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Assessment and improvement of thermal comfort conditions in educational buildings: an example of a secondary school

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PMV/PPD

Abstract: This study, conducted at a secondary school in the cold winter-hot summer climate type of Bingöl, Turkey, measured temperature, air velocity, and relative humidity, while collecting satisfaction surveys. The findings indicate that while winter indoor temperatures generally remain within comfort ranges, some classrooms have indoor radiation temperatures below 17℃. In summer, indoor temperatures often exceed the 26 ℃ comfort threshold, reaching 30-35℃ in August. Air velocity assessments reveal that speeds above 0.4 m/s in summer provide relief from high temperatures, while speeds below 0.2 m/s in winter are adequate. Children show greater sensitivity to high temperatures than adults, adapting by adjusting windows or clothing. The PMV/PPD model inaccurately predicts students' thermal sensations, showing higher dissatisfaction rates in summer (40.4%) compared to winter (6.8%). The study emphasizes the importance of both natural and mechanical ventilation, advocating for natural ventilation due to its energy efficiency and health benefits. The findings suggest that optimizing thermal conditions through sustainable design practices can significantly enhance health, comfort, and learning outcomes in educational settings.

Eğitim Binalarında Termal Konfor Koşullarının Değerlendirilmesi ve İyileştirilmesi: Bir Ortaokul Örneği

Anahtar Kelimeler
İç mekân konforu,
Isıl konfor,
Okul yapıları,
Öğrenci memnuniyeti,
Saha çalışması,
PMV/PPD

Öz: Bu çalışma, Bingöl, Türkiye'deki soğuk kış-sıcak yaz iklim tipinde bulunan bir ortaokulda gerçekleştirilmiştir. Çalışmada sıcaklık, hava hızı ve bağıl nem ölçümleri yapılırken, memnuniyet anketleri de toplanmıştır. Bulgular, kış aylarında iç mekân sıcaklıklarının genellikle konfor aralıklarında kaldığını, ancak bazı sınıflarda iç mekân radyasyon sıcaklıklarının 17℃'nin altında olduğunu göstermektedir. Yaz aylarında ise iç mekân sıcaklıkları genellikle 26℃ konfor eşiğini aşarak, ağustos ayında 30-35℃'ye ulaşmaktadır. Hava hızı değerlendirmeleri, yaz aylarında 0.4 m/s'nin üzerindeki hızların yüksek sıcaklıklardan rahatlama sağladığını, kış aylarında ise 0.2 m/s'nin altındaki hızların yeterli olduğunu ortaya koymaktadır. Çocuklar, yüksek sıcaklıklara karşı yetişkinlere göre daha duyarlıdır ve pencere açma veya giyimlerini ayarlama yoluyla uyum sağlamaktadırlar. PMV/PPD modeli, öğrencilerin termal hislerini doğru bir şekilde tahmin edememekte ve yaz aylarında (%40.4) kış aylarına göre (%6.8) daha yüksek memnuniyetsizlik oranları göstermektedir. Çalışma, doğal ve mekanik havalandırmanın önemini vurgulamakta ve enerji verimliliği ve sağlık yararları nedeniyle doğal havalandırmayı desteklemektedir. Bulgular, sürdürülebilir tasarım uygulamalarıyla termal koşulların optimize edilmesinin eğitim ortamlarında sağlık, konfor ve öğrenme sonuçlarını önemli ölçüde iyileştirebileceğini göstermektedir.

1. INTRODUCTION

The educational environment plays a significant role in influencing students' academic success. Students' awareness of this environment is crucial for learning efficiency and the comfort conditions of the learning area [1-5]. During the school period, students typically spend approximately one-third of their days inside school buildings [6,7]. The comfort conditions of the environment have a direct impact on users' physiological and psychological well-being, which in turn affects their performance of activities [8,9]. Unfavourable comfort conditions in schools, including high temperatures, excessive noise, inadequate lighting, student density, and inadequate equipment for age groups, can negatively affect students' academic performance and cause health problems. Additionally, poor thermal comfort conditions in classrooms can lead to increased energy consumption [10]. The first scientific studies on the effects of thermal comfort conditions in classrooms on students' performance began in the mid-1950s. In recent years, there has been a resurgence of interest in thermal comfort theory, leading to renewed efforts to characterise the thermal environment in a way that is both objective (through measurement) and subjective (through the opinions of users).

In order to achieve optimal comfort conditions, it is essential to consider the individual user's behaviour and spontaneous adaptation to the surrounding environment [11,12]. Further investigation into the relationship between performance and environmental conditions could lead to improvements in comfort levels [13]. A number of studies have demonstrated that the comfort conditions experienced in different types of buildings and climates can vary considerably [14-17]. Consequently, research conducted in different climatic regions is of great importance in terms of comparison and evaluation. Recent studies have revealed that children's metabolic rates, clothing and behaviour differ from adults, and this also creates differences in their feelings of thermal comfort [18-20]. Data on children's thermal comfort are not determined in the standards. Consequently, Yun et al. and Teli et al. have conducted several studies, including those by Teli et al. [19] and Yun et al. [21], which have employed adult PMV models to compare the thermal comfort of children with that of adults. Ter Mors [22] found that the PMV–PPD method underestimated children's thermal sensation by up to 1.5 points in three free-running primary schools in the Netherlands, highlighting children's greater sensitivity to high temperatures and distinct thermal comfort characteristics compared to adults [22]. Furthermore, a study conducted in classrooms in different climates demonstrated that children feel more comfortable at lower temperatures than adults. Yang et al. [23] observed that studies focusing on primary schools where children are located are limited in the literature.

Although recent studies have investigated the thermal comfort and sensations experienced by schoolchildren in cold climate regions [14], it is evident that further research is required in order to achieve more accurate findings. In this study, indoor temperature, relative humidity, air velocity, predicted percentage of dissatisfied (PPD), and the sensation scale for the predicted mean vote (PMV) were examined using both subjective and objective measurements. The study commenced with a comprehensive literature review, during which the scope of the study was delineated. Subsequently, measurements were conducted at the selected school, which is a public institution that caters to students from low- and middle-income backgrounds. The study observed the adaptation of students in the 11-14 age group to indoor thermal environments in naturally ventilated classrooms. The primary objective of the field study is to examine students' feelings and preferences during cooling and heating periods in classrooms within a school building, with the specific aim of determining existing thermal comfort levels to create an environment conducive to studying and intellectual development. The specific aims are to:

- Determine the existing thermal comfort levels for each of the places studied in order to provide a suitable environment for studying and the development of intellectual activities.
- Investigate differences in students' subjective votes regarding the preferred temperature for their best academic performance, taking into account their local context and climatic situation.

The study structure is presented in Figure 1.

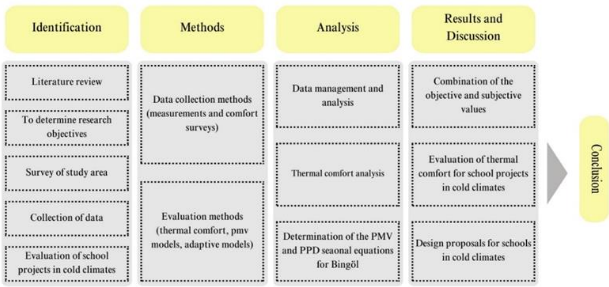


Figure 1. The structure of the study

1.1. Previous Studies

It can be observed that personal factors exert a significant influence on indoor comfort, to a degree that is comparable to that of environmental factors [24]. While environmental factors are defined as indoor air temperature, relative humidity, air velocity and average radiation temperature, personal factors are divided into the individual's clothing thermal resistance and activity level. The Predicted Mean Vote (PMV) thermal sensation index, developed by Fanger [25], is used to express whether an environment is perceived as thermally comfortable by a large group of people. The Predicted Percentage of Dissatisfaction (PPD) index is a metric developed based on the PMV index and used to estimate the percentage of users who are dissatisfied with thermal comfort conditions [26]. The PMV-PPD and adaptive models have been widely used by researchers [27].

The estimation of the PMV and PPD degree in the environment to which standard people are exposed is investigated on a scale in line with the model created by Fanger and enables the determination of acceptable thermal environmental conditions. In an environment with a high number of people; With the help of this scale, environmental conditions are estimated with the response levels of users in the range of ±3 (warm/warm/slightly warm/neutral/slightly cool/cool/cold). The scope of standards can be divided into three categories: indoor environment in general (ISO 17772, EN 15251, EN 16798), thermal environment (ISO EN 7730, ASHRAE 55, GB/T 50785, SS 553), and indoor air quality (ASHRAE 62.1, ASHRAE 62.2, AS 1668- 2, SS 554) [28]. On the other hand, in Europe, ISO 7730 and in North America, ASHRAE Standard 55 are widely accepted for thermal comfort standards [28,29]. Since our study is on indoor thermal environment ISO (International Organization for Standardization) EN (European Norm) 7730, ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) 55 standards are necessary and sufficient to evaluate the results. The ISO EN 7730 thermal comfort standard, based on the PMV model developed by Fanger in 1970, is widely used to evaluate moderate thermal environments in HVAC systems. While its validity in unconditioned environments has been criticized, Fanger suggested the use of PMV in naturally ventilated spaces could be effective with an expectation factor [30]. The PMV model is frequently applied in school thermal comfort assessments.

