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Research Article

A Comprehensive Assessment of Indoor Air Quality and Thermal Comfort in Educational Buildings in the Mediterranean Climate

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Maintaining good indoor air quality and thermal comfort is a challenge for naturally ventilated educational buildings, as it can be difficult to achieve both aspects simultaneously. Nonetheless, most of the existing studies only focus on one aspect. To explore the potential of balancing indoor air quality and thermal comfort, both topics must be investigated concurrently. This study assessed indoor air quality and thermal comfort in 32 naturally ventilated classrooms of 16 primary and secondary schools in the Mediterranean climate, based on a large on-site measurement campaign lasting one year that gathered over 460 hours of data. The research investigated occupants' adaptive behaviors, analyzed the actual thermal comfort of around 600 students, and characterized the representative scenarios leading to good and poor indoor air quality and thermal comfort by clustering analysis. The results showed that poor indoor air quality was mainly due to closing windows and doors in winter, while thermal discomfort mainly occurred in summer because of the high indoor temperature. The findings suggested that a proper ventilation protocol is the key to balancing indoor air quality and thermal comfort.

1. Introduction

Students spend around 70% of their time in the classroom on school days [1]. The environmental quality of the classroom is influenced by many factors, but indoor air quality (IAQ) and thermal comfort (TC) are the main factors affecting students' health, well-being, and productivity [2]. The negative impacts of poor IAQ and thermal comfort have been widely reported, such as the loss of concentration, decline in cognitive ability, headache, fatigue, allergy, and, in particular, a high infection risk of airborne diseases [3–5].

Long-term occupancy and high occupant density often lead to great challenges in maintaining a safe, comfortable environment in the classrooms. More importantly, children are more vulnerable than adults, and their adaptation in the classroom is passive and limited. They usually do not complain when they are not really satisfied with the indoor environment [6]. For these reasons, the IAQ and thermal comfort of educational buildings have been a concern for relevant public authorities and researchers.

Ventilation is the most common way of maintaining good IAQ in schools, and most schools only rely on natural ventilation that changes from time to time [7]. A minimum air change rate per hour is required by relevant standards such as ASHRAE 62.1 [8] and EN 16798-1 [9]. The estimation of the air change rate of the classroom is predominantly achieved by measuring occupant-released CO_2 as a tracer gas. Thus, the indoor CO_2 concentration is a commonly adopted surrogate indicator for the assessment of IAQ for educational buildings [3, 10, 11].

Maintaining good IAQ in schools is challenging. Díaz et al. [12] conducted a study in 8 primary schools in Chile. They found that the indoor CO_2 concentration exceeded the maximum threshold for around 70% of school hours in winter. In a large-scale survey of 100 primary and secondary school classrooms in Switzerland, Vassella et al. [13] demonstrated that approximately two-thirds of the classrooms failed to meet the limit set by the national standard. Cai et al. [14] carried out a study in 21 public schools in China and found that mechanically ventilated classrooms exceeded the CO_2 limit during 40% of the measurement time, compared to 61% in naturally ventilated classrooms. Monge-Barrio et al. [15] performed a measurement campaign in 9 secondary schools in Spain. They discovered that CO_2 concentration values did not meet the national regulation, as the exceedance was 2 times higher due to the lack of a proper ventilation protocol. From these studies, it can be extrapolated that the variability of IAQ of classrooms can be attributed to many factors, including seasons [12], occupancy [15], ventilation system [14], and ventilation strategy [13].

Unlike IAQ, both objective and subjective factors influence students' thermal comfort. Objective factors involve a range of thermal parameters such as temperature, relative humidity, and air velocity. In contrast, subjective parameters derive from the occupants' physical and psychological adaptation [2].

Achieving students' thermal comfort is also a challenge for schools. Firstly, the thermal sensation of children and teenagers is quite different from that of adults [16]. Notably, the models established by ASHRAE 55 [17] and ISO 7730 [18] were developed for adults in offices. This means that students may not necessarily be comfortable even if the temperature in educational centers is set following the thermal requirements specified by the regulations. Korsavi et al. [6] evaluated 8 primary schools in the UK, where 15% and 14% of the children were overheated during nonheating seasons and heating seasons, respectively. Aparicio-Ruiz et al. [19] investigated 3 classrooms in a primary school in Southern Spain during the summer. They found that only half of the students felt comfortable, even though the mean indoor air temperature of classrooms was within the operating range of the national regulation. Secondly, students' thermal comfort varies due to many factors. Zomorodian et al. [5] indicated that students in various climates had different comfort temperatures. Yang et al. [20] assessed a primary school in Sweden and reported that students' thermal neutrality varied from season to season. Al-Khatri et al. [21] investigated 5 girls' secondary schools and 3 boys' secondary schools in Saudi Arabia. The results indicated that the comfort temperature difference between females and males was nearly 2°C. Jiang et al. [22] analyzed 4 schools in northwest China during winter. In nonheated classrooms, students were more accepting of lower indoor temperatures. Shrestha et al. [23] carried out a survey of 8 schools in Nepal. In this case, the heavier clothing of students also led to a low comfort temperature. Considering the aforementioned aspects, students' thermal comfort can be affected by a wide range of factors such as climate [5], season [20], heating systems [22], gender [21], and level of clothing insulation [23].

IAQ and thermal comfort are associated because the outdoor air introduced into the classroom can lead to significant changes in indoor thermal conditions [2]. Heracleous and Michael [24] evaluated a secondary school in Cyprus and found that both indoor air and outdoor temperatures can affect occupants' behavior of opening windows to ventilate the air in the space. Ma et al. [25] demonstrated that maintaining a comfortable thermal environment could reduce the ventilation rate, and consequently, a low level of IAQ could be detected in classrooms. Mohamed et al. [1] found that most of the classrooms experienced overheating for more than 40% of the day. At the same time, the classrooms failed to meet the IAQ requirement of the UK national standard for more than 60% of school hours.

Concerning the Mediterranean area, only a few studies address both topics (IAQ and thermal comfort of schools), as listed in the following: one elementary school study in Greece during spring [26], one secondary school study in Portugal during spring [27], one secondary school study in Cyprus during winter [24] and one preschool study in Spain during winter [28]. The above studies limited the scope to a single climate zone, season, and education level, which may be the shortcomings. In addition, none of the existing studies investigated the representative scenarios that often lead to good and poor IAQ and thermal comfort in classrooms. Hence, a comprehensive investigation is needed of IAQ and thermal comfort of primary and secondary schools in the Mediterranean climate.

For this reason, this paper is aimed at conducting a comprehensive characterization of both IAQ and thermal comfort in educational buildings, based on a large on-site measurement campaign in primary and secondary schools in several regions with specific climate conditions in the Mediterranean climate.

Following this introduction, Section 2 defines the methodology of this study, Section 3 describes the implementation of methodology and measurement campaigns, and Section 4 discusses the analyzed results. The conclusions and recommendations are summarized in Section 5.

2. Methodology

The research methodology of this study consists of four steps (Figure 1).

2.1. Identification and Description of Educational Buildings. Educational buildings must be selected considering representativeness and avoiding potential biases caused by the building and occupants. In this context, a range of factors that may affect IAQ and thermal comfort should be taken into account, such as climate zones, geographic location, construction year, ventilation type, and cooling and heating modes.

Educational centers are mainly used by children and teenagers. Their participation in the research must be based on the consent of all involved parties, such as government authorities, school management boards, teachers, and parents (who may ultimately restrict the availability of expected samples).

2.2. Characterization of Indoor Air Quality and Thermal Comfort. For IAQ, EN 16798-1 [9] specifies 4 categories with corresponding CO_2 concentration limits. The IAQ requirement for the classrooms corresponds to category I, which requires the indoor CO_2 concentration to be within 550 ppm above the outdoor concentration.

For thermal comfort, ISO 7730 [18] specifies the range of operative temperature and relative humidity (RH) for the classrooms with sedentary activity, given a typical clothing insulation value (Iclo) of 0.5 for summer and 1.0 for winter.

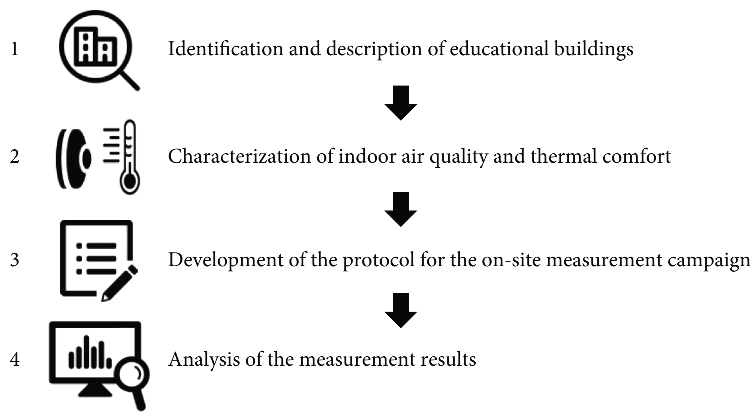


FIGURE 1: Research methodology.

In summer, the recommended operative temperature is between 23 and 26°C, and relative humidity is 60%. In winter, the operative temperature is 20 to 24°C, while the relative humidity is 40%.

According to Kumar et al. [29], the operative temperature (T_{op} (°C)) can be calculated by

$$T_{op} = \frac{(T_r + T_a)}{2} \quad (0 < V_a < 0.2\,\mathrm{m/s}),$$
$$T_{op} = \frac{\left(T_r + \left(T_a \times \sqrt{10V_a}\right)\right)}{\left(1 + \sqrt{10V_a}\right)} \quad (V_a > 0.2\,\mathrm{m/s}), \tag{1}$$

where T_a denotes the air temperature, V_a is the air velocity, and T_r is the mean radiant temperature given by the measurement instrument.

Table 1 summarizes the typical clothing insulation value indicated by ISO 7730 [18] and ASHRAE 55 [17].

Moreover, ISO 7730 [18] stipulates that the actual thermal comfort of occupants needs to be assessed using a thermal sensation vote (TSV) on a 7-point scale, which should be gathered 30 minutes after they have remained in a steady state in a stable thermal condition.

It should be noted that apart from these international standards, relevant national standards and guides should also be considered. The one with stricter criteria should be followed to meet the requirements at both national and international levels.

2.3. Development of the Protocol for the On-Site Measurement Campaign. To conduct the measurement campaign for data collection, a protocol needs to be developed and confirmed with the schools, which describes the measurement process, sensor deployment, and data collection methods. The measurement should follow the premise of avoiding interference in teaching activities in any case. Hence, background information about classrooms, students, and class schedules should be obtained in advance.

The number of sensors depends on the size of the classroom. Mahyuddin and Awbi [31] concluded that one sensor is needed for a space with a floor area below 100 m^2 and three or more sensors for rooms of over 200 m^2 in area. For minimum accuracy of sensors, ASTM D6245-18 [32] and ASHRAE 55 [17] require a ±5% of the measurement range for CO_2 concentration, ±0.2°C for air temperature, ±1°C for mean radiant temperature, and ±5% for relative humidity. The calibration and pretest are recommended to prevent malfunction and reading drift.

