume. Consequently, air exchange takes less time. This can be confirmed by the measured five-minute average air velocity of 0.20 to 0.38 m/s during the regular lesson, as mentioned in Section 2.4. Due to these reasons, the ACH is high in the classroom. Table 5.1 summarizes the ACH to maintain the summer indoor temperature found in the previous studies. An ACH of 42–73 h^{-1} was found with in a study conducted in Nepalese traditional houses for winter thermal improvement during the day (Rijal & Yoshida 2005). According to a study conducted by Chaulagain et al. (2022) in twenty-five typical residential buildings in Nepal, an average ACH of 55.5 was found under natural ventilation at 50 Pa using the fan pressurization method. Tong et al. (2021) found that natural ventilation could reach up to 91 ACH in a free-running room that is suitable for maintaining the indoor air temperature. Yik et al. (2010) found that in a well-ventilated indoor space with approximately 50 ACH, the indoor air temperature can be kept below 28 °C without using cooling. Park et al. (2021) and Aguilar et al. (2022) found that the natural ventilation was greater than 20 ACH in educational buildings during the summer.

A series of values of 20, 40, and 80 air change rate per hour (ACH) were tested to investigate the impact of ventilation on operative temperature. Fig. 5.7 shows that the operative temperature decreases as the ACH increases and becomes minimal beyond 59 ACH, mainly during the daytime. The maximum temperature for the 80 ACH is approximately 1 °C lower than for the base model. As a result of the natural ventilation, the classrooms stay at a lower temperature, and the MRT is reduced, lowering the operative temperature, which improves the perception of thermal comfort among students. Furthermore, the cooling effect of the night ventilation could also reduce the following day's classroom indoor temperature. For security reasons, it might not be possible to leave the windows open during the night.

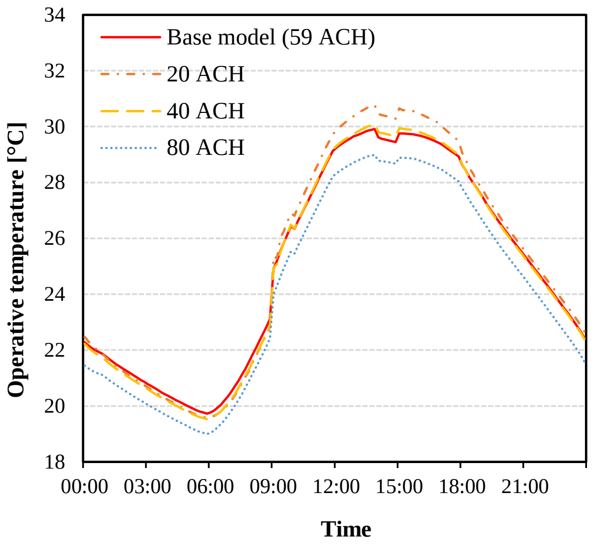


Figure 5.7 Impact on operative temperature due to natural ventilation.

Table 5.1 Summary of ACH and its range in previous studies conducted in various indoor spaces

References	Country	Climate zone	Season	Building type	Method	ACH	ACH range
Rijal & Yoshida (2005)	Nepal	Temperate	Winter	Residential	Simulation	-	42-73
Chaulagain et al. (2022)	Nepal	-	-	Residential	Experiment	55.5	10.4-120.7*
Tong et al. (2021)	Singapore	Tropical	November	Residential	Simulation	91	-
Yik et al. (2010)	China	Hot-humid	Summer	Residential	Simulation	50**	-
Jin et al. (2015)	China	Subtropical	-	Hospital	Simulation	-	30-160
Park et al. (2021)	South Korea	Humid continental	Summer	School	Estimation	-	2.13-22.4
Aguilar et al. (2022)	Portugal, Spain	Hot, warm-dry	March-July	University	Estimation	-	2-21.1

*For brick masonry in cement mortar (BMC) and stone masonry in mud mortar (SMM) type buildings, **Summer energy savings ventilation rate

5.3.6 Thermal insulation

5.3.6.1 Thermal insulation in the external wall

Insulation maintains an indoor temperature reduction, minimizing the heat flow through walls and roofs exposed to direct sunlight during the summer. Well-insulated buildings reduce the transmission of heat flow rates, lowering thermal conductivity and resulting in a more comfortable indoor thermal environment. It is said that insulation applied externally to the external wall is superior to that applied internally. With the same thermal insulation, greater thermal inertia tends to keep the MRT values lower throughout the year; therefore, it can improve thermal comfort during the summer (Su et al. 2022). Lu et al. (2021) found that the effect of outside insulation appears greater than that of the inside with the same wall thermal resistance. Kolaitis et al. (2013) found in a numerical study that external insulation results in approximately 8% higher energy savings than internal insulation on an annual basis.

Various thicknesses of lightweight EPS were applied to investigate their effects on operative temperature. It was applied to the outer surface of external walls of various thicknesses, as shown in Table 5.2, and plastered on the external surface with gypsum having a thickness of 15 mm. In real construction, metal lath is placed over the EPS board, but we have kept it constant during the simulation. Fig. 5.8 shows the fluctuations in operative temperature after using the thermal insulation. Thermal insulation with various thicknesses resulted in a low operative temperature because of a low total U-value as compared to the base model (3.2 W/(m^2•K)). As expected, the thicker the EPS insulation on walls, the lower its U-value. This is due to a decrease in thermal conduction toward the interior surfaces of the walls. The maximum operative temperature for EPS 200 mm is 1.7 °C lower than for the base model. This analysis indicated that the indoor temperature could be reduced.

Table 5.2 External wall insulation made of expanded polystyrene (EPS) and their thermal properties

EPS thickness (mm)	U-value [W/(m^2•K)]	
	Base model	Improved model
50	3.2	0.71
100	3.2	0.40
150	3.2	0.28
200	3.2	0.21

The U-values refer to the values assigned by the simulation software.

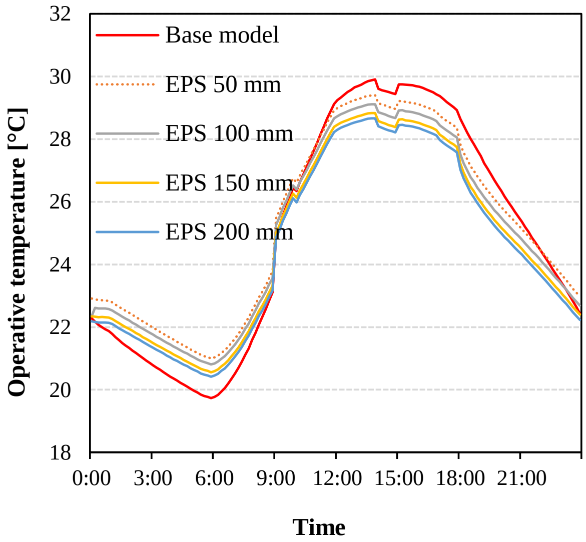


Figure 5.8 Impact on operative temperature due to external EPS wall insulation.