Kwok and Chun [31] examined thermal comfort in naturally ventilated and air-conditioned classrooms in Japan. Havenith [18] measured the metabolic rates and clothing insulation of school children, highlighting age and activity-specific climate control needs. Studies by Zhang et al. [32] and Hwang et al. [33] assessed the applicability of ASHRAE specifications in tropical and subtropical schools. Hussein and Rahman [34] found higher heat tolerance among Malaysian school participants due to the regional climate. Sanders [35] developed indoor air quality standards for primary schools in Texas, finding that location, orientation, material selection, and ventilation system design significantly impact indoor air quality. Poor ventilation was linked to reduced learning performance, health risks, and economic costs.

Yıldırım [36] emphasized the importance of heat and sound control in educational buildings for student health and learning performance, highlighting the role of insulation. The study proposed solutions for heat and sound comfort issues in Turkish schools, noting that thermal comfort improves teacher and student performance. Proper heating in insulated environments can enhance energy efficiency and reduce pollution, with insulation materials impacting indoor air quality. Kocahakimoğlu [37] found daily variations in indoor environmental quality in primary schools, with higher pollutant levels on weekends and indoor ozone levels linked to outdoor conditions [26]. Teli et al. [29] and Humphreys [38] revealed that children's thermal perceptions differ from those of adults, with children being less sensitive to temperature changes. Studies by Hwang et al. [33], Kwok and Chun [31], and Zhang et al. [32] assessed the applicability of ASHRAE specifications in tropical schools. Heracleous and Michael [39] found high thermal tolerance among students in Cyprus during both winter and summer. Rodríguez et al. [15] emphasized behavioural, contextual, and age-related influences on thermal comfort in Bogota schools.

2. MATERIAL AND METHOD

2.1. Location and description of the building and the classrooms

The city of Bingöl is located in the Upper Euphrates Section of the Eastern Anatolia Region in Turkey, at 41º 20' and 39º 56' east longitudes and 39º 31' and 36º 28' north latitudes (Figure 2a). According to the Trewartha climate classification, Bingöl province has a climate type that is cold in winters and hot in summers. According to the universal temperature scale, the average temperature in January is -2.6 °C, while the average temperature in July is 26.7 °C. The research was conducted in a school that provides education to students aged 11-14. The school was built in 2003 and is located among residential settlements (Figure 2b-c). The school has an indoor space of 7400 square meters. Figures 3a-b show the floor plan and entrance facade of the school.

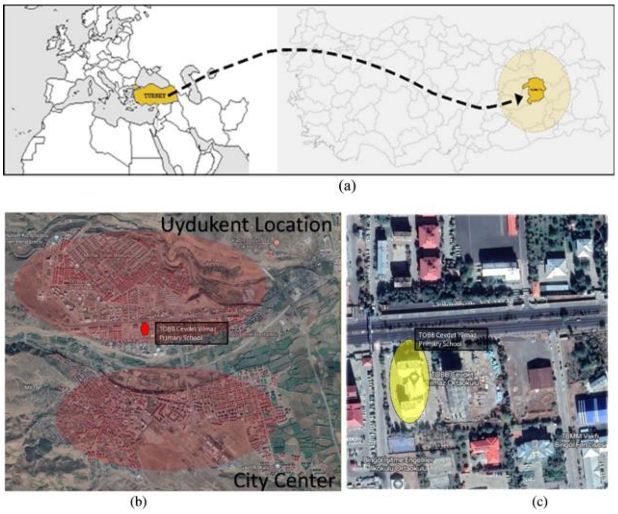


Figure 1.a. The location of Bingöl province on the map of Turkey [40], b,c. The location of the examined school in the city (taken from google earth and edited by the authors)

The school building consists of a U-shaped layout with a basement, ground floor, and three upper floors. Classrooms are primarily located in the north-south oriented side branches, while social activities and common areas are situated in the main middle arm and east-west direction (Figure 3a,3b).


a b

Figure 3.a. The floor plan of the school, b. The view of the entrance facade

The school has a total of 32 classrooms, averaging 53 m² in size with an average of 1.39 m² per student. Window areas in the classrooms where the study was conducted are presented in Table 2. The walls were insulated using the sheathing technique, and the roof design featured a hipped roof system with wide eaves for rain and sun protection. Measurements and evaluations were conducted for the eight classrooms located on the top floor (Figure 4).

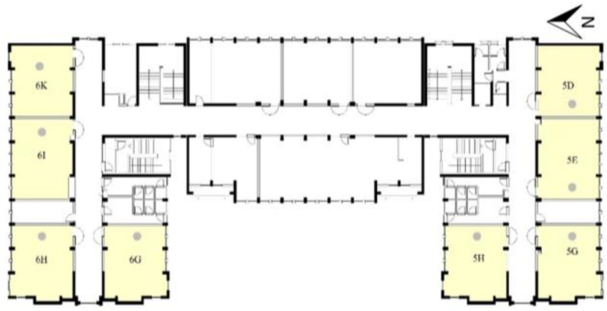


Figure 4. Locations of the classes on the plan

Figure 4 illustrates the distribution of classes within the architectural plan. Four classes (5D, 5E, 5G, 6G) face south, while the remaining four classes (6K, 6I, 6H, 5H) face north. The spatial characteristics of the school and the classrooms where measurements were taken are described in Table 1.

Table 1. Characteristics of the selected classrooms

Class	5G	5H	5E	5D	6G	6H	6K	6I
Width(m)	6.80	6.80	6.80	6.80	6.80	6.80	6.80	6.80
Length (m)	7.60	7.55	7.80	7.60	7.80	7.88	8.60	7.60
Height (m)	3.90	3.90	3.90	3.90	3.90	3.90	3.90	3.90
Volume (m^3)	208.22	207.64	224.48	200.66	209.43	208.85	219.77	200.46
Floor area (m^2)	53.39	53.24	57.56	51.45	53.70	53.55	56.35	51.34
Total door area (m^2)	2.90	2.90	2.90	2.90	2.90	2.90	2.90	2.90
Total windows area (m^2)	11.55	11.55	9.90	8.25	11.55	11.55	9.90	8.25
The ratio of window area to the floor area	0.21	0.21	0.17	0.16	0.21	0.21	0.17	0.16
Number of students in the class	45	40	40	35	42	40	45	40
Wall material	Water-based paint + gypsum plaster + brick wall + eps insulation (8 cm.)							
Floor material	Artificial glossy granite + reinforced concrete							
Ceiling material	Water-based paint + reinforced concrete + eps insulation (10cm) + wooden roof cover							
Lighting type	Fluorescent lamp							
Heating type	Natural gas							

During the preparation phase, several visits were made to the school to obtain building plans, gather operational information, and take photographs of each area. Prior to the commencement of the experiments, teachers were provided with a thermal comfort information form, which outlined the parameters of the study and informed them of the importance of thermal comfort. Students were also given a brief overview of the measurements that would be conducted by the teachers and researchers. Technical equipment was installed in the middle of the classroom for the duration of the study (Figure 5c and Table 1).

2.1. Thermal comfort surveys and Data analysis method

Based on the adaptive approach, which suggests people influence their thermal environment consciously or unconsciously [41], we measured conditions in eight north-south oriented top-floor classrooms, expecting them to experience the greatest heat loss. The first stage of the study involved the evaluation of thermal comfort parameters through measurements. Thermal comfort is defined as "a state of mind that expresses satisfaction with the thermal environment and is evaluated through subjective evaluation" [42]. This was analysed through field measurement studies. The measured and investigated thermal comfort objective parameters are as follows [43,38,44,45]:

- Indoor air temperature : Ti (°C)
- Indoor radiation temperature : TR (°C)
- Relative humidity : RH (%)
- Indoor air velocity : Va (m/s)

The temperature on the surface of the walls surrounding the environment may be higher or lower than that inside the space. For example, while the wall temperatures are below the indoor temperature in winter, they are above the indoor temperature in summer. Heat transfer by radiation occurs between these walls and the human body, causing discomfort to users. Therefore, it is necessary to consider the temperatures taken from the walls surrounding the interior space and to evaluate the radiation temperatures of the space. The radiation temperatures of the space can be calculated using different methods. If the instantaneous indoor temperatures (Ti) are known, the Indoor radiation temperature (TR) value can be calculated with equation 1, depending on the indoor temperature (Ti) [46,47].

$$TR = 0.99 \times T_i - 0.01, \qquad R^2 = 0.99 \tag{1}$$

In this study, indoor comfort conditions were examined during the summer and winter periods at an educational institution in Turkey, where the academic year is divided into two semesters - Fall and Spring. Fall semester starts in September and ends in February, while spring starts in February and ends in June, and summer courses are held during the summer months when there is no regular education. The winter period (cold months) is when education is in session and students are present at school. The measurements used in this study included data from October to March for the winter period and data from June, August, and September for the summer period. Measurements were taken three times a month, once a week during the summer and winter periods in 2021-2023, as well as in August during summer school, at secondary school in Bingöl. During measurement, the probes were positioned 1.1 meters above the ground to replicate the seated position of students and were placed at least 1.5 meters away from external walls and doors. Instruments were shielded from direct sunlight, cleaned, and regularly calibrated [14]. The devices used in the study are listed in Table 2 and images taken during the measurements of the schools and classrooms where the measurements were made are shown in Figure 5 (a, b, c). These testing devices were pre-calibrated before starting the tests, and the measurement time took an average of 45-60 minutes in each classroom. The measurement arrangement was positioned equidistantly according to the sitting position of the students. Throughout the study, classroom windows were closed in winter and opened in summer to facilitate natural ventilation, with consideration given to the students' seating positions.