The deployment of the sensor should follow the criteria established by ASTM D6245-18, ASHRAE 55 [17], and ISO 7726 [33]. ASHRAE 55 [17] specified that the sensor should be located at least 1 m inward of the center of each room's walls, while ASTM D6245-18 [32] recommended locating sensors preferably 2 m away from the following: (i) CO_2 sources (e.g., people in space), (ii) ventilated air with low CO_2 concentration (e.g., windows and doors), and (iii) heat sources (e.g., radiators and heaters).

No recommendation was made by ASTM D6245-18 [32] regarding the height that the sensor should be placed. However, the experimental study by Mahyuddin et al. [34] indicated that the CO_2 sensor should be placed within the occupant's breathing zone, in a range of 0.75-1.80 m above ground, while 1.00-1.20 m is preferred. For the measurement of thermal parameters, ISO 7726 [33] specifies the heights of 0.60 or 1.10 m, which correspond to the occupant's abdominal level when sitting and standing, respectively. To clarify open issues such as sensor location, height, and recording interval, a specific review of sensor deployment based on relevant case studies was conducted and is summarized in Table 2.

For the collection of TSV, relevant research pointed out that children may have difficulties understanding the concept of thermal comfort and expressing their thermal sensations; thus, the TSV graph should be designed in the most understandable way possible for them [42, 43].

2.4. Analysis of the Measurement Results. Firstly, IAQ and thermal comfort should be characterized, respectively, referring to the requirements of relevant standards. Statistical analysis needs to be performed to examine the correlation between relevant influential factors and IAQ/thermal comfort, such as season, climate, education level, geographic location of the building, year of construction, occupancy, ventilation strategy, and heating/cooling mode of the

Table 1: Typical clothing insulation value by item (adapted from [30]).

Item	Iclo
Underwear	
Panties	0.03
T-shirt	0.12
Upper extremities	
Shirt—sleeveless	0.15
Shirt—long sleeve	0.25
T-shirt—sleeveless	0.09
T-shirt—long sleeve	0.20
Light dress	0.20
Cardigan	0.20
Sweater	0.28
Jacket	0.35
Lower extremities	
Long trousers	0.25
Shorts/thin skirt	0.06
Socks	0.03
Closed shoes	0.04
Semiclosed shoes	0.02
Accessories	
Scarf	0.08
Cap	0.50
Mask	0.02
Chair type	
Normal	0.10

classroom. The measurement data usually has a hierarchical structure, as several classrooms or schools are measured in the same educational level, climate zone, and seasons. Hence, the hierarchical linear model should be applied for the statistical analysis. This model classifies the measurement from the same schools, educational level, climate zone, and/or seasons into identical groups and analyzes the statistical differences within and between groups. Relevant influential factors should be defined as independent variables, while indoor CO_2 concentration, operative temperature, and relative humidity are dependent variables.

Then, a simultaneous analysis of IAQ and thermal comfort must be conducted. Both aspects should be analyzed concurrently following the specified requirements. In addition, the representative scenarios that often lead to good/poor IAQ and thermal comfort need to be characterized based on the identified influential factors. Clustering analysis can extract key information from massive data by assigning the samples that share similarities into the same clusters, and highlighting their main features [44], which was applied to identify representative scenarios. Notably, to improve the readability and interpretability of the clustering results, numerical variables should be converted to categorical variables. K-mode clustering was applied in this study, since it is a widely used technique to cluster categorical data. It can identify K-representative clusters with the main features represented by the centroids [45], while the number of clusters k can be identified by the Elbow method [46].

3. Implementation

This section elaborates on the implementation of this study in detail, following the proposed methodology (Section 2). The research characterized and assessed IAQ and thermal comfort in primary and secondary schools in Catalonia, Spain.

3.1. Identification and Description of Educational Buildings. The sample schools were identified and contacted with the help of the Catalan government (Generalitat de Catalunya), but the participation of schools and students in this research completely depended on their willingness. Catalonia is primarily in a Mediterranean climate but has 3 specific climatic zones: Coastal Mediterranean, Continental Mediterranean, and Mountain. The coastal area has typical characteristics of a Mediterranean climate, with warm summers, moderately cold winters, and little rain. The continental region has cold winters and hot weather in summers. In mountainous areas, summers have mild temperatures, but there are high rainfall and snow in winters [47]. In the Coastal Mediterranean climate, Barcelona Metropolitan Area has a temperate climate (Csa in the Köppen climate classification), while Tarragona has a humid subtropical climate with hot summers (Cfa) [48].

In this study, a total of 9 primary and 7 secondary schools were selected, which are located in the aforementioned 4 climate zones and 3 geographic locations (city center, suburb, and rural area). These schools were built between 1953 and 2016, while 5 of them were built before 1979 when the first national standard NBE-CT-79 [49] regulating building thermal conditions was developed. Another 5 schools were constructed between 1979 and 2006, complying with the NBE-CT-79 standard but completely relying on natural ventilation. The remaining 6 schools were built after the establishment of the Spanish Technical Building Code in 2006. Table 3 summarizes the U-values of construction elements of sample schools. These schools are designed with mechanical systems, but it was found that they did not work during the measurement campaign. To distinguish them from the naturally ventilated schools, their ventilation type is labeled as "free-running." In addition, all schools are equipped with radiators but without any cooling system.

To avoid bias in sample selection, 2 classrooms were selected in each school, corresponding to different age groups. In primary schools, classrooms with 5- and 9-year-old students were selected, while in secondary schools, 12- and 16-year-old students' classrooms were selected. One primary school only agreed to measure two classes that both have 9-year-old students. The volume of these classrooms ranges from 114.3 to 249.3 m^3, with an average of 157.7 m^3. The total area of windows and doors varies greatly, from 0.3 to 9.4 m^2 and 1.4 to 3.9 m^2, with an average of 4.5 and 2.1 m^2, respectively. Table 4 summarizes the characteristics of selected schools and classrooms.

Table 2: Case study review on measurement protocol.

Reference	Topic	Year	Region	Season	Education level	Number of room	Measured parameter	Number of instrument	Accuracy	Sensor location	Sensor height	Recording interval
[24]	IAQ TC	2019	Cyprus	Winter	Secondary	4	CO_2 T_a RH T_g V_a	CO_2: 1 TC: 1	±50 ppm ±0.2°C ±3.5% ±0.3°C ±0.01 m/s	Interior perimeter*	1.1 m	5 min
[35]	IAQ TC	2021	China	Winter	Primary	4	CO_2 T_a RH T_g V_a	CO_2: 2 TC: 5	±50 ppm ±0.6°C ±3% ±0.5°C ±0.03 m/s	CO_2: front and back TC: center and 4 corners	CO_2: 0.9 m TC: 1.1 m	\
[28]	IAQ TC	2021	Spain	Spring Winter	Primary	2	CO_2 T_a RH	1	±50 ppm ±0.6°C ±3%	Interior perimeter	1.5 m	15 min
[1]	IAQ TC	2021	UK	Spring Summer	Primary	9	CO_2 T_a T_g V_a RH	1	±50 ppm ±0.6°C ±0.6°C ±0.1 m/s \	Student area	1.1 m	1 min
[36]	IAQ	2019	China	Spring	Primary	3	CO_2	1	±50 ppm	Interior perimeter	1.0 m	5 min
[6]	IAQ	2020	UK	Spring Summer Winter	Primary	29	CO_2	1	±50 ppm	\	1.1 m	5 min
[37]	IAQ	2020	Pakistan	Winter Summer	Primary	11	CO_2	1	±50 ppm	Classroom center	1.8 m	1 min
[38]	IAQ	2021	Spain	Spring	Primary Secondary	18	CO_2	1	±50 ppm	Student area	1.0 m	2 min
[39]	IAQ	2022	Nepal	Summer	Secondary	7	CO_2	1	±50 ppm	Classroom center	1.1 m	10 min
[20]	TC	2018	India	Summer Winter	Primary Secondary	4	T_a RH T_g V_a	1	±0.35°C ±2.5% ±3% ±0.25°C	Classroom center	\	15 min

Table 2: Continued.

Reference	Topic	Year	Region	Season	Education level	Number of room	Measured parameter	Number of instrument	Accuracy	Sensor location	Sensor height	Recording interval
[40]	TC	2019	Greece	Winter	Secondary	1	T_a T_{op} RH V_a	1	\	Student area	1.2 m	5 min
[22]	TC	2020	China	Winter	Primary Secondary	26	T_a RH T_g V_a W_{solar}	5	±0.3°C ±5% ±2°C ±0.05 m/s ±2%	Center and 4 corners	1.5 m	10 min
[41]	TC	2020	UK	Spring Summer Autumn Winter	Primary	32	T_a RH V_a T_r	1	±0.3°C ±0.8% ±0.04 m/s ±0.1°C	Student area	1.1 m	5 min
[19]	TC	2021	Spain	Summer	Primary	3	T_a RH T_g V_a	3	±0.25°C ±3% ±0.25°C ±0.2 m/s	Front and back and classroom center	1.1 m	15 min
[23]	TC	2021	Nepal	Autumn	Secondary	24	T_a RH T_g V_a	1	±0.5°C ±5% ±0.3°C ±0.015 m/s	Classroom center	1.1 m	\

T_a: air temperature; T_g: globe temperature; T_r: mean radiant temperature; RH: relative humidity; V_a: air velocity; W_{solar}: solar radiation intensity. Interior perimeter*: along the wall.

Table 3: U-value of construction elements of investigated schools.

Construction year	Roof (W/m^{2}K)	Exterior wall (W/m^{2}K)	Window (W/m^{2}K)	Reference
1953-1979	1.37-1.92	1.42-3.03	5.70	Gangolells and Casals [50]
1979-2006	0.7-1.4	1.2-1.8	5.70	NBE-CT-79 standard [49]
2006-2016	0.38-0.45	0.66-0.82	1.6-2.0	Spanish Technical Building Code [51]

3.2. Characterization of Indoor Air Quality and Thermal Comfort. Following the defined methodology (Section 2.2), the Spanish standards and guides were reviewed and considered.

For IAQ, compared with the international standard EN 16798-1 [9], the RITE standard [52] specified a lower CO_2 concentration threshold for the classrooms. The Ventilation Guide for Indoor Spaces recently proposed by the Spanish Institute of Environmental Assessment and Water Research [53] even indicated a stricter limit to prevent massive exposure to the SARS-CoV-2 virus in the schools. Table 5 summarizes the IAQ levels with the corresponding CO_2 concentrations applied in this study, assuming an outdoor CO_2 concentration of 420 ppm as recommended by IDAEA [53]. The IDA2 level is the minimum IAQ requirement for the classrooms stipulated by the RITE standard [52], and the safe level represents the optimum requirement by IDAEA [53].

For thermal comfort, Royal Decree 486/2004 [54] established the minimum acceptable requirements for typical sedentary workplaces, where the operative temperature must be between 17 and 27°C and relative humidity must be within 30 to 70%. The RITE standard [52] proposed the optimum thermal requirement with stricter comfort zones given the same assumptions made by ISO 7730 [18]. As both standards do not specify the requirements for the mild season (i.e., spring), it is assumed that the lower and upper limits of operative temperature and relative humidity for summer and winter establish the comfort zone for spring.

The minimum and optimum IAQ and thermal requirements applied in this study are summarized in Table 6.