5.3.6.2 Thermal insulation in the pitched roof

Buildings with large roofs account for a large amount of heat gain or loss (Sadineni et al. 2011). In summer, the roof receives a longer, more intense, and higher amount of solar radiation due to the sun's path (Fig. 5a), and this creates the worst indoor thermal conditions. As the simulated building has a pitched zinc roof, its U-value is higher than the other components due to its lower insulating property. Consequently, more heat is transmitted through the roof, and the attic, as well as the indoor space, becomes warmer throughout the day. Therefore, this section discusses the effects of insulation on the zinc roof in order to solve this issue. Glass wool (GW) insulation of various thicknesses was applied. Table 5.3 shows the properties of the roof for each case. The GW insulation was applied internally below the pitched zinc roof, keeping the other structure constant (Fig. 5.9). Fig. 5.10 shows the impact on operative temperature after applying the various thickness of insulation to the inner surface of the pitched zinc roof. The maximum operative temperature for GW 200 mm is 2.01 °C lower than for the base model. Even though the operative temperature was reduced, a feature of time lag can be seen around 17:00. The effect of the GW 200 mm insulation is higher than in the other cases. Consequently, the thicker the insulation, the lower the operating temperatures that can be achieved during the day. According to Alghamdi et al. (2022), the proper roof construction reduced the operative temperature by 20% by lowering the U-value from 6.22 W/(m^2•K) to 0.24 W/(m^2•K), resulting in 3.25 times fewer thermal discomfort hours for students.

Table 5.3 Zinc roof insulation made of glass wood (GW) and their thermal properties

GW thickness (mm)	U-value [W/(m^2•K)]	
	Base model	Improved model
50	7.1	0.72
100	7.1	0.38
150	7.1	0.26
200	7.1	0.20

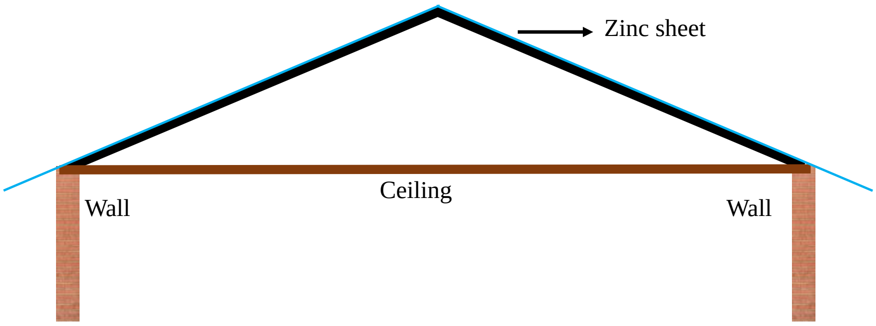


Figure 5.9 Position of thermal insulaiton in pitched roof

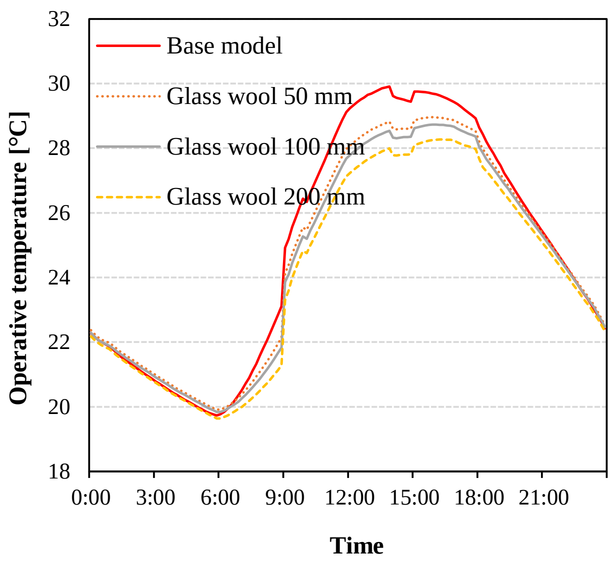


Figure 5.10 Impact on operative temperature due to pitched roof insulation using glass wool (GW).

5.3.6.3 Thermal insulation over the plywood ceiling

There are several ways and kinds of providing insulation below the rafters that minimise and prevent thermal bridges and stabilize the indoor temperature. The simulated building had only 18 mm of white-painted plywood below the pitched roof as its ceiling. Subsequently, we applied 50 to 200 mm of lightweight EPS (Table 5.4). It was applied to the outer side (pitched roof face) of the ceiling (Fig. 5.11). Fig. 5.12 shows the operative temperature fluctuation after applying the insulation above the plywood ceiling. For 50 mm EPS, the effects on operative temperature were minor. The reason might be the 18 mm of lightweight plywood used as the thermal insulating material. But for 100-, 150-, and 200-mm EPS, the temperature is reduced during the day. The maximum operative temperature for EPS 200 mm is 2.5 °C lower than for the base model. Especially during the daytime, due to high solar radiation, the zinc roof is heated up, and ultimately the inner roof surface temperature increases. The results showed that if we use suitable insulation material, for example, EPS, the indoor temperature can be reduced during the day.

Table 5.4 Ceiling insulation made of expanded polystyrene (EPS) and their thermal properties

EPS thickness (mm)	U-value [W/(m^2•K)]	
	Base model	Improved model
50	3.8	0.74
100	3.8	0.41
150	3.8	0.28
200	3.8	0.22