Table 2. Characteristics of the selected classrooms

Parameters	Instrument	Range	Accuracy
Outdoor Temp.	Testo 480 CMI	0 to 60 °C	±0.5
Comfort Temp.	Testo 480 CMI	0 to 60 °C	±0.5
Relative Humidity (RH)	Testo 480 CMI	0 to 100%	± (1.0% RH + 0.7% Reading)
Air flow rate	Hot Wire Anemometer DT8880	0.1 to 25.0 m/s	± %5 ± 0.1m/s
Globe Temperature	Cool-Us CU-IT InfraRed Thermometer	0 to 50 °C	± 0.4 °C

a b c

Figure 5. a,b. Images from classes during measurement, c. Measurement set views

Thermal comfort ranges, given in ASHRAE Standard 55 and ISO 7730 international standards [48,49,42], were considered for evaluation using tables and graphics. The recorded data were analysed in detail to evaluate Fanger's indices, PMV and PPD, for thermal comfort according to International ASHRAE Standard 55 and ISO 7730 standard [50,25].

In the study, a survey was administered to the students during the measurements in the classes where measurements were made. The scope of this study encompassed a total of 264 individuals aged 11-14, surveyed in eight classrooms. In alignment with the methodology employed in this study, Teli et al. [29] surveyed an average of 230 pupils aged 7-11 in all eight classrooms of the school during the heating season. Additionally, the suitability of the school where the research was conducted for the study was also taken into consideration. However, it was selected as it had the highest number of students among the schools that were rebuilt following the 2003 Bingöl earthquake. In line with the research objectives, a study was conducted with secondary school students. In determining the schools to be studied, conditions such as suitability, ease of accessibility, voluntariness in participation, and obtaining a sufficient number of participants were taken into consideration in terms of researchers, school administrators and teachers. A total of 124 male (42%) and 170 female (58%) students participated in the study. Although there is a uniform, which is an official dress code determined by the school, wearing a uniform is not mandatory. Some students wore loose clothing, but it was observed that most students came to school in the form determined by the administration. Consequently, average clothing insulation values for children were calculated (ISO 7730). In addition, the questionnaire administered to all classes at the beginning of the lesson during the measurements. They were in class for about 60 minutes. During the process of conducting objective measurements, students were requested to complete a questionnaire. Participants were given the questionnaires 30 minutes after entering the classroom to ensure they had sufficient time to acclimate to the environment (Duration of one lesson 45-60 min.). Teachers were asked to assist in making the questionnaire understandable. The survey questions briefly included the following topics:

- Respondent's thermal sensation rating for the indoor thermal environment, based on the 7-point ASHRAE thermal sensation scale (cold, cool, slightly cool, neutral, slightly warm, warm, hot).
- Feeling of comfort.
- Dress information.
- Feeling of tiredness.
- Students' activities during the survey.

As a result of the study, evaluations were made by comparing the results of the surveys and measurements.

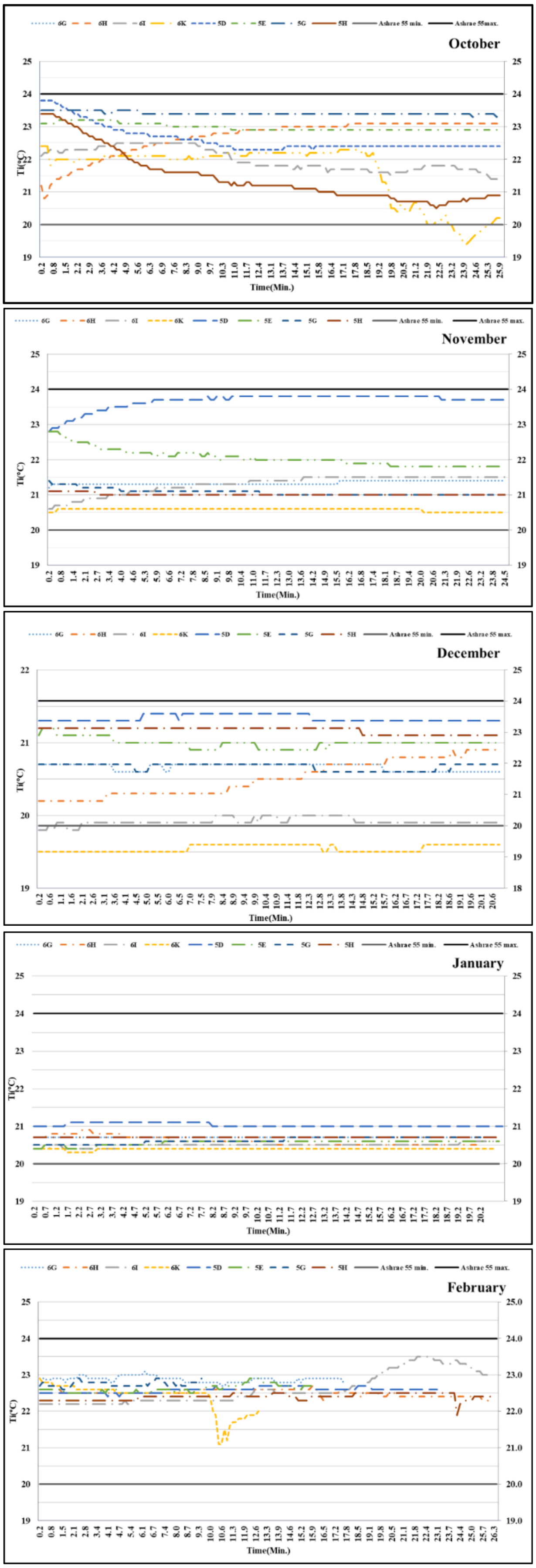
3. RESULTS AND DISCUSSION

In this study, indoor comfort conditions were examined during the summer and winter periods at an educational institution in Turkey, where the academic year is divided into two semesters - Fall and Spring. The measurements used in this study included data from October to March for the winter period and data from June, August, and September for the summer period. Measurements were taken three times a month, once a week in 2020-2022.

In this study, indoor air temperature (Ti), indoor radiation temperature (TR), relative humidity (RH), and air velocities (Va) were measured, and graphs based on instantaneous and periodic average data were created. As mentioned before since our study is on an indoor thermal environment ISO EN 7730, and ASHRAE 55 standards are necessary and sufficient to evaluate the results. According to ISO 7730, the winter comfort temperature for 50% relative humidity is 20-24°C, while it is known to be 23-26°C in the summer period [51,26]. In the Khovalyg et al. [29] study, the winter temperature range is 19-25℃ according to the ISO7730 standard, while it is 20.5-24.5℃ according to Ashrae 55. Again, according to the ISO7730 standard, the summer temperature range is 22-27℃; According to Ashrae 55 it is 24-27℃. As can be seen, ISO 7730 keeps the comfort range wider, while Ashrae 55 narrows the comfort range by 2-3℃. While ISO 7730 has different categories, Ashrae does not have any categories and determines the acceptable values of the thermal environment. In this regard, ASHRAE 55 summer and winter comfort temperatures were taken as reference in the range of 23-26°C and 20-24°C, respectively, and relative humidity was taken as reference in the range of 30-60% for both summer and winter periods.

3.1. Indoor Air Temperature Measurement Results of Spaces

Figure 6 presents graphs illustrating the temporal evolution of indoor air temperatures in classrooms during the winter months. To facilitate comparison, the lower and upper limits (20-24°C) of the ASHRAE 55 standard for winter are also included in the same graphs. The data in the graphs indicates that indoor temperatures in the classrooms from October to March range between 20-25°C. It can be observed that the indoor temperature values for these months remain within the standard value range. In March, the indoor temperature in the 5D and 5G classrooms falls slightly below the standard minimum value of 19°C. However, the overall indoor temperature in March ranges from 19-22°C, which is close to the standard values.