3.3. Implementation of the Measurement Protocol in the On-Site Measurement Campaign. The measurement campaign was conducted from April 2022 to January 2023 (Figure 2), following the protocol defined in Section 2.3.

The technical specifications of the measurement instrument are summarized in Figure 3. The sensor was calibrated by the manufacturer and pretested by researchers in advance. All readings were recorded in a 1-minute interval.

The measurement lasted all day long during school hours, generally from 9:00 to 15:00 in spring and winter, while the school usually began and ended one hour earlier in summer. The measurement instrument was deployed in the classroom for 10 minutes before the beginning of the first class and was always preferentially placed in the center of the classroom at a 1.1 m height (whenever feasible). In classrooms with high occupancy where the desks and seats could not be moved, the sensor was located at the closest point to the center. A distance of 2 m was ensured from any disturbance (students, windows, doors, walls, and radiators). The location of the equipment was confirmed with the teachers before the class to avoid affecting teaching activities and the movement of students.

To protect the privacy of students during the measurement campaign, the Catalan government prohibited the researchers to conduct written surveys and to take photos and video records. In this context, researchers collected information about students' gender and clothing and recorded the change in occupancy (students and teachers) and the behavior of opening windows and doors in the classroom through observation and notes during the entire survey.

In each measurement day, the TSV was collected by the teachers one time in each classroom, usually at the end of the class to ensure that the students had been in a sedentary state for 30 minutes. Teachers explained the concept of thermal sensation and showed TSV graphs (Figure 4) in advance, to ensure that all students understood correctly. The TSV graphs are specifically designed for this study based on the opinions of native Spanish speakers and teachers.

3.4. Analysis of the Measurement Results. Following the methodology defined in Section 2.4, IAQ and thermal comfort were assessed, respectively, following the thresholds of CO_2 concentration, operative temperature, and relative humidity indicated in Tables 5 and 6. Relevant influential factors of IAQ and thermal comfort were analyzed statistically. The collected measurement data has a 4-level hierarchical structure, season, climate, educational level, and school, which was defined in the model.

Then, the simultaneous analysis of IAQ and thermal comfort was performed. Depending on the satisfaction of the minimum and optimum requirements (Table 6), IAQ and thermal comfort were classified into 3 categories: (1) good (the optimum requirement is achieved), (2) acceptable (the minimum requirement is accomplished), and (3) bad (both requirements are not satisfied). IAQ and thermal comfort of the classrooms were characterized concurrently according to these 3 categories given the measured time.

The representative scenarios within each category were identified with K-mode clustering analysis. The occupancy ratio of the classroom and opening area of windows and doors were categorized to improve the readability and interpretability of the clustering results, as shown in Table 7. The categorization was based on the characteristics of the measured data (i.e., the range of occupancy ratio and opening areas), due to the lack of reference values.

The analysis was performed on the Google Colab platform using Python 3.7.3 [55]. Python packages of NumPy [56], Pandas [57], and Statsmodels [58] were adopted for data processing and statistical analysis. Kmodes [59] and Kneed [60] packages were used for clustering analysis and

Table 4: Characteristics of selected schools and classrooms.

School code	Climate type	Education level	Geographic location	Construction year	Ventilation type	Room code	Student age	Number of student	Volume (m^3)	Window area (m^2)	Door area (m^2)
BP1	Coastal Mediterranean (Csa)	Primary	City center	1975	NV	I4	5	17	145.9	7.0	3.4
						4T	9	20	144.3	6.6	1.7
BP2	Coastal Mediterranean (Csa)	Primary	Suburb	1987	NV	I4	5	23	180.2	4.2	1.7
						4T	9	23	165.0	3.6	1.8
BP3	Coastal Mediterranean (Csa)	Primary	City center	1980	NV	4TA	9	20	145.7	6.6	1.7
						4TB	9	20	150.3	4.9	1.7
LP1	Continental Mediterranean	Primary	City center	2007	FR	I4	5	22	190.1	1.2	3.7
						4T	9	25	146.9	5.6	1.6
LP2	Continental Mediterranean	Primary	Rural	1976	NV	I4	5	14	169.3	2.5	3.2
						4T	9	24	169.1	5.9	1.6
TP1	Coastal Mediterranean (Cfa)	Primary	City center	1980	NV	I4	5	12	249.3	3.9	1.8
						4T	9	20	173.2	4.1	3.4
TP2	Coastal Mediterranean (Cfa)	Primary	Rural	2010	FR	I4	5	12	154.7	2.1	3.9
						4T	9	16	135.4	3.0	1.4
GP1	Mountain	Primary	Rural	2006	FR	I4	5	23	164.8	3.9	3.6
						4T	9	26	133.4	3.3	1.6
GP2	Mountain	Primary	Suburb	1993	NV	I4	5	11	147.7	0.3	3.4
						4T	9	11	197.0	2.3	2.1
BS1	Coastal Mediterranean (Csa)	Secondary	Suburb	1975	NV	1ESO	12	15	136.7	4.8	1.4
						4ESO	16	15	138.0	3.0	1.4
LS1	Continental Mediterranean	Secondary	Suburb	1953	NV	1ESO	12	16	148.2	2.4	1.7
						4ESO	16	21	152.5	2.3	1.9
LS2	Continental Mediterranean	Secondary	Rural	2016	FR	1ESO	12	26	154.0	7.7	1.8
						4ESO	16	24	154.2	7.7	1.8
TS1	Coastal Mediterranean (Cfa)	Secondary	City center	1986	NV	1ESO	12	11	176.4	9.4	1.7
						4ESO	16	22	176.6	8.1	1.7
TS2	Coastal Mediterranean (Cfa)	Secondary	Suburb	2012	FR	1ESO	12	19	156.3	5.1	1.7
						4ESO	16	28	158.7	5.1	1.7
GS1	Mountain	Secondary	Rural	2008	FR	1ESO	12	15	135.2	6.5	1.9
						4ESO	16	14	139.8	6.5	1.9
GS2	Mountain	Secondary	City center	1956	NV	1ESO	12	18	114.3	1.2	1.6
						4ESO	16	24	148.3	4.5	1.6

FR: free-running; NV: natural ventilation.

Table 5: IAQ levels with corresponding indoor CO_2 concentration limit.

IAQ level	Safe	IDA1	IDA2	IDA3	IDA4
Indoor CO_2 concentration (ppm)	700	770	920	1220	1620

Table 6: IAQ and thermal comfort requirements.

	IAQ	Thermal comfort		
Parameter	CO_2 concentration		Operative temperature	Relative humidity
Minimum requirement	920 ppm (IDA2 level)		17-27°C	30-70%
		Spring	21-25°C	40-60%
Optimum requirement	700 ppm (safe level)	Summer	23-25°C	45-60%
		Winter	21-23°C	40-50%

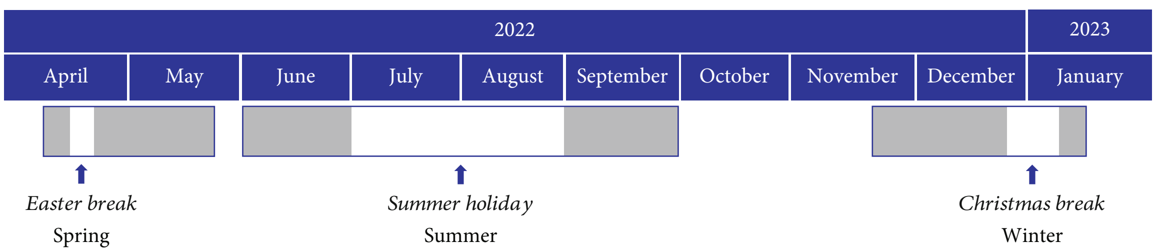


Figure 2: Timeline for the measurement campaign.

Model	Photo	Parameter	Range	Resolution	Accuracy
Delta ohm HD32.3		CO_2	0–5000 ppm	1 ppm	±50 ppm
TP3275 globe temperature		Air temperature	−20–80°C	0.1°C	±0.1°C
probe, HP3217B4 IAQ probe,		Relative humidity	0–100%	0.1%	±2%
AP3203 omnidirectional		Globe temperature	−30–120°C	0.1°C	±0.1°C
hotwire probe		Air velocity	0.02–5 m/s	0.01 m/s	±0.05 m/s

Figure 3: Technical specifications of the measurement instrument.

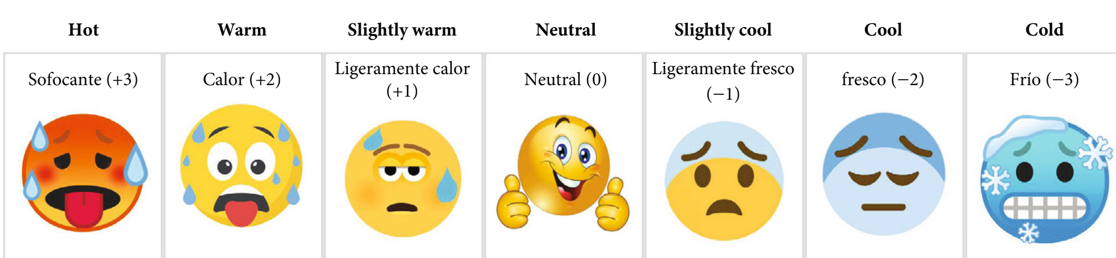


Figure 4: Thermal sensation vote graphs used in this study.

Table 7: The categorization of occupancy ratio and total opening area.

		Occupancy ratio of the classroom		
Category	Empty	Low	Medium	High
Categorization value	0	<0.066* person/m^3	0.066-0.133 person/m^3	>0.133 person/m^3
		Total opening area of windows and doors		
Category	Closed	Small	Medium	Large
Categorization value	0	<3 m^2	3-6 m^2	>6 m^2

*Corresponding to 10 people in a classroom with 150 m^3.

Table 8: Summary of measured indoor thermal parameters in each season.

Parameters	Season	Mean	Min	Median	Max	Std.
CO_2 concentration (ppm)	Spring	744	347	669	2446	291
	Summer	593	341	517	4015	294
	Winter	1194	348	904	4950	805
Operative temperature (°C)	Spring	22.53	17.93	22.17	29.49	2.16
	Summer	28.18	22.29	28.18	36.44	2.29
	Winter	21.24	12.52	21.40	33.41	1.78
Air temperature (°C)	Spring	22.68	18.40	22.30	29.73	2.20
	Summer	28.22	22.20	28.20	35.33	2.31
	Winter	21.43	10.53	21.55	36.70	1.87
Globe temperature (°C)	Spring	22.45	17.70	22.10	29.40	2.14
	Summer	28.15	22.30	28.10	36.90	2.29
	Winter	21.15	12.90	21.30	34.38	1.81
Mean radiant temperature (°C)	Spring	22.38	17.38	22.03	29.33	2.12
	Summer	28.15	22.30	28.18	38.83	2.30
	Winter	21.07	12.95	21.13	34.33	1.97
Relative humidity (%)	Spring	44.9	24.2	44.6	67.1	9.3
	Summer	50.2	26.1	51.6	71.7	8.1
	Winter	47.0	23.7	46.3	69.2	9.3
Air velocity (m/s)	Spring	0.025	0.000	0.000	1.398	0.071
	Summer	0.064	0.000	0.013	1.443	0.128
	Winter	0.021	0.000	0.000	0.723	0.054

elbow point detection, and Matplotlib [61] and Seaborn [62] were used for data visualization.