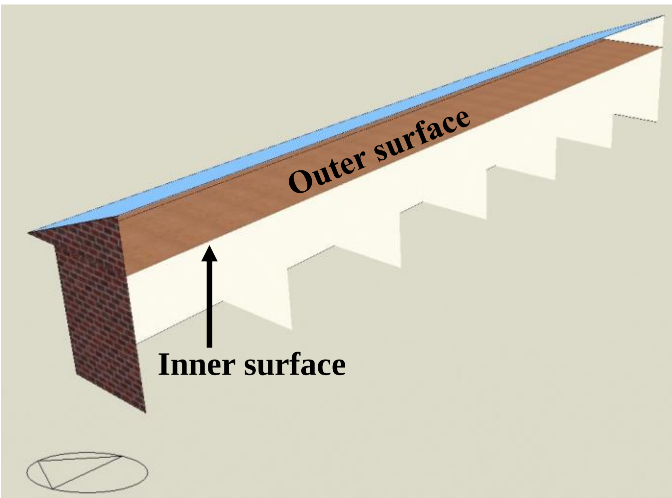


Figure 5.11 Position of thermal insulaiton in ceiling

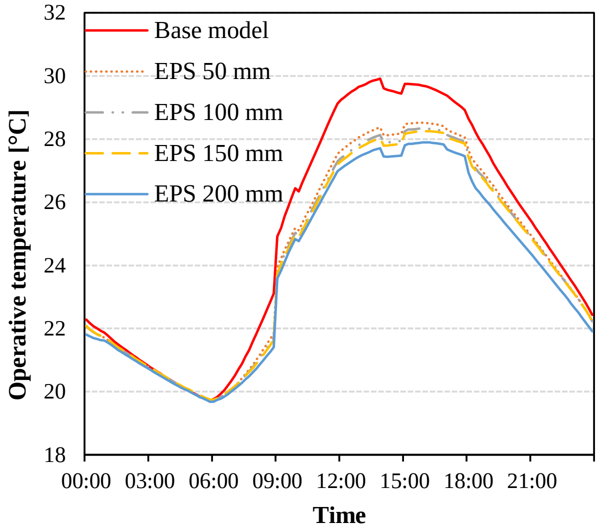


Figure 5.12 Impact on operative temperature due to ceiling insulation using Expanded polystyrene (EPS).

5.3.7 Thermal mass in external walls

This section is to analyse the impact of cast concrete as thermal mass, with different thicknesses employed for thermal improvement. Table 5.5 shows the thickness of cast concrete and the U-value of the improved wall. Fig. 5.13 shows that the use of cast concrete (dense) as thermal mass in external walls reduces the operative temperature. At 14:00, the maximum operative temperature is 2.4 °C lower than the base model for cast concrete, 150 mm. The impact of a thicker thermal mass has less swing than the impact of a low-thermal mass on operative temperature, which follows the outdoor air temperature pattern. The operative temperature is shifted to a later time due to so-called “thermal lag”, which is due to the storage of heat in walls and increases the time of heat transfer from the outside to the inside. The figure shows that the temperature is high after 16:00, which is almost the end of the lecture in the school. Zahiri and Altan (2016) suggested using thick, heavyweight thermal mass to reduce the indoor air temperature in the warm season. Su et al. (2022) found that adding thermal mass to an envelope can not only increase the winter indoor mean air temperature by more than 18 °C but also reduce the fluctuation of indoor air temperatures and relative humidity in classrooms.

Table 5.5 Thermal mass applied to the base case and their thermal properties

Cast concrete thickness (mm)	U-value [W/(m^2•K)]	
	Base model	Improved model
100	3.2	2.6
200	3.2	2.2
300	3.2	1.9

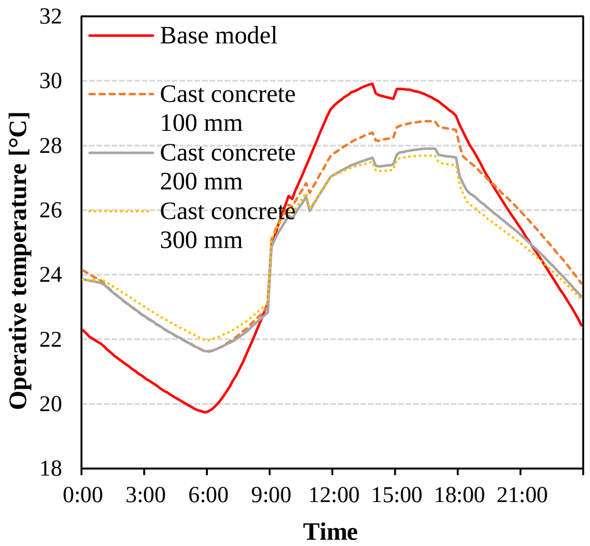


Figure 5.13 Impact on operative temperature due to use of cast concrete as thermal mass.

5.3.8 Integrated optimum model

According to the literature review, we found that some studies employed an overlay of single optimal technology while running the simulation (Zahiri & Altan 2016 & Tong et al. 2021). This study also used that concept, using optimum design technology to investigate the impact of each strategy on thermal conditions (operative temperature) that are feasible, effective, and practical to apply in existing and new school buildings. Increasing the thickness of insulation or thermal mass can be effective to reduce the operative temperatures. However, it reduces the classroom area, and thus optimal selected case might be appropriate for improving models. Therefore, this section is to investigate the impact of combined optimal passive strategies. They are selected from the previously analysed sections based on their maximum impact on reducing the operative temperature. Table 5.6 shows the optimum design cases of each strategy selected for the integrated design. Fig. 5.14 shows the operative temperature of the integrated optimum model. An analysis showed that the maximum operative temperature is decreased by 3.3 K. The operative temperature is maintained at 24.6 °C at 10:00 and 26.7 °C at 16:00, showing that they fall within the 90% acceptability limits according to the ASHRAE adaptive standard (ASHRAE 2017). Even at night, around 00:00–9:00, the operative temperature is lower than approximately 22.5 °C. Kuczynski et al. (2021) also found that the combined effect of thermal mass, ventilation, and blinds resulted in lowering the temperature below the maximum limit by 7.4 K during summer. Zahiri & Altan (2016) found that the combined optimum factors from the passive design strategies of orientation, shading, thermal mass, natural ventilation, and insulation decreased the indoor air temperature by approximately 5 K. Kang et al. (2015) found that the integration of passive and active strategies in a Korean school building reduced the energy consumption to 21.82 kWh/(m^2•year), which is close to the approximate energy-saving rate of 51%.

Table 5.6 Structure of the base model and the integrated model

Passive design strategy	Base model	Integrated model
Natural ventilation	59 ACH	80 ACH
External wall insulation	102 mm Brick, internal cement plaster	200 mm EPS
Ceiling insulation	Plywood 18 mm	200 mm EPS
Pitched roof insulation	Zinc sheet 3 mm	200 mm GW
Thermal mass	102 mm Brick, internal cement plaster	300 mm Cast concrete

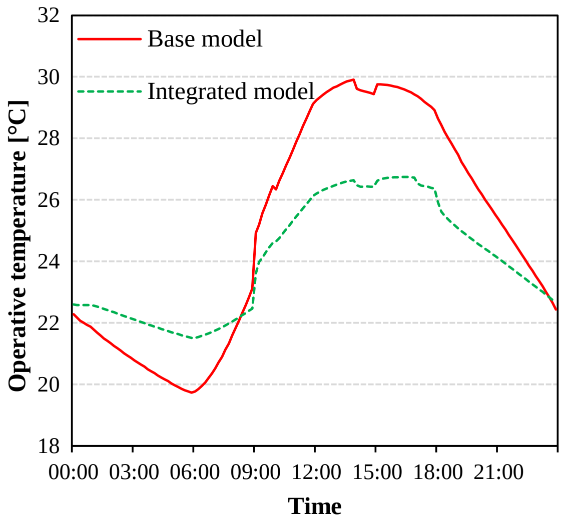


Figure 5.14 Impact on operative temperature due to integrated design strategy.