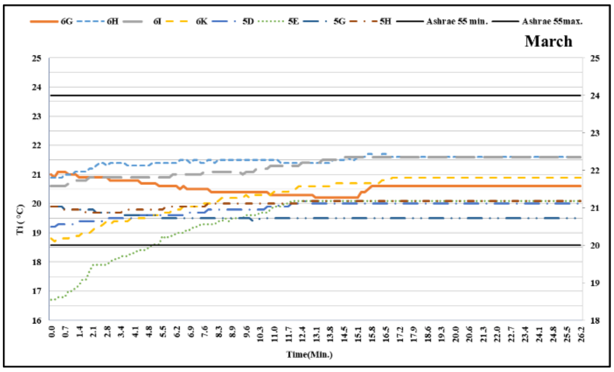
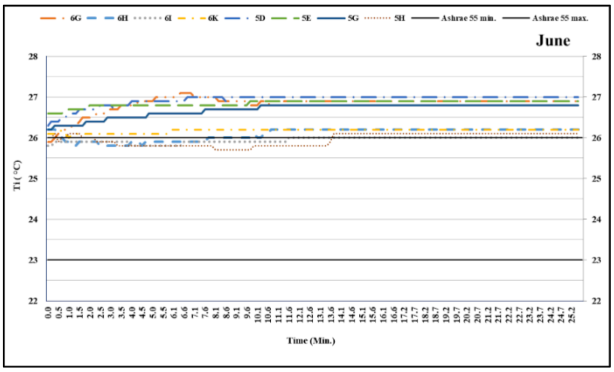
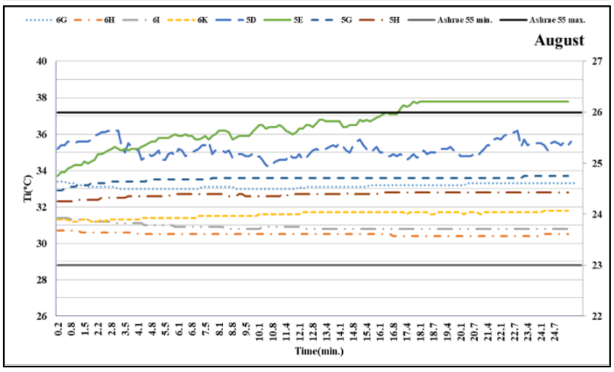


Figure 6. The temperature of indoor classrooms during the winter period

Figure 7 presents the instantaneous indoor air temperatures of the classes during the summer period. In order to facilitate comparison, the summer temperature lower and upper limits (23-26°C) of the ASHRAE 55 standard are also provided. The results in Figure 7 indicate that the temperature values for June, August and September are in the range of 25-28°C, 30-37°C and 23-26°C, respectively. Therefore, the values of June and September are within the standard range. However, for August, which is the hottest and driest month of the year, it is observed that the comfort value is significantly exceeded. Consequently, it can be concluded that indoor temperatures in educational institutions exceed the upper limit of the comfort standard, particularly during the hottest months of the year in this region, namely July and August. It is therefore necessary to implement measures to reduce temperatures to the standard value range.





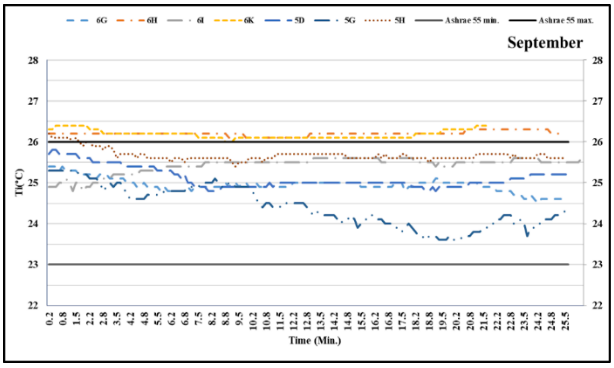


Figure 7. The mean indoor air temperature of the classrooms during the summer period

3.2. The Results of the Indoor Radiation Temperatures Measurements of the Spaces

Indoors radiation temperatures play a crucial role in providing suitable comfort conditions and ensuring appropriate insulation in buildings. Proper insulation can help maintain appropriate radiation temperatures, preventing wall temperatures from dropping too low in winter and rising too high in summer. For example, during the winter months, outdoor temperatures can be very cold, causing wall temperature values to be slightly lower than indoor temperatures. However, to ensure comfort, a maximum difference of 3°C is required between the wall temperature and the indoor temperature. If the temperature difference is greater than 3°C, radiation heat transfer between the body and the cold wall can cause discomfort, even if the environment is heated. Therefore, according to TS 825 (standard in Turkey) insulation standards, the wall temperature value should be at least 17°C. Similarly, during the summer months, air temperatures in various regions can reach very high temperatures such as 40°C. However, the indoor temperature will be lower than this value. Walls facing the warm environment will be warmer than the interior, and even if the interior is ventilated with a device such as an air conditioner, discomfort can occur due to radiation from the high-temperature outer wall to the person's body. Therefore, the insulation properties of the building should be designed so that the interior surface temperature is no more than 3°C lower than the indoor temperature values (for all surfaces such as roof, wall, etc.) Appropriate thermal insulation must be used in the building to provide summer and winter comfort conditions (TS 825). With proper thermal insulation, heat losses from inside to outside are prevented in winter, and heat transfer from outside to inside is prevented in summer. Comparisons of indoor temperature and indoor radiation temperature values of classrooms in winter and summer seasons are given in table 3 and Figure 8 (a, b).

Table 3. A comparison of the mean indoor temperature during the winter and summer seasons, along with the indoor radiation temperature values

Average parameters	5G	5H	5E	5D	6G	6H	6K	6I
	Winter period							
T_i	19.6	19.9	18.8	19.6	20.6	21	20	21.1
***RH* (%)**	36.6	35.6	38.6	36.4	40.1	40	48.9	39.7
T_R	16.1	15.3	12.8	18.3	18.3	17.6	18.3	16.62
	Summer period							
T_i	30.5	29	31	31	30	28	28	28
***RH* (%)**	23	23	21	22	25	25	23	25
T_R	27	28	29	28	28	26	27	27

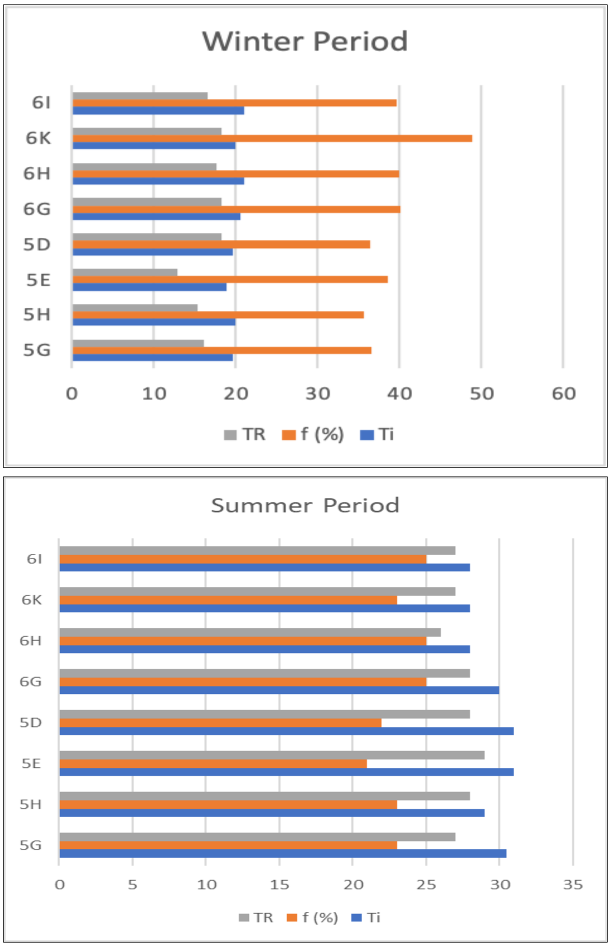
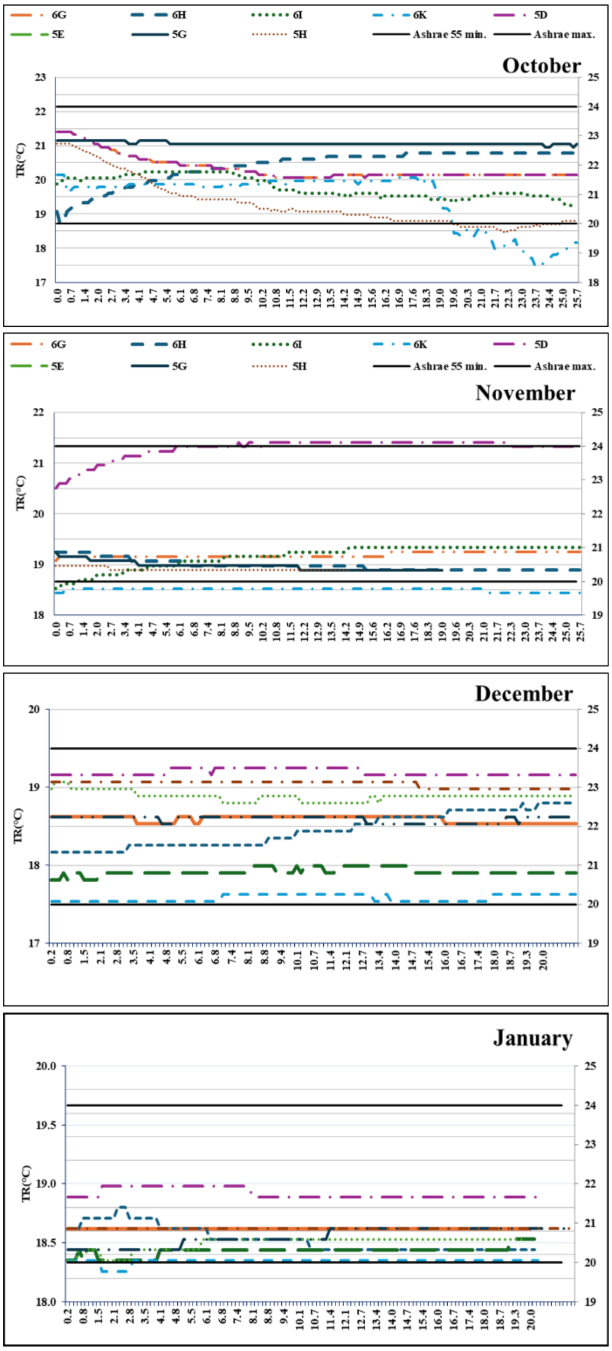