4. Results

This section presents the assessment of results regarding IAQ, thermal comfort, and simultaneous analysis of both aspects.

4.1. Statistical Summary of Measured Indoor Environmental Parameters. Table 8 summarizes the statistical details of measured indoor environmental parameters in investigated classrooms by season. The mean indoor CO_2 concentration in summer was 593 ppm, which met the safe level requirement (700 ppm) by IDAEA [53]. In spring, the value was 774 ppm and achieved the minimum acceptable IAQ requirement-IDA2 level (920 ppm) specified by the national regulation RITE standard [52]. In contrast, the mean indoor CO_2 concentration in winter reached 1194 ppm, suggesting a potential of poor IAQ in classrooms. The mean air velocity in summer (0.064 m/s) was much higher than in spring (0.025 m/s) and winter (0.021 m/s). Due to the use of heating systems, the classrooms had similar mean operative temperatures in winter (21.24°C) and spring (22.53°C); both were within the comfort range specified by the RITE standard. However, the average operative temperature in summer reached 28.18°C, which was even higher than the maximum acceptable temperature limit (27°C) specified by Royal Decree 486 [54], indicating a high risk of thermal discomfort. The average indoor relative humidity ranged from 44.9% to 50.2%, which were all within the comfort range specified by the RITE standard.

4.2. Indoor Air Quality Analysis. Section 4.2.1 discusses the assessment results of measured classrooms, and Section 4.2.2 analyzes relevant influential factors.

Table 9: Descriptive statistics of the measurement results.

Room code	CO_2 concentration (ppm)					Operative temperature (°C)					Relative humidity (%)				
	Min	Median	Mean	Max	Std.	Min	Median	Mean	Max	Std.	Min	Median	Mean	Max	Std.
BP1_4T	378	642	648	1208	156	17.50	21.52	23.80	36.44	4.53	25.3	40.9	41.4	60.6	8.9
BP1_I4	367	562	584	904	123	18.05	21.60	22.67	27.73	2.80	24.2	36.5	39.8	58.1	10.9
BP2_4T	385	688	1083	3443	797	18.12	20.42	22.56	29.07	3.94	32.1	53.2	49.2	69.1	12.7
BP2_I4	381	714	751	1879	302	17.93	20.50	21.65	26.60	2.84	34.2	52.6	48.4	61.5	9.4
BP3_4TA	367	555	560	990	125	19.54	23.72	25.35	32.72	4.28	30.0	36.1	36.4	46.5	4.1
BP3_4TB	394	579	608	1073	133	20.07	22.60	25.25	33.65	4.67	26.1	33.7	33.5	45.8	4.9
BS1_1ESO	358	600	756	2259	455	18.64	20.58	21.96	26.53	2.52	53.1	56.0	57.3	69.2	3.4
BS1_4ESO	414	762	831	1963	349	19.50	22.29	23.31	27.44	2.45	48.7	55.8	56.1	65.1	3.3
GP1_4T	379	637	821	2177	415	19.26	23.40	23.95	30.28	2.90	37.3	47.7	48.2	68.1	5.0
GP1_I4	372	515	536	977	119	12.52	22.39	23.71	30.90	3.93	33.4	41.3	42.8	56.2	4.5
GP2_4T	384	772	881	1918	368	19.48	24.61	23.73	25.84	1.78	38.6	46.6	46.4	51.2	2.4
GP2_I4	347	676	727	1421	297	17.84	24.84	25.02	31.88	3.36	26.1	40.7	40.5	50.3	5.7
GS1_1ESO	356	669	923	2446	525	18.66	23.47	25.04	32.61	3.43	33.2	46.5	46.0	58.4	5.8
GS1_4ESO	393	922	1017	1947	488	18.11	21.05	24.08	32.57	4.94	32.7	43.8	43.3	54.0	4.9
GS2_1ESO	605	1600	1910	4602	886	18.25	21.39	22.05	26.01	2.27	34.5	53.5	51.8	67.5	8.3
GS2_4ESO	377	983	1184	3473	758	16.14	22.43	22.54	26.61	2.16	32.0	50.0	48.1	61.9	8.5
LP1_4T	348	714	827	1839	384	18.88	23.94	25.09	32.43	3.48	34.7	41.9	42.4	53.1	4.0
LP1_I4	388	848	901	1793	328	18.05	21.15	22.88	29.24	3.86	38.3	44.7	45.6	53.9	3.6
LP2_4T	393	912	1144	3333	720	16.07	18.90	21.90	29.40	4.80	43.7	52.6	53.1	67.3	5.5
LP2_I4	419	758	882	2012	368	19.34	23.23	23.92	29.00	3.03	33.2	47.4	49.2	67.9	9.7
LS1_1ESO	361	1077	1218	2934	768	20.64	24.14	25.68	31.87	3.40	31.2	43.7	44.3	53.0	3.8
LS1_4ESO	369	763	1048	4901	852	19.10	21.82	24.14	32.87	4.60	24.2	46.9	50.0	63.9	8.2
LS2_1ESO	410	878	1211	3779	796	20.22	23.09	24.02	29.25	2.70	40.6	57.3	54.9	64.3	6.3
LS2_4ESO	423	784	1275	3510	877	20.58	23.35	24.59	28.57	2.28	49.2	56.3	55.7	61.7	2.7
TP1_4T	363	493	663	1370	280	18.49	26.36	24.03	27.78	3.17	34.4	43.6	45.3	54.8	5.7
TP1_I4	341	472	581	1180	244	16.33	20.47	21.87	27.07	3.49	36.9	52.6	52.3	58.9	3.6
TP2_4T	359	586	616	1351	202	17.18	21.54	22.62	29.53	3.34	39.7	45.0	47.8	60.7	6.5
TP2_I4	346	517	541	940	139	15.22	25.02	24.29	28.07	2.59	23.7	36.1	42.1	71.7	13.5
TS1_1ESO	491	2894	2572	4950	1641	19.30	21.65	24.16	30.25	4.12	46.9	59.8	59.9	65.6	3.8
TS1_4ESO	356	610	790	2490	419	18.65	22.18	23.70	30.04	3.45	39.9	52.6	52.4	63.8	5.4
TS2_1ESO	405	552	700	2612	413	17.65	27.55	25.72	33.41	3.49	27.8	48.9	49.8	67.1	7.7
TS2_4ESO	422	725	839	2348	368	16.90	22.98	24.47	31.63	4.59	33.5	45.1	46.5	68.7	8.1

4.2.1. Indoor Air Quality Assessment. Table 9 summarizes the statistical details of indoor CO_2 concentration in classrooms, and Figure 5(a) shows the IAQ assessment results of the measured classroom. In terms of the satisfaction of the minimum IAQ requirement (IDA2 level). On average, the IAQ of all investigated classrooms reached the IDA2 level nearly 71% of the time, whereas half of the classrooms were above the average level. Approximately 88% of the classrooms met the minimum requirement for up to 50% of the measured time.

For the achievement of the optimum IAQ requirement (safe level). In general, all the classrooms ensured a safe IAQ level 53% of the time, while 14 classrooms had a level above average. Over half of the classrooms met the optimum requirement for over 50% of the time in the measurement.

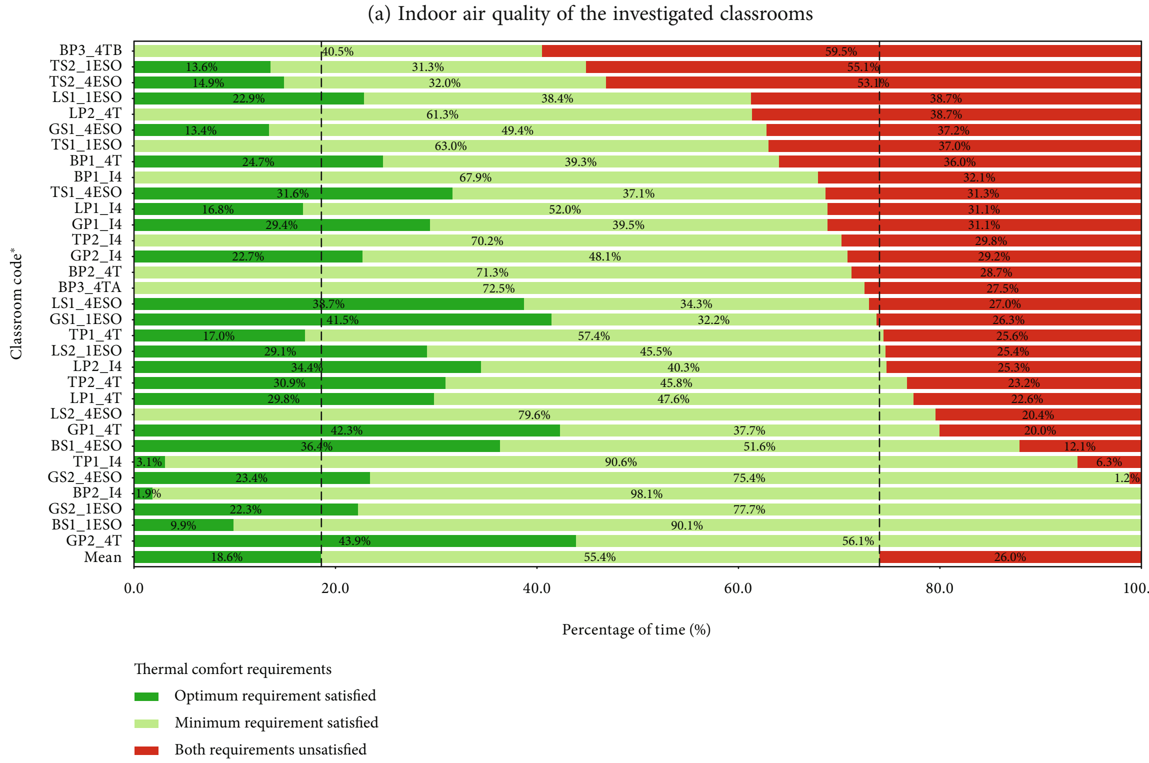
It is noteworthy that the initial CO_2 concentration of 81% of the measurements was below the threshold of safe level (700 ppm), but 8% exceeded the IDA2 level (920 ppm), which depends on whether the classroom was adequately ventilated at the end of the class in the previous day.

4.2.2. Influential Factor Analysis of Indoor Air Quality. Table 10 summarizes the statistical analysis results. For IAQ, correlated factors were found to be educational level, occupancy ratio, and opening area of windows and doors (ventilation strategy).

The most relevant factors are occupancy and ventilation, which determine the generation and removal of CO_2 in space. The results of statistical analysis indicated a positive correlation between the indoor CO_2 concentration and the occupancy ratio (person/m^3) and a negative correlation with the opening of windows and doors in the classroom. Both correlations are statistically significant with p values of less than 0.001. During the measurement campaign, classrooms

*The classroom code corresponds to the combination of school and room codes in Table 4.

(a) Indoor air quality of the investigated classrooms



*The classroom code corresponds to the combination of school and room codes in Table 4.

(b) Thermal comfort of the investigated classrooms

Figure 5: Indoor air quality assessment results of the investigated classrooms.

Table 10: Statistical analysis results.