In the present study, using the simulation, it was found that the passive kind of improvement could be useful for thermal comfort improvement. Based on the discussion with other studies, it looks like a minor improvement. However, the improved idea should be useful in the temperate climate of Nepal, but it is unlikely to be suitable for other climatic areas due to geographic variation. The impact of the integrated model would be different if the optimum cases of each strategy were different. An idea of improvement and its impact may not be sufficient as there are still other strategies left to be investigated. If the optimum cases are increasing, the impact would be different, but that should be practical for what we follow in this study.

5.3.9 Overall discussion

This section discusses the perceived thermal comfort of the students and the improved operative temperature, as discussed in Sections 3 and 4. The indoor globe temperature and air temperature are very close and did not vary significantly where the outdoor air temperature is correlated to the indoor temperature, as shown in Fig. 5a. Within this context, almost 63% of the students evaluated their responses in the central three categories according to ASHRAE 80% acceptability (ASHRAE 2017), and the remaining responses indicate that they are in discomfort and want improvement or some more accessible adaptive behaviour. Using the thermal perception of the students, their respective comfort temperatures are calculated. The average globe and air temperatures are close to the calculated average comfort temperature during school hours. The average comfort temperature in the three investigated schools differs slightly from each other. A similar trend in the results was also found by Rijal (2021) within the same area in the extreme cold climate of Nepal, which was due to the exposed indoor temperature. However, the average comfort temperature of this study is close to the findings of the previous studies under the naturally ventilated condition. Singh et al. (2019) concluded that outdoor climatic conditions have a stronger influence on indoor comfort temperatures, which are higher in summer than in winter.

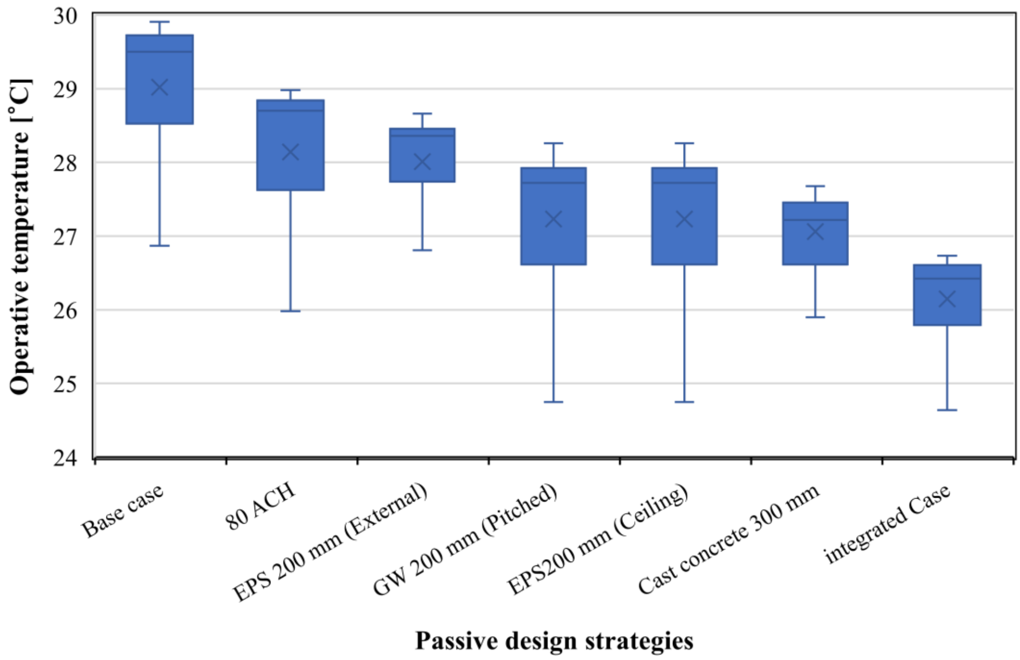


Figure 5.15 Box plots of operative temperature at optimum and integrated passive strategies.

We simulated the indoor operative temperature using various passive design strategies to find the optimum case for each strategy. We employed passive designs that are practical for the school building in reality. If the improvements using individual passive designs are made, the maximum indoor operative temperature is found to be lowered by 1.2 to 2.5 °C for the base model and by 3.5 K using the integrated model. Fig. 5.15 concludes the impact of each strategy, quantifying how each passive strategy impacts the indoor operative temperature. The improvement in temperature is seen for the integrated case compared to the base model and a few other individual design strategies alone. The operative temperature is maintained close to the comfort temperature of 27 °C or below this value, as discussed in Section 3.2. This indicates that the temperature is found to be within the acceptable limit after allowing the integrated design.

Previous simulation studies in school buildings also found a similar trend of reduction in indoor temperature when passive design strategies are employed (Zahiri & Altan 2016, Cuce et al. 2019, Mohamed et al. 2021, & Alwetaishi et al. 2021). Boutet and Hernández (2021) found a reduction in indoor air temperature of up to 6 °C. An experiment in a naturally ventilated Indian school by Garg et al. (2016) found that the use of a cool roof coating reduces the indoor air temperature by 1.5 to 2 °C. Park et al. (2020) found that the retrofitting technology improved the thermal comfort of students by 34%. The zinc-roofed building creates the worst indoor thermal conditions during wintry nights and summery days. In a simulation model of temporary zinc shelters in the temperate climate of Nepal, Thapa et al. (2019) found that by lowering the U-value of walls and roofs and adding insulation such as cellular polyethylene foam and clothes, the indoor air temperature can be kept above 11 °C. Another study by Shahi et al. (2021) in residential buildings in Nepal investigated that the enhancement of thermal insulation and reduction of infiltration increased the indoor air temperature by 1.1–1.8 °C during winter. Therefore, the results and the discussions made above showed that the operative temperature obtained after using the passive design strategy would be acceptable to the students during the school hour, which improves the thermal comfort.
There have been several studies conducted in naturally ventilated (free-running) school buildings in different climates to assess the adaptability of the thermal comfort of students. From the above discussions, it can be confirmed that by using passive design technology, it is possible to create a more livable and easily adaptable indoor temperature without using mechanical equipment that uses electricity or other kinds of energy sources. To compensate for the heating or cooling demand, adaptation to the environment created by passive design strategies would be the best solution. Therefore, the improvement of indoor temperature using passive design is directly related to providing sufficient thermal comfort and rational energy-saving potential (Sadineni et al. 2011 & Chen et al. 2015).