Figure 8.a. Comparison of winter indoor temperature, indoor radiation temperature values, b. Comparison of summer indoor temperature, indoor radiation temperature values

The instantaneous indoor radiation temperatures, calculated using equation 1 as a function of the indoor temperature, are shown in Figures 9 and Figure 10 for the winter and summer periods, respectively. Figure 9 indicates that, during the winter period, the indoor radiation temperatures generally fall below the lower limit of the ASHRAE 55 standard, with the exception of October, November, and December. The indoor temperature graphs presented earlier indicate that the indoor temperatures range between 20 and 25 degrees Celsius in October and November, 20 and 22 degrees Celsius in December and January, and decrease slightly to 19 and 22 degrees Celsius in March. It is evident that the indoor radiation temperatures for these months decreased by 1-2°C and fell below the lower limit of the comfort conditions in some classes in October and November, and below the lower limit for all classes in December and January.

As can be observed, while the indoor temperatures are within the comfort range in winter, the indoor radiation temperatures are at the lower limit of TS 825. It is evident from Table 3 and Figure 8 that the wall temperature value drops to 12°C in March, which is below the 17°C threshold set out in the TS 825 standard. While proper heating can be achieved, it cannot be said that proper insulation has been provided. This is problematic, as the wall temperature has dropped to 12°C even in March. The indoor radiation temperatures will be lower due to the wall temperatures in February and January when the cold is more severe. This will cause condensation on the walls and, subsequently, mould growth.



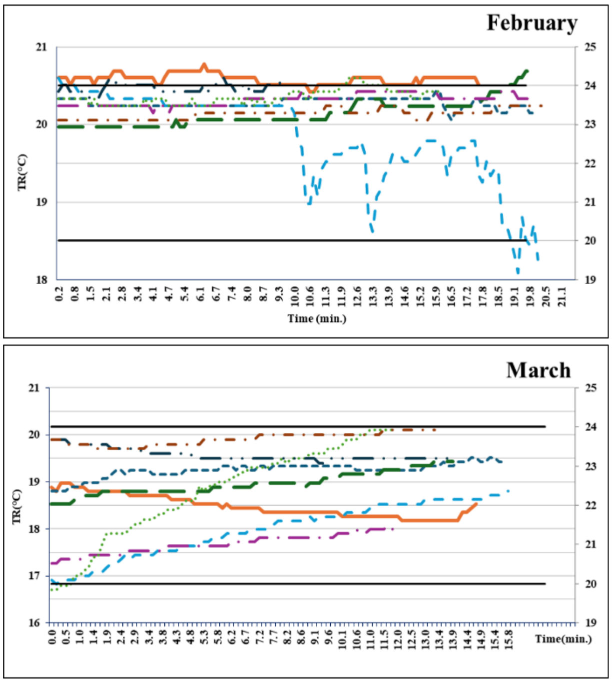
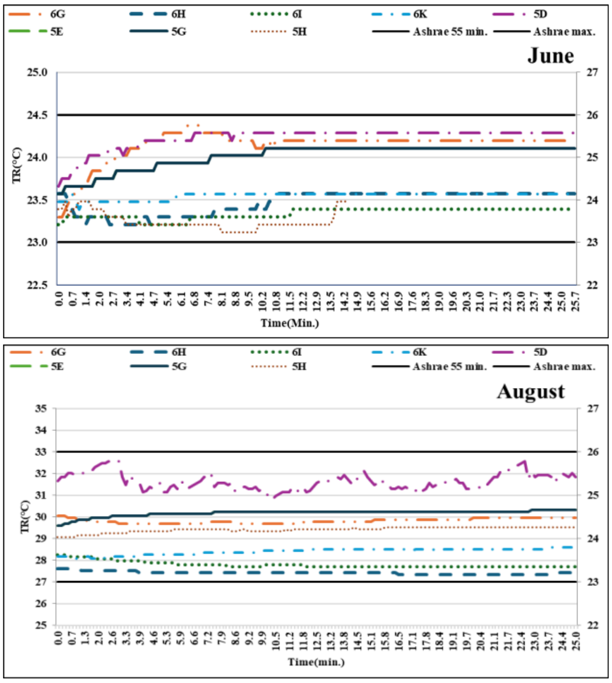


Figure 9. Indoor radiation temperatures in the winter period

Figure 10 presents the instantaneous indoor radiation temperatures during the summer months. The data indicates that the values in June fall within the ASHRAE standard limits and are therefore suitable for comfort conditions. However, the temperature values in August exceed the standards by approximately 30°C, with maximum values observed. In contrast, temperatures in September are below the standard. As with the overall conclusion drawn from the indoor temperature results presented in these graphs, it is evident that necessary precautions should be taken to manage high temperatures when these spaces are used in July and August, which are the hottest and driest months of the summer.



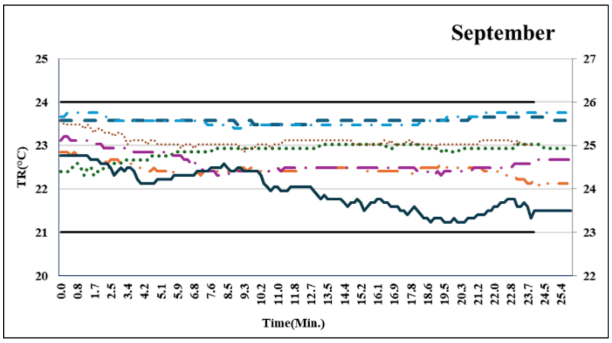
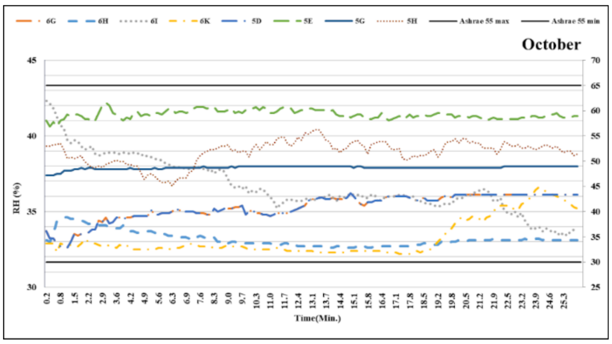


Figure 10. Summer Indoor radiation temperatures

3.3. The results of the relative humidity measurements of the spaces

Relative humidity is another important parameter that affects thermal comfort. It is defined as the ratio of the amount of water vapour in the air to the maximum amount of water vapor it can hold at the same temperature, expressed as a percentage. As shown in Equation 2, it is calculated by dividing the absolute pressure of the air by the saturation pressure at the same temperature. According to the ASHRAE 55 standard, the recommended relative humidity range for comfort is between 30-65%. However, some sources suggest that a range of relative humidity of 35-60% would be more suitable [51]. It is useful to evaluate the relative humidity discomfort in cases where it is below the lower limit and above the upper limit. If the relative humidity value falls below the lower limit (below 30-40%), it causes health problems such as dryness and itching on the skin and lips. On the other hand, in cases of over 65%, it will cause discomfort such as difficulty in breathing, excessive sweating, and feeling of suffocation. These conditions can have a significant impact on human work and productivity. The World Health Organization reports that there is a possibility of airborne transmission as well as human-to-human transmission of viruses. It has also been determined by many studies that contamination and viruses are frequently transmitted through the air. This situation is closely related to the amount of humidity in the air. The rate of spread of influenza (flu) virus is higher when the relative humidity is below 40% (Metz, 2015). This is why low relative humidity is a major contributing factor to seasonal flu outbreaks, especially during the winter months [52].