Independent variable	Dependent variable: CO_2 concentration						Dependent variable: operative temperature						Dependent variable: relative humidity					
	Coef.	Std. err.	z	$P > \|z\|$	[0.025	0.975]	Coef.	Std. err.	z	$P > \|z\|$	[0.025	0.975]	Coef.	Std. err.	z	$P > \|z\|$	[0.025	0.975]
Season[T.Summer]	41.19	96.28	0.43	0.669	-147.51	229.89	6.43	0.76	8.42	<0.001	4.93	7.93	2.29	2.51	0.91	0.363	-2.64	7.21
Season[T.Winter]	385.13	97.27	3.96	<0.001	194.49	575.78	-3.34	0.77	-4.36	<0.001	-4.84	-1.84	6.68	2.52	2.65	0.008	1.75	11.61
Climate[T.Coastal (Cfa)]	-160.25	127.35	-1.26	0.208	-409.84	89.35	0.08	1.02	0.08	0.934	-1.91	2.08	1.37	3.35	0.41	0.683	-5.19	7.93
Climate[T.Coastal (Csa)]	-123.55	127.08	-0.97	0.331	-372.63	125.53	-0.90	1.02	-0.88	0.378	-2.89	1.10	0.51	3.35	0.15	0.879	-6.05	7.07
Climate[T.Mountain]	-125.66	121.84	-1.03	0.302	-364.46	113.15	0.55	0.98	0.56	0.574	-1.36	2.46	-6.03	3.21	-1.88	0.060	-12.32	0.26
Education[T.Secondary]	387.52	95.99	4.04	<0.001	199.39	575.66	-0.10	0.77	-0.13	0.895	-1.61	1.41	5.33	2.53	2.11	0.035	0.37	10.28
Building location[T.Rural]	-81.83	111.74	-0.73	0.464	-300.84	137.17	-0.44	0.90	-0.50	0.621	-2.20	1.31	5.87	2.95	1.99	0.046	0.10	11.64
Building location[T.Suburb]	-142.33	98.25	-1.45	0.147	-334.89	50.24	0.35	0.79	0.45	0.653	-1.19	1.90	3.14	2.59	1.22	0.224	-1.93	8.22
Construction year[T.Before 1979]	-1.72	116.39	-0.02	0.988	-229.83	226.40	-1.38	0.93	-1.48	0.138	-3.21	0.44	4.04	3.07	1.32	0.188	-1.98	10.05
Construction year[T.1979 to 2006]	216.80	121.75	1.78	0.075	-21.82	455.42	-0.84	0.98	-0.87	0.387	-2.76	1.07	4.75	3.21	1.48	0.139	-1.54	11.04
Heating Mode[T.On]	29.58	37.19	0.80	0.426	-43.31	102.47	2.50	0.11	22.10	<0.001	2.28	2.72	-8.80	0.37	-23.69	<0.001	-9.53	-8.07
Time	0.45	0.02	18.49	<0.001	0.40	0.49	0.01	0.00	66.58	<0.001	0.01	0.01	0.00	0.00	-10.65	<0.001	0.00	0.00
Occupancy ratio	2374.74	41.49	57.24	<0.001	2293.42	2456.06	3.22	0.12	26.24	<0.001	2.98	3.46	17.85	0.40	44.17	<0.001	17.06	18.64
Opening area of window	-102.44	2.20	-46.58	<0.001	-106.75	-98.13	-0.07	0.01	-10.79	<0.001	-0.08	-0.06	-0.53	0.02	-24.89	<0.001	-0.58	-0.49
Opening area of door	-71.54	3.21	-22.32	<0.001	-77.82	-65.26	-0.15	0.01	-16.14	<0.001	-0.17	-0.14	-0.36	0.03	-11.54	<0.001	-0.42	-0.30

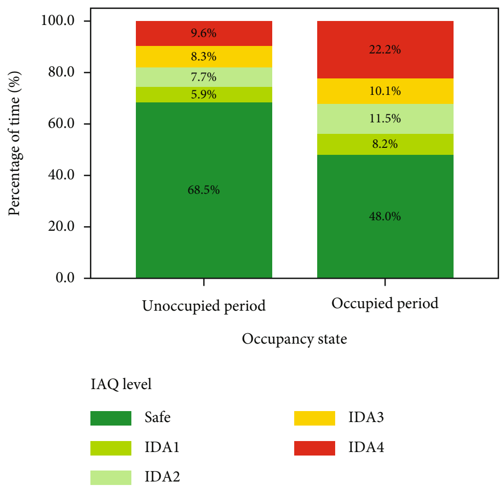


Figure 6: IAQ levels according to the occupancy state.

were occupied by students for around 70% of the time. Figure 6 shows the IAQ level during unoccupied and occupied periods. As expected, the proportion of the safe level significantly decreased during the occupied period, which implies an increased infection risk due to the presence of the students.

Natural ventilation enables the renewal of indoor air but is manually controlled by opening windows and doors. During the measurement campaign, the researchers did not intervene in the opening of windows and doors in the classrooms. Hence, the occupants' ventilation behavior in schools was observed. The outcomes showed that classrooms had cross ventilation up to 54% of the time. The ventilation was carried out only by opening doors 19% of the time, which is slightly higher than only by windows (15%), while for the rest of the time, the windows and doors were completely closed (no ventilation). Cross ventilation is the most effective strategy for improving indoor air quality in the classroom. As seen in Figure 7, cross ventilation maintained the IAQ above the IDA2 level in 90% of the observations and at a safe level in 70% of the observations. In comparison, ventilation by windows had better effects than doors, which is consistent with the findings of other studies [6, 63].

The statistical analysis results show that the CO_2 concentration in the classroom is statistically different in winter than in spring and summer. As seen in Figure 8, classrooms had better IAQ in spring and summer than in winter. In summer, the IAQ was above the IDA2 level more than 90% of the time, compared with less than 50% in winter. The average indoor CO_2 concentration in winter was 1194 ppm, which is significantly higher than that of spring (744 ppm) and summer (593 ppm). There is no significant difference in terms of occupancy for each season. Therefore, such a discrepancy was mainly due to different ventilation practices in schools. In summer and spring, the classrooms had cross ventilation for nearly 78% and 69% of the time, respectively, compared to less than 29% in winter. In winter, the windows and doors were completely closed for 23% of the time, and ventilation was carried out mainly by opening doors, which is consistent with the fact that the classroom occupants declined to open the window due to the low outdoor temperatures.

Moreover, there is a statistically significant difference in CO_2 concentration between educational levels (with p values < 0.001), while the rest of the factors are not correlated. In general, primary schools had better IAQ than secondary schools (Figure 9). The average CO_2 concentration of primary schools was 744 ppm, while that of secondary schools was 1083 ppm. Such a discrepancy is believed caused by occupancy, generation ratio, and ventilation. The average occupancy ratio of primary classrooms was 20% lower than that of secondary classrooms, while primary students generate around 28% less CO_2 than secondary students [64]. Besides, primary classrooms had more cross ventilation than secondary classrooms by 10% on average.

4.3. Thermal Comfort Analysis. Section 4.3.1 discusses the assessment results of thermal comfort, Section 4.3.2 analyzes relevant influential factors, and Section 4.3.3 assesses the actual thermal comfort of students.

4.3.1. Thermal Comfort Assessment. Table 9 summarizes the statistical details of operative temperature and relative humidity in classrooms, and Figure 5(b) shows the assessment results of thermal comfort in the measured classrooms.

In general, the investigated classrooms met the minimum thermal requirement (Table 6) 74% of the time, while 14 classrooms were above average. More than 90% of the classrooms achieved the minimum requirement at least 50% of the measured time. In contrast, the optimum thermal requirement was met only 19% of the measured time, while 8 classrooms did not meet the optimum requirement in all the measurements.

Table 11 summarizes the accomplishment of minimum and optimum thermal requirements in terms of operative temperature and relative humidity. Regarding the satisfaction of the minimum thermal requirement, the relative humidity was within the required range for 97% of the measured time, but the operative temperature exceeded the upper limit for nearly 23% of the time. For the optimum thermal requirement, the relative humidity was within the required range 53% of the time, but the optimum temperature was achieved only 36% of the time.

Concerning the initial thermal conditions of the classrooms during the measurement campaign, only 17% of the measurements achieved the optimum requirement, while 62% met the minimum requirement. Notably, 21% of the measurements initially failed to meet the minimum thermal requirements due to a high indoor temperature of above 27°C in summer.

4.3.2. Influential Factor Analysis of Thermal Comfort. The statistical analysis results (Table 10) indicated that season, occupancy ratio, ventilation strategy, and heating mode of the classroom are influential factors of thermal comfort.

The results demonstrate that operative temperature is statistically correlated with the season with a p value < 0.001, while relative humidity is independent of the season. In

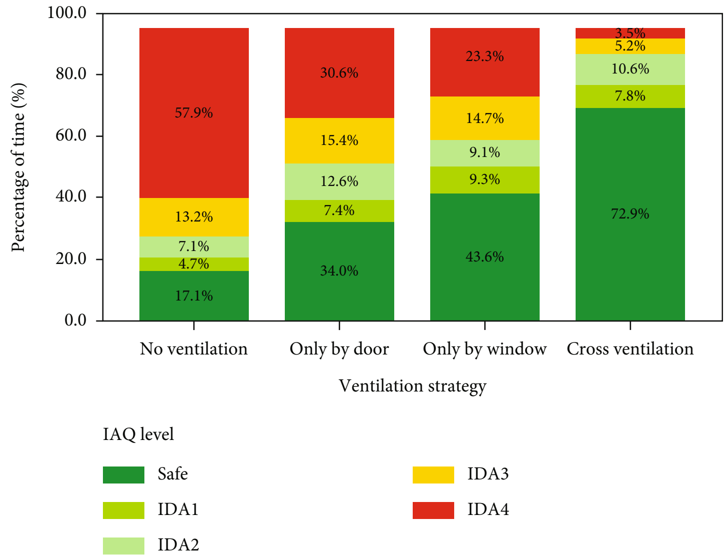


Figure 7: IAQ levels according to the ventilation strategy.