5.4 Conclusions

The major findings are as follows:

1. The indoor globe temperatures are correlated with the outdoor air temperature. The results showed that approximately 63% of the students perceived the hot environment as preferring the cooler environment. Within this context, the average comfort temperature was 26.9 °C.
2. The based model was generated and validated using measured globe temperature and simulated operative temperature. After that, various kinds of passive design strategies were applied to identify the optimum and integrated design conditions to maintain the operative temperature within the acceptable limits. The individual simulation results of each strategy showed that the operative temperature was improved during the school hour if the passive design strategies were applied and the temperature was maintained at approximately 28 °C.
3. The integrated design showed that the maximum operative temperature was decreased by 3.3 K and maintained the operative temperature below 27 °C, which is the required comfort temperature for the students during the hot summer. Therefore, it would be wise to prioritize such strategies to increase thermal comfort in school buildings.

Therefore, selecting an appropriate passive design strategy during the design stage or retrofitting it provides significant opportunities to maintain a comfortable thermal environment and minimise the cost of energy use that is required to maintain a comfortable indoor temperature. The findings of this study and passive cooling strategies can be applied to similar types of school buildings in temperate climates. This study alone does not provide all the necessary and sufficient information on passive design improvements for thermal comfort conditions in naturally ventilated school buildings. Therefore, further studies should be conducted in different seasons and climates to better understand the impact of passive design improvements or the creation of comfortable environments in Nepalese school building designs. However, we believe that the findings of this study will lead to improvements in existing and new school buildings.

Chapter: 6 Conclusions and recommendations

6.1 Introduction

This chapter presents the conclusions obtained so far from the previous chapters. This chapter concludes the results of the investigations done on the major topics of adaptive thermal comfort, natural ventilation, CO_2 concentration as indoor air quality, and passive improvement of the thermal environment. Finally, it presents an overall summary of the research, outlines the answers to the research questions, outlines the limitations of this research, and suggests issues for future work and further investigation. They are presented in sections below.

6.1.1 Conclusions of Chapter 3

The conclusions from Chapter 3 present the results of a thermal comfort study conducted for the first time in Nepalese school buildings. The thermal measurement of environmental quantities and comfort survey were conducted over three weeks in October 2017. Some of the most significant findings are also included from the data analysis of the 2019 survey. Altogether, 72 sets of measured environmental quantities and 2454 thermal sensation responses from 818 students were obtained. The following conclusions are presented:

1. According to the comparison of the indoor globe and operative temperatures with the outdoor air temperature, as well as the indoor and outdoor water vapour concentrations, natural ventilation of the classroom performed relatively well.
2. Approximately three-quarters of the students participating in the survey were comfortable under similar indoor and outdoor thermal environments; this is probably because of natural ventilation. Discomfort was due to the higher temperature caused by the thermally poor characteristics of the building envelopes, such as zinc roofs or walls.
3. The mean comfort temperature estimated from all data was 26.9 °C, which is the same for both autumn and summer. The comfort temperature of the students in private schools was lower than that in public schools and female students had higher comfort temperatures than male students. The students with comfort temperature beyond the temperature limits prescribed by ASHRAE showed a tendency to adapt to their indoor thermal environment.
4. Differences in clothing insulation and comfort temperature in terms of gender and school type were observed. The clothing adaptive behaviour was weak up to 30 °C and more responsive at outdoor air temperatures above 30 °C.

6.1.2 Conclusions of Chapter 4

To our knowledge, investigating the indoor air quality associated with ventilation and indoor CO_2 concentration in naturally ventilated school buildings in the temperate climate of Nepal is the first study. We made the measurement of CO_2 concentrations in classrooms during the summer of 2019 and have developed a method for estimating the time variant number of air change per hour (ACH) and indoor CO_2 concentrations. The following conclusions are presented:

1. The measurement showed that the indoor CO_2 concentrations were much lower than the acceptable limit, and most students accepted the indoor air quality.
2. Time-variant ventilation and CO_2 concentration calculation methods were developed for naturally ventilated classrooms.
3. The estimated indoor CO_2 concentrations matched well with the measured CO_2 concentrations. This confirmed that the estimating method developed is highly accurate and can be used to estimate indoor CO_2 concentration.
4. Using the measured results along with the CO_2 emission rate, the time-variant number of air change was estimated. It was found that the ventilation was performed sufficiently.
5. The indoor CO_2 concentration was estimated at two scenarios: 50% and 25% reductions in ACH to demonstrate the future condition if some renovation is done or if wooden window shutters are replaced by glass sheets. The results showed that the indoor CO_2 concentrations were still lower than the acceptable limit. It is an important point for the improvement because the glass windows which are high priority effect on natural ventilation performance.

6.1.3 Conclusions of Chapter 5

This study investigates, through a field survey and simulations, the impacts of various passive design strategies on comfort conditions in a naturally ventilated school building in the temperate climate of Nepal. The study investigated how the operative temperature, an index for thermal comfort, can be improved using passive design strategies during the summer. This concept can be used as a retrofit in the case study building or similar types of school buildings, and the concept should work for school buildings that are going to be built in the future in study areas or similar types of climates. The major findings are as follows

1. The indoor globe temperatures are correlated with the outdoor air temperature. The results showed that approximately 63% of the students perceived the hot environment as preferring the cooler environment. Within this context, the average comfort temperature was 26.9 °C.
2. The based model was generated and validated using measured globe temperature and simulated operative temperature. After that, various kinds of passive design strategies were applied to identify the optimum and integrated design conditions to maintain the operative temperature

within the acceptable limits. The individual simulation results of each strategy showed that the operative temperature was improved during the school hour if the passive design strategies were applied and the temperature was maintained at approximately 28 °C.

3. The integrated design showed that the maximum operative temperature was decreased by 3.3 K and maintained the operative temperature below 27 °C, which is the required comfort temperature for the students during the hot summer. Therefore, it would be wise to prioritize such strategies to increase thermal comfort in school buildings.

6.2 Clarifications on research questions

Based on the study conducted using various methods in this study, we came up with answers to the research questions raised in Section 1.5. This study is an initial attempt and has investigated and evaluated the real situation of naturally ventilated secondary school buildings both qualitatively and quantitatively. Therefore, this study answers the research questions that are articulated.