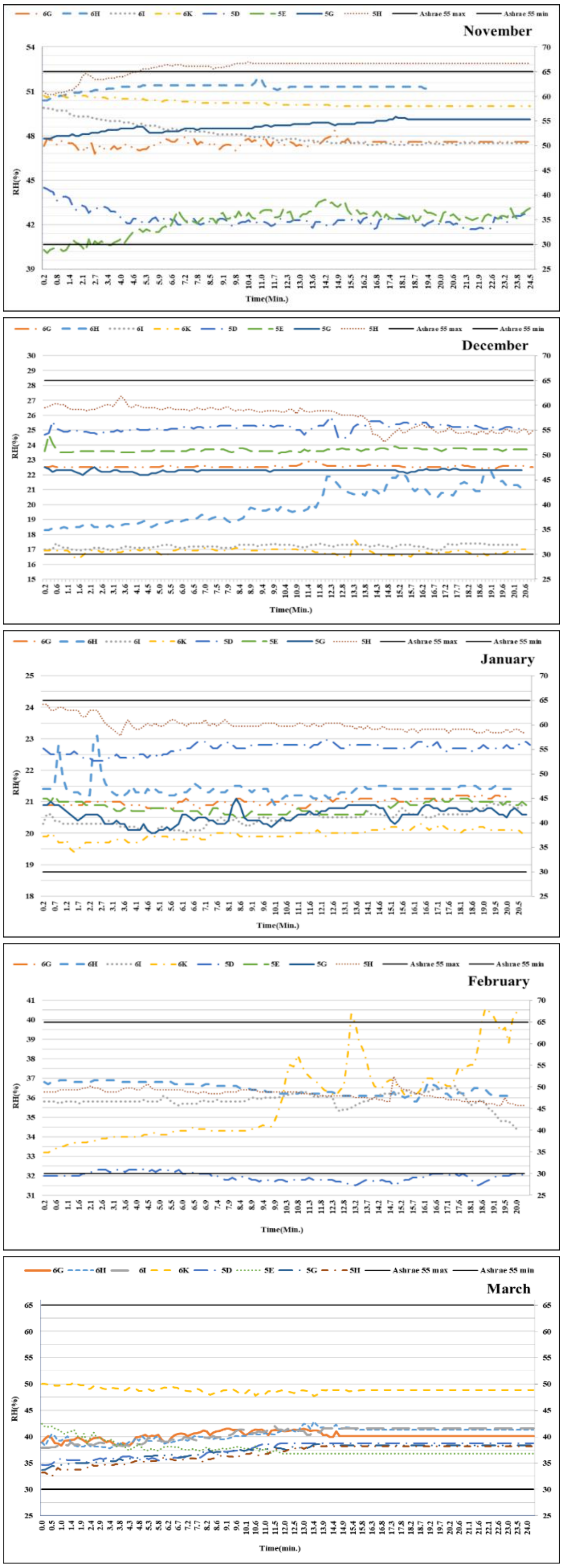


Figure 11. Relative humidity values in winter period

Figure 11 presents instantaneous relative humidity graphs for different spaces during the winter months. Based on these graphs for the winter period in Figure 10, it can be seen that relative humidity rates fall within the standard range except December and January months. However, in December and January, relative humidity rates are between 15-25%, indicating discomfort. This extreme drop in relative humidity can be attributed to the hot and dry weather during these months in 2022-2023. As a matter of fact, according to Turkey's meteorological data, 2022 December has been recorded as 15 sunny days and 8 rainy days. In summary, the months of December and January were quite dry in the related year. As for the summer period, the relative humidity values for most classes are close to the lower limit of 30-35% (as shown in Figure 12). Therefore, it can be concluded that these classes are generally uncomfortable, especially in August when humidity levels are lowest. Table 3 also provides similar results for relative humidity values. The average humidity level during the winter period is above 35%, while the average values during the summer are at around 30%, dropping to 12% in August, which is the hottest and driest month of the summer.

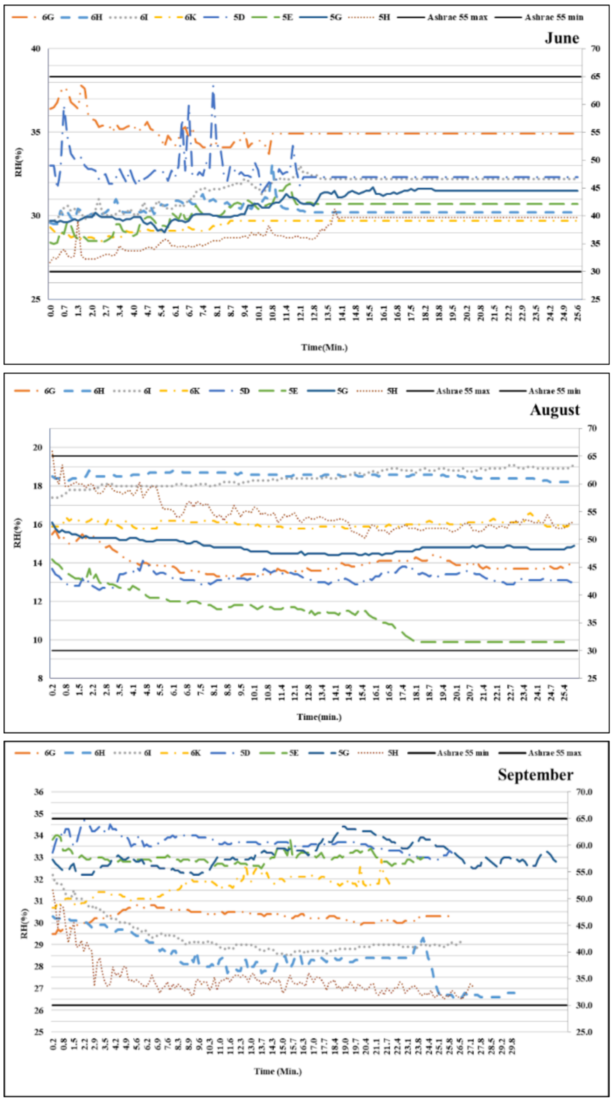
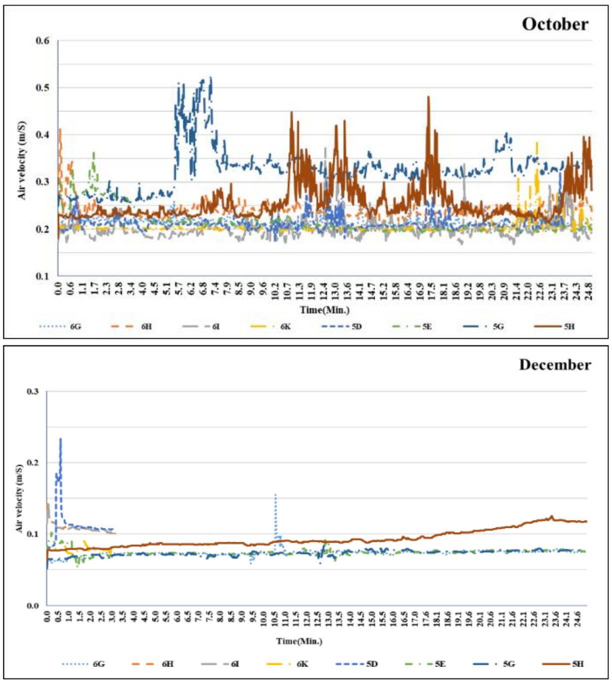


Figure 12. Relative humidity values in the summer period

3.4. The results of the air velocity measurements of the spaces

Measurements were made in naturally ventilated classrooms with air circulation through windows and doors. Lee and Zakaria (2024) state in their study that classroom ventilation is very important when it comes to creating a successful learning environment, with several advantages in terms of comfort and productivity for both students and teachers [58].

The comfort conditions of an environment are closely related to the air velocity, as well as the temperature and humidity of the ambient air. While stagnant air at low temperatures does not cause discomfort, it can become suffocating in high temperatures. For instance, at an ambient temperature of 20 °C, a comfortable air velocity is 0.15 m/s, whereas at an ambient temperature of 24 °C, an air velocity of 0.22 m/s is more suitable for comfort [53]. Therefore, buildings should be designed to make the most of natural ventilation, taking into account the climatic conditions of the region and the orientation of the building. In this regard, it is recommended that buildings be designed in a manner that optimises the utilisation of natural ventilation, taking into account the climatic conditions of the region and the orientation of the building. The air velocities of the classes for the winter and summer periods are presented in Figures 13 and 14. From the winter period graph, it can be seen that the air velocities of the classes are at the standard value in December. However, the data for October is mostly above 0.2 m/s, which is uncomfortable. In some classes, the data for January exceeds 0.2 m/s. In February, the air velocities in the 5H and 5D classes increased to 1 m/s at certain moments due to door or window openings. However, when considering all other classes, the velocity values were consistently below 0.2 m/s throughout the measurement period. It is evident that the velocity value exceeded 0.2 m/s during the measurement period in almost all classes in October. This can be attributed to the fact that October is a transitional month between the summer and winter periods, with doors and windows not generally kept closed during this time. It is understood that the values in December, January, and February, which are the other months of the winter period, are generally below 0.2 m/s (Figure 13).