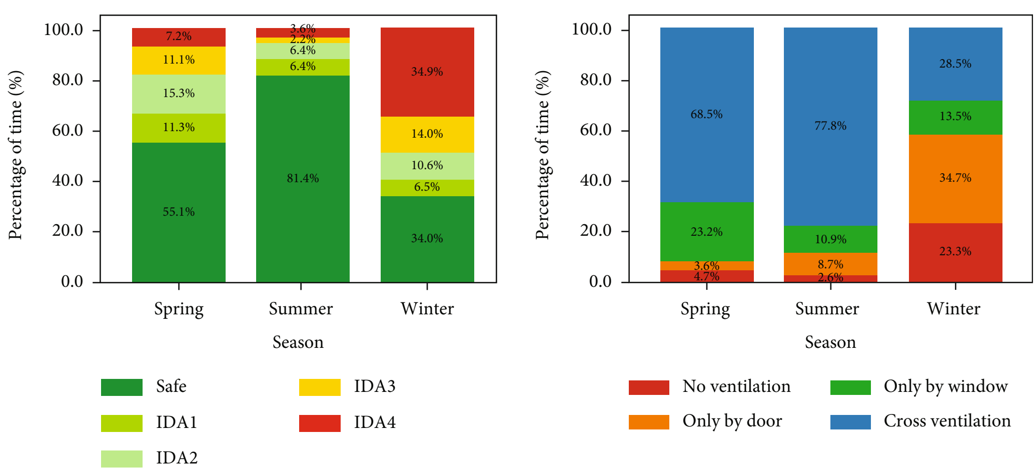


Figure 8: IAQ levels and ventilation by season.

addition, both indoor operative temperature and relative humidity are not correlated with the climate and geographic location of the building, which is mainly attributed to the fact that the indoor thermal condition of the classrooms was regulated by the adaptive behavior of the occupants and the heating systems. The average operative temperature in spring was 22.53°C, slightly higher than that in winter (21.24°C); both were within the required range of optimum temperature. In spring and winter, the minimum temperature requirement was achieved more than 95% of the measured time, whereas the satisfaction of the optimum temperature requirement was 14% higher in spring than in winter (Figure 10). In comparison, the average operative temperature in summer was 28.18°C. The indoor operative temperature exceeded the upper limit of the minimum acceptable value (27°C) during 67% of the measured time and exceeded the optimum temperature limit (25°C) nearly 93% of the time. During the summer measurement campaign, teachers and students frequently complained to the researchers that it was too hot to withstand, particularly in the afternoon.

Both operative temperature and relative humidity are statistically correlated with the occupancy, ventilation state, and heating mode of the classroom (with p values < 0.001). Temperature and relative humidity are positively correlated with the occupancy ratio, indicating that an increase in occupancy may lead to higher indoor operative temperature and relative humidity. Natural ventilation had a negative impact on the indoor thermal condition in general. As seen in Figure 11, ventilation brought in cool, dry air from outside in spring. On the contrary, it introduced a lot of heat from outdoor air into the classrooms in summer, leading to a significant reduction in the satisfaction of the optimum temperature requirement. Since heating systems were turned on in winter, ventilation had almost no impact on the indoor temperature, but it positively affects the indoor humidity as it removed the moisture from indoor air, which reduces

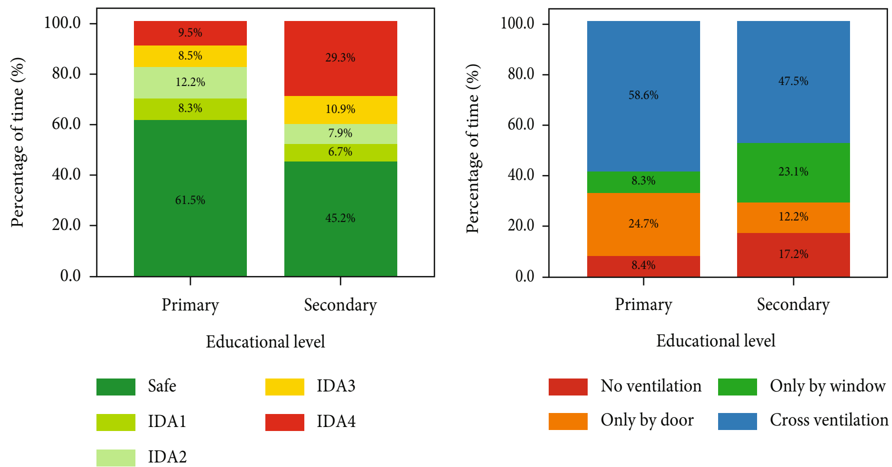


Figure 9: IAQ levels and ventilation by educational level.

Table 11: Satisfaction of minimum and optimum thermal requirements in terms of operative temperature and relative humidity.

	Minimum thermal requirement	Optimum thermal requirement
	Operative temperature	
Below the lower limit	0.5%	25.3%
Within the required range	76.8%	35.9%
Above the upper limit	22.7%	38.8%
	Relative humidity	
Below the lower limit	3.0%	28.0%
Within the required range	97.0%	53.2%
Above the upper limit	0.0%	18.8%

the condensation risk that may lead to the growth of mold. During the winter measurement, radiators in 3 classrooms were completely turned off during the measurement day. The analysis found that the overall satisfaction of the optimum temperature increased owing to the heating, but an overheating problem was detected (i.e., the temperature was above the optimum limit 13.3% of the time). This can be attributed to the lack of a thermostat that controls the heating system in almost all the classrooms. In addition, although heating systems evaporated the moisture in the air, the satisfaction of the optimum humidity requirement slightly dropped in general.

Although the indoor thermal condition is not statistically correlated with the building construction year, the analysis of winter data found that the schools built after 2006 had a higher proportion above the optimum temperature limit of 23°C by nearly 10% of the time on average (Figure 12), which suggests an overheating problem and potential waste of energy for heating.

4.3.3. Thermal Comfort of Students. During the measurement campaign, students' activity state, clothing, and actual thermal sensation were investigated. Measurement data revealed that students remained in a sedentary state for over 80% of the time in the classroom and performed light activities (such as having breakfast and doing craft projects) and medium activities (walking) for around 10% of the time, respectively.

The clothing insulation of students in each season is summarized in Table 12. It was observed that students wore fewer clothes than adults in general. The total students' clothing insulation value was lower than the recommended value of ISO 7730 [18] in all seasons. In addition, gender was a relevant factor of divergence since the average clothing insulation value was greater in female students than in male students.

Furthermore, students' actual thermal sensation votes were collected and analyzed. The TSV frequency values were 596 in spring, 599 in summer, and 592 in winter. In terms of educational centers, 55% of the TSV corresponded to primary schools and 45% were from secondary schools. Regarding gender, 49% collected were from female students and 51% were from male students. Figure 13 shows the distribution of students' TSV in each season. As shown, thermal neutrality reached the highest level in winter, while most of the students felt hot (from +1 to +3) in summer and felt between neutral (0) and a little bit hot (+1) in spring. The average values of students' TSV in spring, summer, and winter were 0.76, 1.26, and -0.04, respectively. Male students felt hotter than female students. In spring, summer, and winter, the average TSV of female students were 0.61, 1.08, and -0.26, while those of male students were 0.91, 1.41, and 0.16, respectively.

Linear regressions were established between the mean thermal sensation vote (MTSV) of students and the operative temperature at the time of TSV (Figure 14). The neutral temperature of primary schools was found to be lower than that of secondary schools in spring and winter, but they were

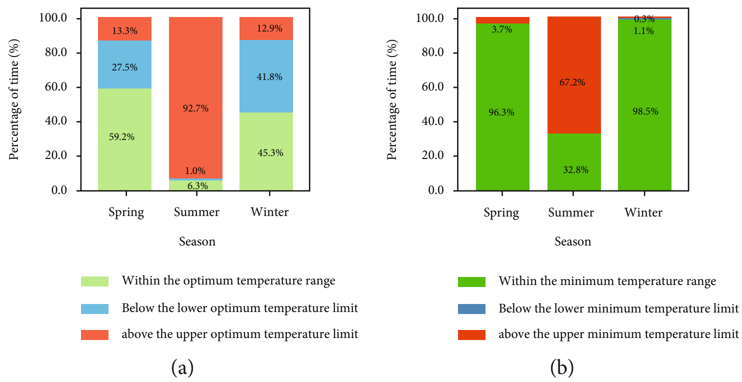


Figure 10: Thermal comfort assessment results of the investigated classrooms.

quite similar in summer. In comparison with secondary students, primary students have a higher metabolic rate per kg body weight, limited adaptive opportunities in classrooms, and more class schedules for outdoor activities. These factors result in a difference in their thermal perception and ultimately lead to a lower comfort temperature [5]. On average, the neutral temperatures in spring, summer, and winter were found to be 21.7°C, 25.3°C, and 21.0°C, respectively. These neutral temperatures are very close to the upper and lower limits of the optimum temperature range specified by the RITE standard [52]. The regressions had R^2 values of over 0.8 in summer, which indicates that over 80% of the variance in MTSV is attributed to changes in operative temperature. Both schools had lower R^2 values in spring and winter, which implies a greater influence of occupants' adaptive behaviors such as opening windows and changing clothes [65].

4.4. Simultaneous Analysis of Indoor Air Quality and Thermal Comfort. Figure 15 categorizes IAQ and thermal comfort of the measured classrooms simultaneously, following the methodology defined in Section 3.4. The horizontal axis denotes the indoor air quality aspect, and the vertical axis represents the thermal comfort aspect. The size of the bubbles refers to the percentage of observations for each category in all measurements.

As seen, the optimum requirements of both IAQ and thermal comfort were achieved in 7.5% of the measured time. In contrast, only 0.3% of observations were labeled completely as bad, which means a failure to meet the minimum requirements of both aspects. For nearly 30% of the observations, one aspect reached a good level, while the other achieved an acceptable level. Then, for 9% of the observations, both aspects only reached the acceptable level. Overall, the investigated classrooms achieved acceptable and good levels of both IAQ and thermal comfort aspects for over 46% of the measured time.

Figures 16(a) and 16(b) summarize the identification results of representative scenarios under each IAQ and thermal comfort category with clustering analysis. The results showed that good IAQ and thermal comfort could hardly be achieved simultaneously in summer. According to the measurement results, only 7% of the observations in the good IAQ and good TC category were in summer, while the figure was 48% and 45% for spring and winter, respectively. For a good IAQ and acceptable TC category, the summer's observation was also less than 29%. Besides, it was found that almost all observations in the good IAQ and bad TC category were from summer. In comparison, spring and winter create favorable conditions for ensuring good and acceptable IAQ and thermal comfort in the classrooms.

For the categories involving bad IAQ, secondary schools accounted for a high proportion. The main reason is that, as previously mentioned, the occupancy ratio of secondary schools is usually higher than that of primary schools, while these students also generate more CO_2 than children. Therefore, it is necessary to limit the number of students in secondary school classrooms to guarantee a satisfactory IAQ level. Furthermore, the ventilation strategy is critical to maintaining a good IAQ. Most of the observations in categories with bad IAQ are related to a small opening area of windows and doors. Cross ventilation with a sufficient total opening area (>3 m^2) can guarantee good or acceptable IAQ in most cases, which should be adopted by schools, as strongly recommended by IDAEA [53].

Temperature was the main factor leading to poor thermal comfort in schools. For categories involving bad TC, 87% of the observations exceeded the upper limit of minimum acceptable temperature. Only in a few cases in winter, the temperature was below the acceptable limit. In contrast, relative humidity usually caused a decline in thermal comfort level, particularly in winter. When ventilation and heating occurred at the same time, the relative humidity fell below the lower acceptable limit, leading to a bad TC (cluster 5 in good IAQ and bad TC category). When there was a lack of sufficient ventilation, the relative humidity was often higher than the optimum limit, which reduces the possibility of achieving good thermal comfort in the classrooms (clusters 2 and 5 in bad IAQ and acceptable TC category).

The results of representative scenarios suggest that clustering analysis is an effective and efficient way to analyze large measurement databases.