1. Under the condition of naturally occurring ventilation, it was seen that the indoor thermal environment is highly impacted by the outdoor thermal environment.
2. The students are adapted in the classrooms using various adaptive behaviours.
3. The indoor air quality associated with ventilation and CO_2 concentration was evaluated by both subjective and objective methods. They were found to be sufficient and acceptable to students.
4. The school buildings are mostly ventilated naturally through windows or doors. The natural ventilation made by them was quantified developing a transient mass balance equation. It was found that the ventilation was high. It should be taken seriously for the winter season for thermal comfort.
5. There are passive and active methods of improving or maintaining the thermal environment and thermal comfort of students. This study chose the passive method and analysed its impact through building simulation. The building simulation showed that the operative temperature, the index for thermal comfort, can be maintained near the value of comfort temperature of 27 °C.

6.3 Overall conclusions

This study investigated the current indoor environmental quality associated with thermal comfort conditions, natural ventilation conditions, and passive types of thermal improvement in naturally ventilated school classrooms in Nepal through field studies, modelling, and a simulation approach. Despite the growing concern about IEQ associated with comfort conditions and air quality in school buildings at the global level, little attention has been paid, and we still don't know the actual IEQ conditions in school buildings in Nepal. The literature reviews have shown the lack of studies in

school buildings in Nepal. No scientific research has been found in this field to date, and to our knowledge, this is the first research in this field in Nepal. This is the research gap, and we are encouraged to investigate it.
For these reasons, field studies were done in the naturally ventilated school buildings, which use no mechanical equipment to maintain the indoor thermal environment located in the temperate climate of Nepal. Indoor and outdoor environmental quantities were measured in each classroom at each school building, as well as a questionnaire survey to which students responded, evaluating their immediate classroom thermal environment. The statistical analysis was made based on the collected data to extend the understanding of the thermal comfort of students, natural ventilation, and thermal environment of school buildings. Modelling of CO_2 concentration was done to estimate the time-variant natural ventilation and CO_2 concentration. The impact of passive design strategies on a case study school building was studied through building simulation.
In terms of thermal comfort, this study showed that most of the students adapted to and felt comfortable under the condition of an indoor natural thermal environment in school buildings. The comfort temperature for male and female students is different in public and private schools owing to clothing insulation. This study found that the comfort temperature for autumn and summer is nearly the same, indicating that students can adapt to a wider range of indoor temperatures. The clothing adaptive behaviour was seen to be more responsive when the outdoor air temperatures rise.

The developed model of transient mass balance of CO_2 concentration and the findings of this study should be useful for the evaluation of school buildings if they are to be improved or renovated in the future. In terms of indoor air quality, they are so far much better than that in some of the developed countries. This is good for all of us to rethink the role of natural ventilation for rational indoor air quality from the view point of global environmental issues in association with energy use. Further, in order to make the classrooms safe from the infections of airborne diseases, natural ventilation could be an on-site sustainable mitigation strategy.
Selecting an appropriate passive design strategy during the design stage of a building or retrofit provides significant opportunities to maintain a comfortable thermal environment and, of course, minimise the cost of energy use that is required to maintain a comfortable indoor temperature. The findings of this kind of study and passive cooling strategies might apply to similar types of school buildings in temperate climate. This study alone does not cover all the necessary information on passive design improvements for thermal comfort in school buildings. Therefore, further field and simulation studies should be conducted in other seasons and climates to better understand the impact of passive design improvements or the creation of comfortable environments in Nepalese school building design. But we believe that the findings of this study will lead us to improve existing and new school buildings.

6.4 Limitations

Nepal has very diverse type of climate and this study alone cannot reflect the real situation of thermal comfort and thermal environment of other places which is left as a future work for the upcoming researchers. The thermal comfort studies were not done during the winter and have not covered sufficient whole year data for analysis. This study did not cover the thermal comfort level of the university student or higher levels.

Ventilation and CO_2 concentration are not the only parameters that affect indoor air quality. There are various other factors that are left for future studies. The modelling done for CO_2 concentration is only applicable to naturally ventilated buildings like the school buildings investigated in this study. This study presented the impact of passive design strategies on a case study school building done with limited strategies through simulation. There is a need for further simulation studies to confirm the present findings with caution. In Nepal, there are various types of schools with different designs because there are no strict design guidelines and standards. Therefore, further studies are needed to identify the optimum and the integrated case to be applied in the real design. It is recommended to do further research on other types of modern and multi-story school buildings because this study has been conducted for a specific type of school building. We did not investigate ways to improve the opening, like windows. The investigated school buildings were used during the day and were naturally ventilated through windows. Generally, the student density was high. Consequently, if we close or reduce the opening area, that will increase the indoor CO_2 concentration. Therefore, we improved the parameters, such as insulation, thermal mass, and so on, this time. A significant question of what thermal comfort in winter is and how to improve thermal comfort in winter is still unknown and unanswered in this thesis. Therefore, winter field investigations will be needed in the future to fill this gap. The methods employed can, however, be applied to other buildings and climates with similar characteristics. In general, the analysed strategies and their impacts on the indoor thermal environment are understood, but other measures of strategies such as window-to-wall ratio (WWR), shading, glazing, etc. are still left for future research because they are unknown and therefore require study to determine their impacts. The thermal comfort conditions were explained with the help of operative temperature, which could be different if we used air temperature or radiant temperature alone.

6.5 Recommendations for future research

This study alone does not cover all the necessary information on IEQ associated with thermal comfort, indoor air quality, and thermal environment in school buildings. This research has answered on several topics in the field of thermal comfort, indoor air quality, and passive types of thermal improvement in naturally ventilated secondary school buildings in Nepal. Additionally, this research has filled gaps in the IEQ field and has contributed to the development of new questions for future research. Therefore,

1. Further field studies should be conducted in other seasons and regions to better understand the thermal comfort in Nepalese school buildings. In peak summer and winter, the students must wear lighter or heavier clothes according to school rules; this influences the thermal perception and adaptation in the classroom to a great extent. In peak seasons, better understanding can be gleaned if temperature and humidity are continuously monitored and the variation in student activity is recorded.
2. The CO_2 concentration and natural ventilation of classrooms were used as proxy indicators of indoor air quality. It is necessary to conduct further research on indoor air pollutants and their effects on students' health, performance, and productivity.
3. It is recommended for further investigation on passive design through simulation, utilizing locally available and environmentally friendly building materials to construct the building during the construction phase, which creates a comfortable indoor thermal environment and saves the energy that is to be used for cooling or heating the building.

Currently available policies or rules for the school building's design and for a comfortable thermal environment for students are not based on research-based standards, and there is a need to develop new standards for Nepalese school buildings. A continuation of research would hopefully draw attention to this field in Nepalese school buildings, providing students with better thermal environments and comfort, thereby positively affecting academic performance.