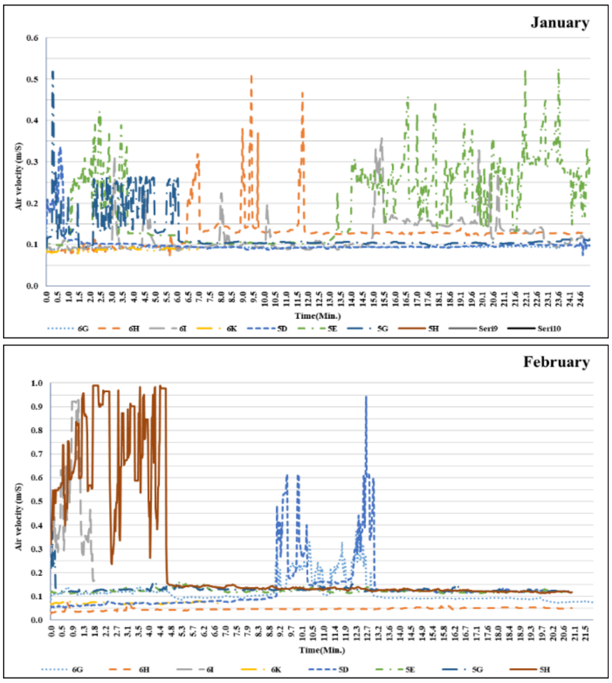
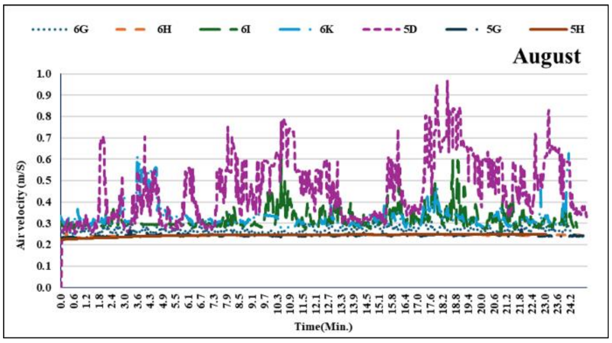


Figure 13. Air velocities of the winter period

Figure 14 presents summer air velocities. The August graph shows that only classes 5H and 5G have air velocities close to the standard value (approximately 0.2 m/s), while the other classes have much higher air velocities. The optimal air velocity for comfort during summer is 0.22 m/s at an ambient temperature of 24 °C (Halıcı 2019). Given that the average ambient temperature in August is 33 °C, an ambient air velocity of around 0.4 m/s is not considered uncomfortable, as it will mitigate the effect of the sweltering heat. Since ventilation is achieved through window openings in the summer period and measurements are taken while the windows are open, it is apparent that the air velocities are higher (around 0.4 m/s) compared to the winter months. Nevertheless, prolonged exposure to air velocities of 0.6 or 0.8, as illustrated in Figure 14, may have detrimental effects on one's health, even during the summer months.



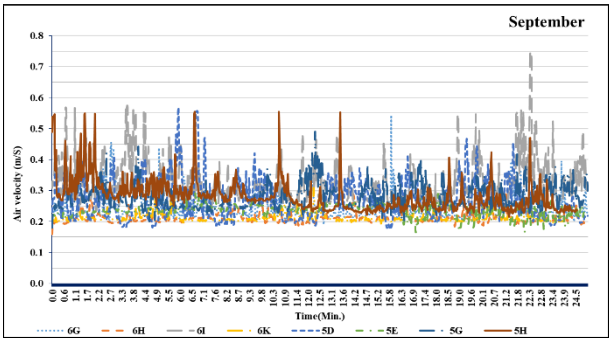


Figure 14. Air velocities of the summer period

3.5. Thermal responses: thermal sensation and thermal preference votes

The evaluation of the survey data applied during measurements in the classrooms is included in this section. According to the survey data applied during the study, students expressed a preference for additional insulation layers, such as school jackets, coats, or thermal underwear, to prevent heat loss from the body during the winter months. Consequently, the "clo" values of average clothing insulation for children are employed in ISO 7730. The clothing thermal resistance was calculated as 0.35 for the summer period and 0.70 for the heating period, providing an "error band" for PMV estimation. As there was no significant difference in the values of the thermal parameters, each class was characterised by a single PMV and PPD value. A total of 3% of the collected responses were excluded from the data analysis. This approach of excluding inconsistent responses from the analyses was adopted in line with previous studies [29,54]. The PPD values derived from the measured data were contrasted with the percentage of dissatisfied individuals estimated by evaluating the questionnaires. The thermal sensations of the users were gauged using the ASHRAE scale, with thermal sensation values (TSV) ranging from cold (TSV = -3) to hot (TSV = +3) (Table 4).

Table 4. The thermal sensation scale (TSV)

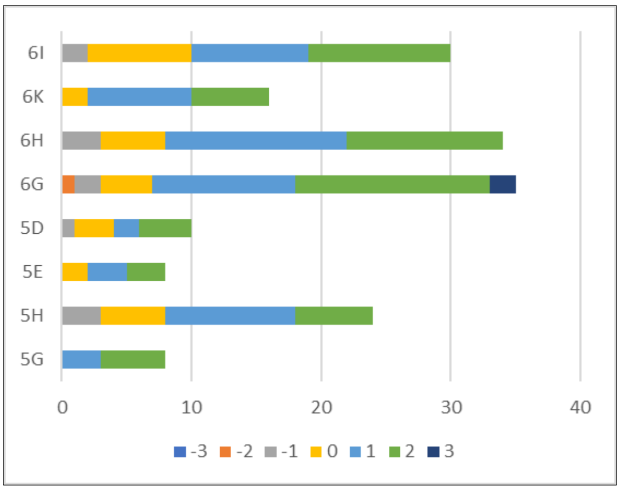
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
-3	-2	-1	0	+1	+2	+3

In the PMV formula (ISO 7730), the metabolic rate is factored in two ways. The metabolic rate of an average adult at rest (RMR) is integrated into the empirical equation with a resting value of 58.15 W/m². This is described as the ratio of the metabolic rate during physical activity to the resting metabolic rate, commonly referred to as "MET." According to ASHRAE [29], 1 MET is defined as "the metabolic rate of a sedentary person (seated, quiet): 1 MET = 58.15 W/m² = 50 kcal/(h·m²)." By its design, the PMV equation is tailored to adult physiology. Additionally, the metabolic rates per unit skin surface area for various activities provided by frequently used standards reflect typical values for an average adult. These values are derived from experiments involving adult subjects and may not directly apply to children. Children have a higher resting metabolic rate per kilogram of body weight compared to adults, which gradually decreases as they grow. Furthermore, children's school day activities differ significantly from those of adults. Consequently, there is a pressing need for a thermal comfort model that specifically addresses the physiological characteristics of children.

Table 5. Survey results according to the thermal sensation scale

Period		T_i	Thermal Sensation scale (TSV)							Total
			-3	-2	-1	0	1	2	3	
Winter Period	5G	19.6	0	0	0	0	3	5	0	10
	5H	19.9	0	0	3	5	10	6	0	26
	5E	18.8	0	0	0	2	3	3	0	8
	5D	19.6	0	0	1	3	2	4	0	10
	6G	20.6	0	1	2	4	11	15	2	34
	6H	21	0	0	3	5	14	12	0	34
	6K	20	0	0	0	2	8	6	0	18
	6I	21.1	0	0	2	8	9	11	0	30
	Total		0	1	11	29	60	64	5	170
	%		0	0.6	6.5	17.1	35.2	37.6	3.0	
Summer Period	5G	26.7	0	0	0	7	5	6	0	18
	5H	25.8	0	0	0	1	4	2	0	8
	5E	26.8	0	0	0	8	6	2	0	16
	5D	26.9	0	0	2	6	5	5	0	18
	6G	26.8	0	0	0	6	7	9	8	30
	6H	26	0	0	2	2	5	5	0	16
	6K	26.1	0	0	0	0	4	4	0	8
	6I	25.9	0	0	0	2	4	4	0	10
	Total		0	0	4	32	40	37	11	124
	%		0	0	3.2	25.8	32.3	29.9	8.9	
Cumulative total			0	1	15	61	100	101	16	
%			0	0.4	5.1	20.7	34.0	34.4	5.4	

Several previous thermal comfort studies with children used calculations in the PMV model to address the difference in metabolic rates. Havenith [18] determined that metabolic rates for school activities are in the range of 52-64 W/m2. This value is approximately 10% lower than the adult's sedentary activities (office work) (70 W/m2) equivalent. Children's RMR has been measured in numerous studies over the past 20 years, but there is no standard value that can be used to calculate the "MET" for the "average" child. For this reason, the metabolic rate used in the literature was calculated as 1.2 MET (58/48.8) (sedentary activity) [24,29,55]. The survey results according to the thermal sensation scale are shown in Table 5 and Figure 15 (a, b). According to the related table survey results of the thermal sensation scale, 124 surveys were collected in this period due to the winter period coinciding with the Covid epidemic, and 170 surveys were collected in the summer period due to the decrease in the effect of the epidemic and normalization of the process.