4.5. Discussion of Results. Maintaining good IAQ in the classroom is not a simple and easy task. As observed in many studies, classrooms did not meet the IAQ requirement of relevant standards over 50% of the time [12, 14, 25]. This is often caused by a lack of adequate ventilation, particularly in winter, because occupants usually have less willingness to

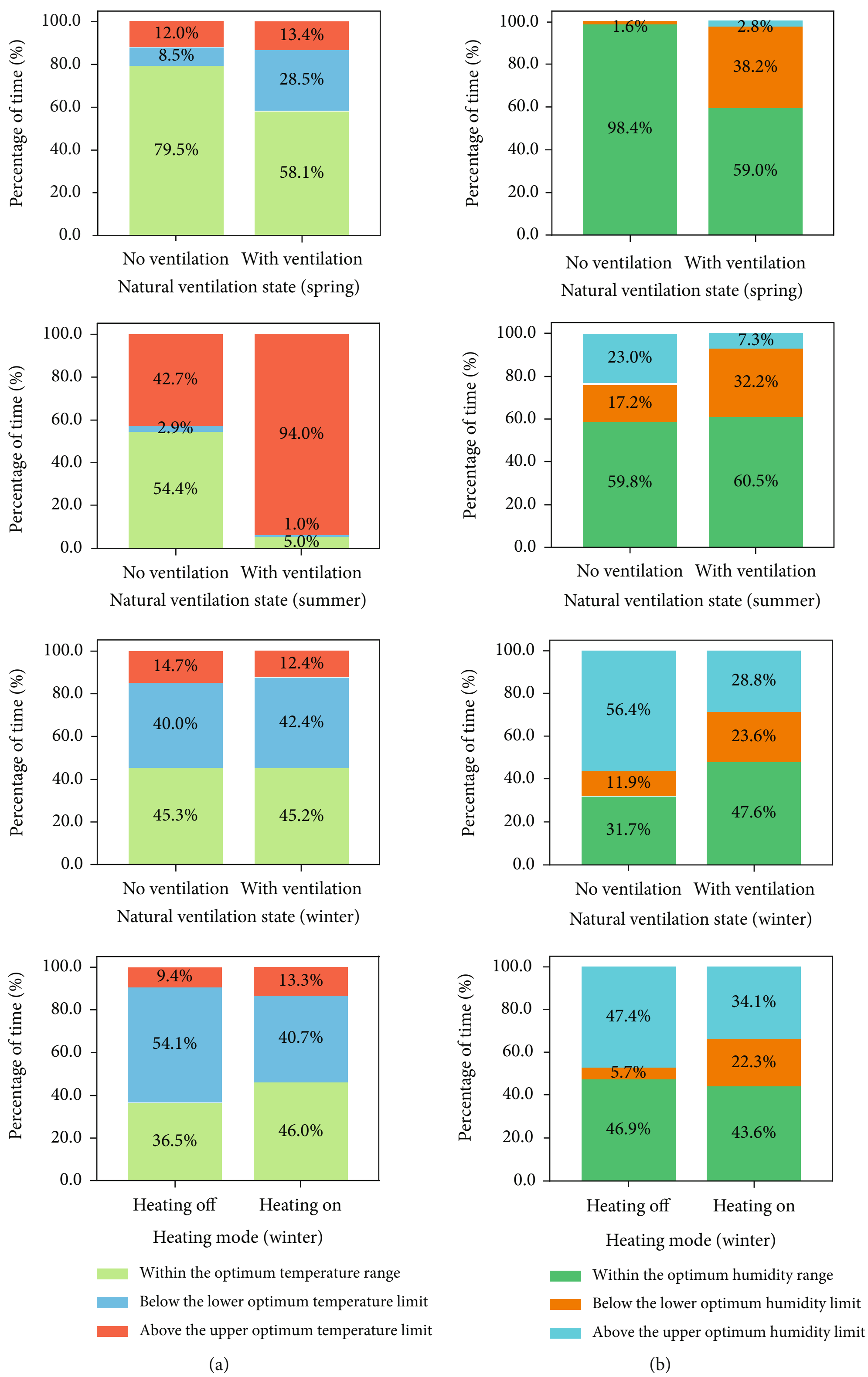
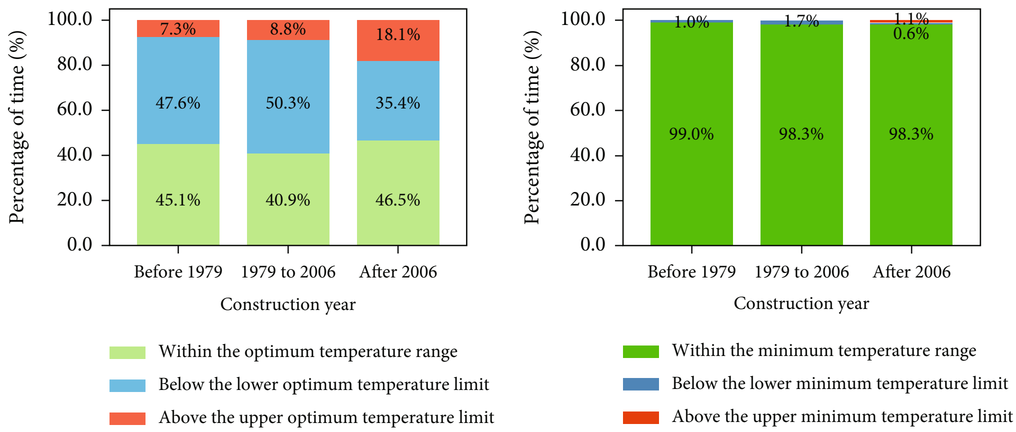


FIGURE 11: Satisfaction of optimum temperature (a) and humidity (b) requirements according to the ventilation state and heating mode.



(a) (b)

Figure 12: Satisfaction of optimum (a) and minimum (b) temperature requirements by building construction year.

Table 12: The average clothing insulation value of students in each season.

Iclo	Spring	Summer	Winter
Female students	0.65	0.41	0.79
Male students	0.61	0.38	0.79
Average	0.63	0.39	0.79

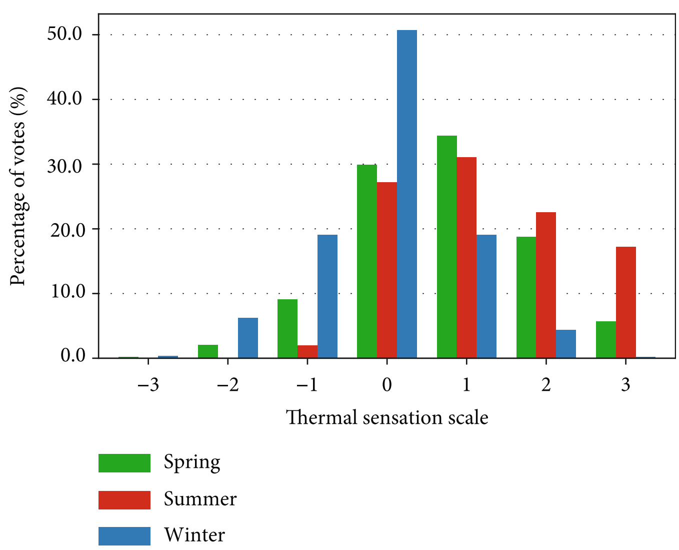


Figure 13: Students' TSV in all seasons.

open windows and doors in cold weather to ensure thermal comfort needs. In this study, classrooms failed to achieve the acceptable IAQ level nearly 49% of the time in winter, mainly due to a substantial reduction in cross ventilation. These findings are consistent with previous studies, which suggest the need of a proper ventilation protocol in schools. Monge-Barrio et al. [15] found that after adopting a clear ventilation protocol, IAQ in classrooms was significantly improved and the average CO_2 concentration dropped by 1400 ppm. Miranda et al. [66] discovered that when a ventilation protocol was enforced, IAQ in classrooms fully met the requirement 100% of the time, with a CO_2 concentration maintained below 800 ppm. These studies all pointed out that students' thermal comfort was inevitably compromised due to the enforced ventilation protocol in winter. Therefore, more attention should be given to the balance of IAQ and thermal comfort when developing ventilation protocols [67]. But till now, there is a lack of reference in relevant standards combining both aspects [68]. Accordingly, the representative scenarios of good and poor IAQ and thermal

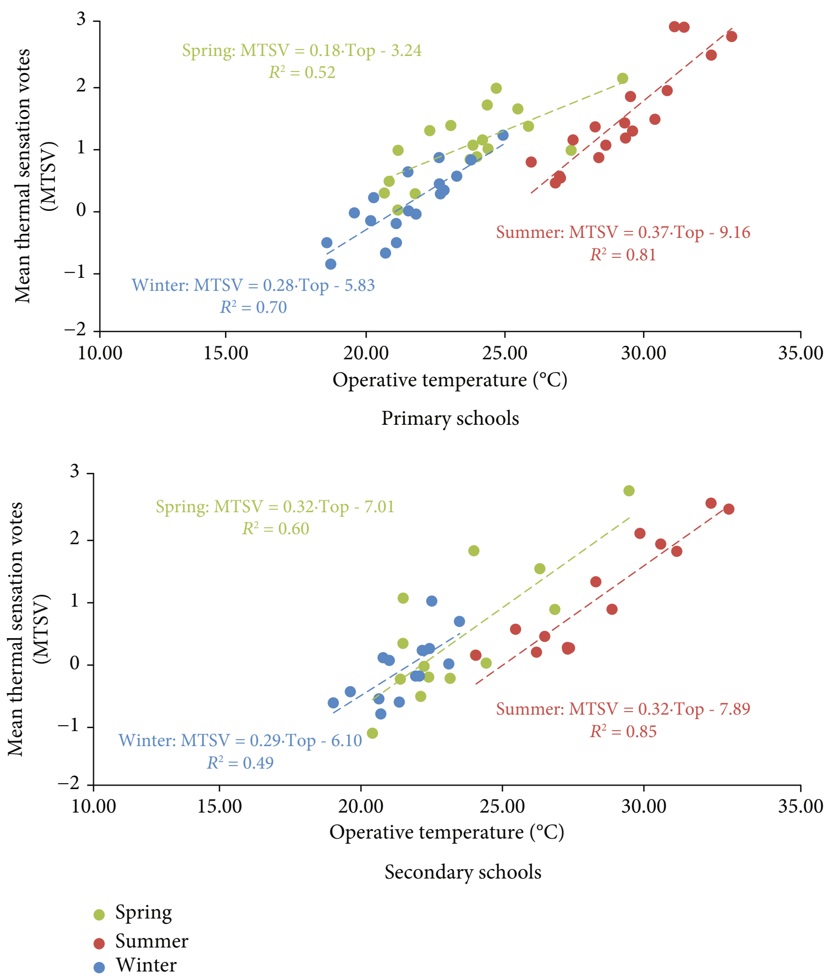


Figure 14: Linear regression between MTSV and operative temperature for primary and secondary schools.