This study is focusing on a temperate climate; it’s a mild climate. Nepal has various geographies and different climates. The results of this study are hopefully applicable to school buildings made from similar building materials in a similar type of temperate climate and topography. Further studies are needed in other areas and climates.

The quantitative or qualitative findings of this study, such as comfort temperature, ventilation, or improvement ideas, are valuable for school building designers and policymakers, who have to consider these things before construction or design in terms of thermal comfort, IEQ, and thermal environment. Chapter 3 focused on aspects of thermal comfort such as perception and comfort temperature, from which it was found that the suitable temperature for students is around the 27 °C or 24–30 °C range during summer. To maintain such a range of comfort temperatures without mechanical controls, higher levels of natural ventilation than 25 h^{-1} are needed, as described in Chapter 3. Chapter 5 has used the findings of Chapters 3 and 4 for improvement. Chapter 5 strongly recommends that Nepal follow the passive design path to improve the thermal environment of classrooms or school buildings.

Appendix I Methods of finding unknown CO_2 concentration between two intervals of times

$C_r(t) = C_r(1)$

$C_r(t + \Delta t') = C_r(1) + \Delta C_r{}'$

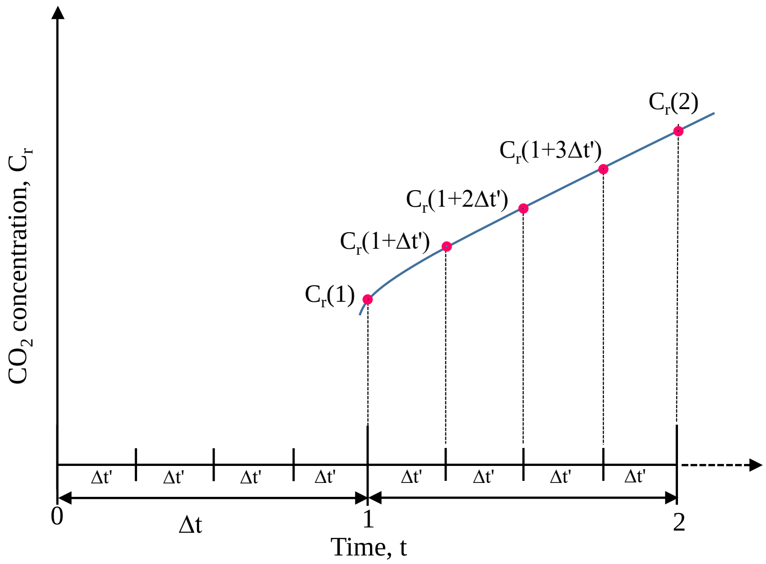
$C_r(t + 2\Delta t') = C_r(1) + 2\Delta C_r{}'$

....

$C_r(t + n\Delta t') = C_r(1) + n\Delta C_r{}'$

$\Delta C' = \frac{C_r(t+n\Delta t') - C_r(1)}{n}$

where $C_r(t+n\Delta t')$: Indoor CO_2 concentration at time $t+n\Delta t'$, $C_r(1)$: Initial indoor CO_2 concentration, n: Number of time intervals



Appendix II Mass balance equation

[Input of mass] = [Mass stored] + [Output of mass]

$n_p G\Delta\mathrm{t} + C_o V_o \Delta\mathrm{t} = V_r \Delta C_r + C_r V_o \Delta t$

$n_p(n)G(n)\Delta t + C_o(n)V_o(n)\Delta t = V_r\{C_r(n) - C_r(n-1)\} + C_r(n)V_o(n)\Delta t$

$$C_r(n) = \frac{V_o(n)\Delta t}{V_r + V_o(n)\Delta t} C_o(n) + \frac{n_p(n)G(n)\Delta t}{V_r + V_o(n)\Delta t} + \frac{V_r C_r(n-1)}{V_r + V_o(n)\Delta t}$$

$If\ N(n) = \frac{V_o(n)\times 3600}{V_r}$, then

$$C_r(n) = \frac{N(n)(\frac{V_r}{3600})\Delta t}{V_r + N(n)(\frac{V_r}{3600})\Delta t} C_o(n) + \frac{n_p(n)G(n)\Delta t}{V_r + N(n)(\frac{V_r}{3600})\Delta t} + \frac{V_r C_r(n-1)}{V_r + N(n)(\frac{V_r}{3600})\Delta t}$$

$$C_r(n) = \frac{N(n)(\frac{\Delta t}{3600})}{1 + N(n)(\frac{\Delta t}{3600})} C_o(n) + \frac{n_p(n)G(n)\Delta t}{V_r(1 + N(n)\left(\frac{\Delta t}{3600}\right))} + \frac{1}{1 + N(n)(\frac{\Delta t}{3600})} C_r(n-1)$$ [Implicit equation]

Appendix III Questionnaire survey

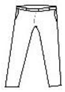
SUMMERTIME THERMAL COMFORT QUESTIONNAIRE SURVEY 2019

東京都市大学 TOKYO CITY UNIVERSITY

Personal information

Name:		Gender: □Male□Female	Height:
Class:	Age:		Weight:

Clothing (Tick your dress) आफ्नो मिल्ने पोशाकमा चिनो लगाउनुहोस्

□ Shirt full 	 □ Shirt half	□ T- shirt half 	 □ T- shirt full	 □Coat	 □ Sweater full	□ Sweater half 	 □Vest
 □ Pant full	□ Pant half 	□ Skirt 	 □ Trouser	□ Slipper 	 □ Shoes full	□Shoes half 	□Socks  full
							□Socks  half

Others….

Fill the appropriate number in the box. बक्समा तपाईलाई उपयुक्त लागेको नम्बर भर्नुहोस्

Q1. How do you feel about the classroom thermal environment? तपाई अहिले कक्षाको तापिय वातावरणको बारेमा कस्तो अनुभव गर्नुहुन्छ?

1.Very cold जाडो	**2**.Cold चिसो	**3**.Slightly cold अलिकति चिसो	**4**.Neutral ठिक्क (चीसो तातो दुबै छैन)	**5**.Slightly hot अलिकति तातो	**6**.Hot तातो	**7**.Very hot गर्मी

☐ Morning ☐ Midday ☐ Afternoon

Q2. How do you prefer the classroom air temperature at this time? अहिले, कक्षाको वायुको तापक्रम कस्तो चाहनुहुन्छ?

1.Much warmer धेरै न्यानो चाहन्छु	**2**.A bit warmer अलिकति न्यानो चाहन्छु	**3**.No change एतिकै ठिक्क छ	**4**.A bit cooler अलिकति शितल चाहन्छु	**5**.Much cooler धेरै शितल चाहन्छु

☐ Morning ☐ Midday ☐ Afternoon

Q3. Do you feel overheating? अहिले , धेरै गर्मीको अनुभव गर्नु भएको छ?