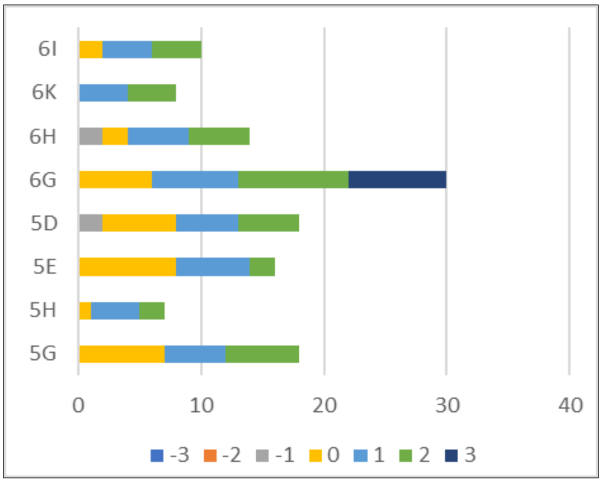


Figure 15. a. Graph of winter period survey results according to ASHRAE Thermal Sensation Scale, b. Graph of summer period survey results according to ASHRAE Thermal Sensation Scaled

In the winter period, 17.1% of students voted 'neutral,' while 58.8% voted within the comfort range (-1 to +1). During the summer period, 25.8% voted 'neutral,' and 61.3% voted within the comfort range (-1 to +1). Overall, it was found that students generally fell within the comfort range in both seasons. Some students felt the classrooms were too cool in winter, but this was due to their clothing choices, as many wore coats and thermal underwear. The majority of students (89.9%) voted within the range of 0 to +2, indicating their comfort level. Factors contributing to this comfort level included high-temperature natural gas heating, double-glazed windows, and crowded classrooms. During the summer period, even with windows open, 88% of students voted within the range of 0 to +2, while nearly 78% expressed a desire for cooler classrooms in summer. The measurements showed that the thermal comfort level was generally within the standard range, except for August. The PMV average was 0.34 with a PPD index of 36.2%. According to surveys, 6.8% of students were dissatisfied during the winter period, while 40.4% were dissatisfied during the summer period. This indicates that students' thermal comfort aligns with the measurements but differs slightly from the PMV model, highlighting the unique thermal sensations of children. Factors such as limited control over windows and clothing adjustments in classrooms may contribute to these differences.

Mustapha et al. (2024) state that, in general, the reliability and validity of different methods used in thermal comfort studies depend on the specific context and purpose of the assessment. In addition, the combination of different methods, such as the use of field measurement methods to measure actual thermal conditions and the use of subjective assessments to capture the individual experiences and preferences of building occupants, can provide a more comprehensive and reliable assessment of thermal comfort in classrooms and emphasises the importance of future research in different climate zones [59]. In this context, the results of this study conducted in a cold climate region provide reliable, original and valuable data.

4. CONCLUSION AND RECOMMENDATIONS

In this study, thermal comfort research was conducted during the summer and winter periods from 2021 to 2023, as well as in August during the summer school session, at a secondary school in Bingöl. This school has the highest number of students among the secondary schools built after the 2003 earthquake in Bingöl. The research was conducted using both qualitative and quantitative research techniques, with questionnaires used for the qualitative aspect and devices used for the quantitative aspect. The study involved evaluating the responses of 264 students, aged 11 to 14, who each completed a questionnaire containing 28 questions. Simultaneously, climatic variables were also measured to correspond with the students' thermal perception. The analytical study includes a comparison between the students' thermal sensation and preference, the derivation of thermal neutrality and comfort range, and a comparison of results with national and international thermal comfort standards. Uncomfortable temperatures directly or indirectly affect the comfort status of individuals. So, this can harm student's health, work efficiency, and energy savings. According to the measurement results, although the indoor temperatures are in the comfort range in the winter period, it has been observed that the indoor radiation temperatures of some classrooms are below 17℃ in the winter months. During summer, the indoor temperature is generally above the comfort upper value (Ti > 26℃), reaching high temperatures of 30-35℃, especially in August, the hottest month.

Comfort conditions are closely related to the relative humidity and air velocity as well as the temperature of the indoor air. The relative humidity of the ambient air is also adversely affected in case of hot or cold conditions of outside. It has been determined from the results that both summer and winter relative humidity values are generally low. The shift of relative humidity to the uncomfortable range brings along various diseases and disorders, especially viruses such as influenza virus in winter. Low relative humidity also increases the risk of contamination. It is known that virus transmission is less, especially at high temperature and relative humidity values [56]. Uncomfortable relative humidity will also cause an increase in upper respiratory tract infections, as well as cause dryness, irritation, and itching on the skin. In this regard, it is essential to have devices that control humidity and temperature in places such as schools, universities, student dormitories, factories, and work workshops where many people gather. However, it is useful to inform people about situations where these parameters are in the uncomfortable zone. Accordingly, it is necessary to take measures such as automatic activation of the heater or air conditioner when necessary, operating the device that humidifies the environment in case of low humidity, or lowering high humidity through the air conditioner.

Apart from temperature and relative humidity, air velocity is also a parameter to be considered. In transition months between the summer and winter periods (like October and November), doors and windows are not kept closed generally. So, in these months, the air velocity has exceeded 0.2 m/s. The values for the winter (December, January, and February) period, when the doors and windows are kept closed, are generally below 0.2 m/s and are in the standard range. The air speeds of the summer season were generally around 0.4 m/s, and it cannot be said to be uncomfortable as it will reduce the overwhelming effect of the extremely high-temperature values in the relevant months. As well-known stagnant air at low temperatures does not disturb; In case of high temperatures, the stagnant air will be suffocating. For example, while the airspeed is 0.15 m/s at an ambient temperature of 20 °C, 0.22 m/s at an ambient temperature of 24 °C is more suitable for comfort [53]. In this regard, natural or mechanical ventilation of the environment is even more important. Although some studies say that mechanical ventilation is more suitable for Thermal comfort in Schools [57], natural ventilation should be preferred more since mechanical ventilation includes both energy consumption and negative conditions such as sick building syndrome. Therefore, it should be designed to make maximum use of natural ventilation, taking into account the climatic characteristics of the region where the buildings will be constructed and the location of the building according to the directions.

The study revealed that children are more sensitive to high temperatures compared to adults, and thus prefer lower temperatures in classrooms. Children tend to adapt to thermal sensations by opening and closing windows and doors, as well as wearing light clothing during the summer period in classrooms where they spend most of their day. During the winter period, it was observed that they tend to wear thicker clothing to maintain thermal comfort. The PMV/PPD model does not provide full success in predicting the thermal sensations of students in naturally ventilated classrooms. While it shows the maximum percentage (31.6%) of the students who are not satisfied with the indoor conditions, the thermal sense of 89.1% of the students falls within the comfort range (-1 to +1). According to the surveys, only 6.8% of the students were dissatisfied during the winter period, while 40.4% were dissatisfied during the summer period. So, it was determined that the thermal comfort of the students was compatible with the measurements and slightly different from the PMV model. The extremely high temperature and dryness of the summer months, in which it is seen, caused the dissatisfaction rate to be higher. Insufficient ventilation also affects this situation negatively. This result also shows that children's thermal sensations are different from adults. Children's behaviour in adapting to the environment by opening and closing windows or adjusting their clothes in classrooms may explain such differences. A lot of work has been and continues to be done on the indoor thermal comfort of educational buildings. These studies carried out in different climatic regions, are of great importance for comparison and evaluation. It is expected that this study will lead to further research for schools in the region. Considering the relationship between energy efficiency, physical comfort conditions, and learning in school buildings, it would be beneficial to include passive features in school buildings to make them thermally comfortable throughout the year while using minimal energy, and thus make them sustainable.

Finally, although this study was conducted in Bingöl, further research is needed in schools located in different climate regions to assess thermal comfort conditions more broadly. To enhance the generalizability of the findings, conducting similar studies in other climates will provide a more comprehensive understanding. Implementing sustainable design practices in school buildings can significantly improve health, comfort, and learning outcomes in educational environments.

Acknowledgement

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