1.Feeling अनुभव गरिरहेको छु	**2**.Not feeing अनुभव गरिरहेको छैन

☐ Morning ☐ Midday ☐ Afternoon

Q4. Does this thermal condition acceptable for you? अहिले,के यो कक्षाको तापिय वातावरण तपाईंको लागि स्वीकार्य छ?

1.Acceptable स्वीकार्य छ	**2**.Unacceptable स्वीकार्य छैन

☐ Morning ☐ Midday ☐ Afternoon

Q5. How do you feel the humidity (dampness) of air? तपाईंलाई अहिले कक्षाको हावाको आद्र्रता (ओसिलोपन) कस्तो लाग्छ?

1.Very dry धेरै सुक्खा	**2**.Dry सुक्खा	**3**.Slightly dry अलिकति सुक्खा	**4**.Neither dry nor humid न त सुक्खा न त आर्द्र	**5**.Slightly humid अलिकति आर्द्र/ओसिलो	**6**.Humid आर्द्र/ओसिलो	**7**.Very humid धेरै आर्द्र/ओसिलो

☐ Morning ☐ Midday ☐ Afternoon

Q6. Is your skin moisture/sweating now? के तपाईंलाई अहिले पसीना आऐको छ?

1. None छैन	**2**.Slightly अलिकति आऐको छ	**3**.Moderately सामान्य आऐको छ	**4**.Profuse अत्यधिक आऐको छ

☐ Morning ☐ Midday ☐ Afternoon

Q7. How do you prefer the humidity of the air right now? तपाईं अहिले हावाको आद्र्रता (ओसिलोपन) कस्तो चाहनुहुन्छ?

1.Much drier धेरै सुक्खा चाहन्छु	**2**.A bit drier अलिकति सुक्खा चाहन्छु	**3**.None एतिकै ठिक्क छ	**4**.A bit more humid अलिकति आर्द्र चाहन्छु	**5**.Much more humid धेरै आर्द्र चाहन्छु

☐ Morning ☐ Midday ☐ Afternoon

Q8. How do you feel about the air movement at this time? अहिले कक्षाको हावाको गतिको बारेमा कस्तो अनुभव गर्नुहुन्छ?

1.Very high अति धैरै गति छ	**2**.High धैरै गति छ	**3**.Slightly high अलिकति उच्च गति छ	**4**.Neither high nor low ठिक्क छ	**5**.Slightly low अलिकति कम गति छ	**6**.low कम गति छ	**7**.Very low धैरै कम गति छ

☐ Morning ☐ Midday ☐ Afternoon

Q9. How do you prefer the air movement right now? अहिले, कक्षामा हावाको गति कस्तो चाहना गर्नुहुन्छ?

1. Much more धैरै चाहन्छु	**2**.A bit more अलिकति धैरै चाहन्छु	**3**.No change एतिकै ठिक्क छ	**4**.A bit less अलिकति कम चाहन्छु	**5**.Much less धैरै कम चाहन्छु

☐ Morning ☐ Midday ☐ Afternoon

Q10. Rate your present learning productivity affected by the quality of the classroom thermal environment.

कक्षाकोठाको तापिय वातावरणको गुणस्तर तपाइँको पढाइको लागि कत्तिको उत्पादनमूलक छ ?

1.Much higher than normal सामान्य भन्दा धेरै बढी	**2**.Slightly higher than normal सामान्य भन्दा अलिकति बढी	**3**.Normal सामान्य	**4**.Slightly lower than normal सामान्य भन्दा अलिकति कम	**5**.Much lower than normal सामान्य भन्दा धेरै कम

☐ Morning ☐ Midday ☐ Afternoon

Q11. At this time, how would you rate the overall comfort in classroom (considering all the above factors?)

माथि उल्लेख गरिएको सबै कारकहरू (तापक्रम, आद्र्रता, हावाको गति) सोच्दा तपाईको आनन्दपन कस्तो छ ?

1.Very comfortable धेरै आनन्द	**2**.Moderately comfortable आनन्द	**3**.Slightly comfortable अलिकति आनन्द	**4**.Slightly uncomfortable अलिकति असहज	**5**.Moderately uncomfortable असहज	**6**.Very uncomfortable धेरै असहज

☐ Morning ☐ Midday ☐ Afternoon

Q12. How do you feel about the lighting level in your classroom at this time? यस समयमा तपाईको कक्षामा प्रकाशको स्तर कस्तो अनुभव गर्नुहुन्छ?

1.Very bright धेरै उज्यालो छ	**2**.Bright उज्यालो छ	**3**.Slightly bright हल्का उज्यालो छ	**4**.None ठिक्क छ	**5**.Slightly dim अलिकति अँध्यारो छ	**6**.Dim अँध्यारो छ	**7**.Very dim धेरै अँध्यारो छ

☐ Morning ☐ Midday ☐ Afternoon

Q13. How do you prefer the lighting level of the classroom right now? तपाईं अहिले कक्षामा प्रकाशको स्तर कस्तो चाहनुहुन्छ?

1.Much dimmer धेरै अँध्यारो चाहन्छु	**2**.A bit dimmer अलिकति अँध्यारो चाहन्छु	**3**.No change एतिकै ठिक्क छ	**4**.A bit brighter अलिकति उज्यालो चाहन्छु	**5**.Much brighter धेरै उज्यालो चाहन्छु

☐ Morning ☐ Midday ☐ Afternoon

Q14. How do you perceive the air quality right now? अहिले, कक्षाको हावाको गुणस्तर कस्तो छ?

1. Clearly acceptable धेरै स्वीकार्य छ	**2.** just acceptable स्वीकार्य छ	**3.** Just unacceptable अस्वीकार्य	**4.** Clearly unacceptable धेरै अस्वीकार्य

☐ Morning ☐ Midday ☐ Afternoon

Q15. Which of the following control do you use to adjust in the classroom?

निम्न मध्ये तपाइँ कक्षाकोठाको तापिय वातावरणमा समायोजन हुन कुन नियन्त्रण प्रयोग गर्नुहुन्छ? [एक भन्दा बढी चयन गर्नुहोस्]

1. Open windows
2. Close windows
3. Air-conditioning on
4. Air-conditioning off
5. Ceiling fan
6. Portable fan
7. Position change
8. Blinds/curtains open
9. Blinds/curtains closed
10. Take out clothes
11. Drinking water
12. None of these

Other specify

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	Morning		Midday		Afternoon

Thank you for taking part in the thermal comfort survey.

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