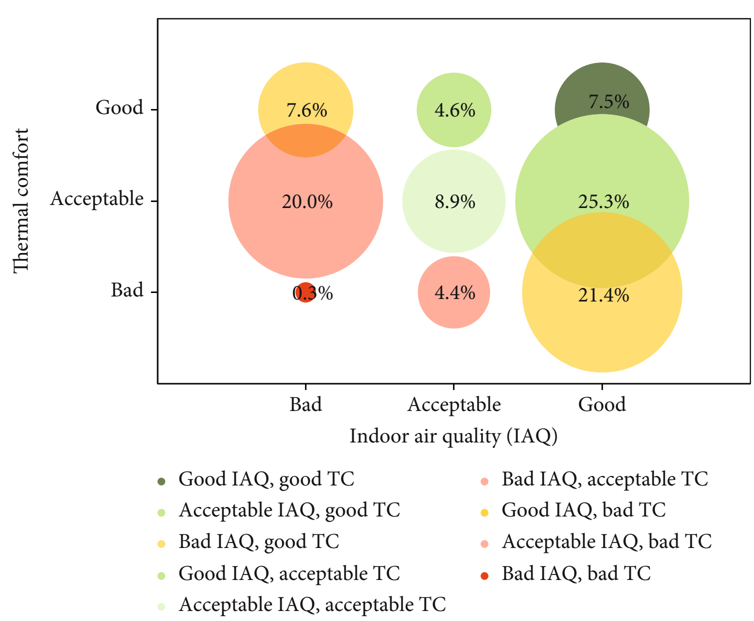
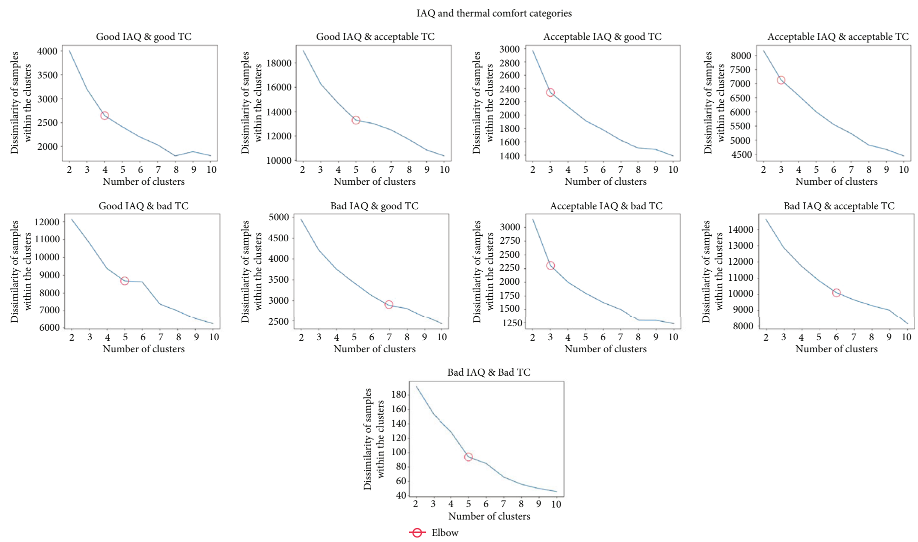


Figure 15: Indoor air quality and thermal comfort of the investigated classrooms.



(a) The number of representative clusters k identified by the Elbow method

Cluster No.	Percent*	Season	Educational level	Occupancy ratio	Total opening area	Ventilation strategy	Heating mode	CO_2 level	Operative temperature	Relative humidity
Good IAQ & good TC (7.5% observations)										
1	2.07%	Spring	Secondary	High	Medium	Cross ventilation	Off	Safe	Within the range	Within the range
2	1.51%	Winter	Primary	High	Medium	Cross ventilation	On	Safe	Within the range	Within the range
3	2.15%	Spring	Primary	Low	Small	Cross ventilation	Off	Safe	Within the range	Within the range
4	1.79%	Winter	Primary	Empty	Small	Only by door	On	Safe	Within the range	Within the range
Good IAQ & acceptable TC (25.3% observations)										
1	5.73%	Spring	Primary	High	Medium	Cross ventilation	On	Safe	Within the range	Below optimum limit
2	4.80%	Winter	Primary	Empty	Small	Only by door	On	Safe	Below optimum limit	Within the range
3	4.23%	Winter	Primary	Empty	Medium	Cross ventilation	On	Safe	Below optimum limit	Below optimum limit
4	7.87%	Summer	Primary	Medium	Medium	Cross ventilation	Off	Safe	Above optimum limit	Within the range
5	2.58%	Spring	Secondary	Medium	Small	Cross ventilation	Off	Safe	Below optimum limit	Within the range
Acceptable IAQ & good TC (4.6% observations)										
1	2.00%	Spring	Secondary	Medium	Small	Cross ventilation	On	IDA2	Within the range	Within the range
2	1.56%	Winter	Primary	Empty	Small	Only by door	On	IDA2	Within the range	Within the range
3	1.08%	Spring	Secondary	High	Medium	Cross ventilation	Off	IDA1	Within the range	Within the range
Acceptable IAQ & acceptable TC (8.9% observations)										
1	4.36%	Winter	Primary	Low	Small	Only by door	On	IDA2	Below optimum limit	Within the range
2	3.13%	Spring	Primary	High	Small	Cross ventilation	On	IDA2	Within the range	Below optimum limit
3	1.41%	Spring	Secondary	Medium	Small	Cross ventilation	Off	IDA1	Below optimum limit	Within the range
Good IAQ & bad TC (21.4% observations)										
1	6.42%	Summer	Primary	High	Medium	Cross ventilation	Off	Safe	Above minimum limit	Within the range
2	4.54%	Summer	Primary	Medium	Medium	Cross ventilation	Off	Safe	Above minimum limit	Within the range
3	6.78%	Summer	Secondary	High	Large	Cross ventilation	Off	Safe	Above minimum limit	Below optimum limit
4	1.51%	Summer	Secondary	Empty	Small	Only by window	Off	Safe	Above minimum limit	Within the range
5	1.95%	Winter	Primary	Empty	Medium	Cross ventilation	On	Safe	Within the range	Below minimum limit
Bad IAQ & good TC (7.6% observations)										
1	2.42%	Spring	Secondary	High	Small	Only by window	Off	IDA4	Within the range	Within the range
2	0.65%	Summer	Secondary	Empty	Small	Only by door	Off	IDA4	Within the range	Within the range
3	0.74%	Winter	Secondary	Medium	Small	Only by window	On	IDA4	Within the range	Within the range
4	1.78%	Winter	Primary	Medium	Small	Only by door	On	IDA3	Within the range	Within the range
5	0.71%	Spring	Secondary	Medium	Small	Cross ventilation	On	IDA3	Within the range	Within the range
6	0.69%	Winter	Secondary	High	Closed	No ventilation	On	IDA4	Within the range	Within the range
7	0.59%	Spring	Secondary	Medium	Closed	No ventilation	Off	IDA3	Within the range	Within the range
Acceptable IAQ & bad TC (4.4% observations)										
1	2.02%	Summer	Primary	Medium	Medium	Cross ventilation	Off	IDA2	Above minimum limit	Below optimum limit
2	1.41%	Summer	Secondary	High	Medium	Cross ventilation	Off	IDA1	Above minimum limit	Within the range
3	0.94%	Spring	Primary	High	Medium	Cross ventilation	On	IDA2	Within the range	Below minimum limit
Bad IAQ & acceptable TC (20.0% observations)										
1	5.74%	Winter	Secondary	High	Closed	No ventilation	On	IDA4	Below optimum limit	Above optimum limit
2	5.30%	Winter	Secondary	Medium	Small	Only by door	On	IDA4	Within the range	Above optimum limit
3	3.10%	Winter	Primary	High	Small	Cross ventilation	On	IDA3	Below optimum limit	Within the range
4	2.04%	Winter	Secondary	High	Small	Only by door	On	IDA4	Above optimum limit	Within the range
5	1.69%	Winter	Secondary	Medium	Closed	No ventilation	On	IDA4	Within the range	Above optimum limit
6	2.12%	Winter	Secondary	High	Small	Only by window	On	IDA4	Below optimum limit	Above optimum limit
Bad IAQ & badTC (0.3% observations)										
1	0.09%	Summer	Primary	High	Medium	Cross ventilation	Off	IDA3	Above minimum limit	Below optimum limit
2	0.04%	Winter	Primary	High	Small	Cross ventilation	On	IDA3	Below minimum limit	Below minimum limit
3	0.07%	Summer	Secondary	Medium	Medium	Cross ventilation	Off	IDA3	Above minimum limit	Within the range
4	0.06%	Summer	Primary	Medium	Small	Only by window	Off	IDA3	Above minimum limit	Below optimum limit
5	0.08%	Summer	Secondary	High	Small	Only by window	Off	IDA3	Above minimum limit	Within the range

*Percentage of observations

(b) The representative scenarios with each indoor air quality and thermal comfort category

Figure 16: Clustering analysis results.

comfort identified in this study lay the foundation for the development of such a proper ventilation protocol.

Ensuring the thermal comfort of students is also a challenging issue. Due to the difference in thermal sensation, children usually have a lower comfort temperature than adults. In this study, students' neutral temperatures were found to range from 21.0 to 25.3°C, which is close to the values observed in relevant studies under similar climatic conditions [5, 19, 27]. These values are generally lower than the university students' comfortable temperatures summarized in existing research [16, 69]. In this context, indoor temperature values specified by existing building codes and standards may not properly fit the needs of primary and secondary students. Moreover, children's adaption in classrooms is often passive and limited, while teachers have the initiative to control indoor thermal conditions. Kumar et al. [70] investigated the adaptive behaviors of university students and identified diverse adaptive opportunities such as turning on fans/air conditioners, operating windows and doors, changing clothing, changing postures, and walking indoors or outdoors. These options are usually not applicable to children because they have to ask for the teacher's permission [5, 20]. Accordingly, these factors may ultimately lead to lower satisfaction with the indoor thermal environment in classrooms, as observed in this and other relevant studies [6, 19]. These issues deserve more in-depth explorations in further research to guarantee a comfortable indoor environment for students.

5. Conclusions and Recommendations

This research conducted a comprehensive assessment of IAQ and thermal comfort of educational buildings, based on an on-site measurement campaign involving around 600 students in 32 classrooms of primary and secondary schools in the Mediterranean climate.

For IAQ, the investigated classrooms met the minimum IAQ requirement for 71% of the time and maintained a safe level avoiding massive exposure to the COVID pandemic 53% of the time. Occupancy and ventilation were found to be the most significant influential factors that cause the discrepancy in indoor CO_2 concentration across the seasons. The classrooms had cross ventilation for more than half of the measured time in general, and occupants preferred ventilating the space by opening doors, especially in winter.

Concerning thermal comfort, the measured classrooms satisfied the minimum thermal requirement for 74% of the time, but the optimum requirement was achieved less than 19% of the time. Poor thermal comfort was given by a high indoor air temperature in summer. The analysis found that indoor thermal conditions can be affected by factors such as season, occupancy, ventilation, and the heating mode of the classroom. The average value of the clothing insulation of students was lower than that specified by ISO 7730 [18]. TSV analysis confirmed that female students are more sensitive to colder temperatures. In addition, students' neutral temperature was found to be very close to the upper and lower limits defined by the RITE standard [52].

When IAQ and thermal comfort aspects were assessed simultaneously, the minimum requirements of both aspects were achieved 46% of the time, but the optimum requirements were satisfied only 7.5% of the time. It was found that good IAQ and thermal comfort can hardly be achieved simultaneously in summer, while spring and winter render favorable conditions. Inadequate ventilation in winter not only results in a bad IAQ in the classrooms but also leads to relatively high humidity, which reduces the potential of achieving good thermal comfort. Besides, secondary schools should limit the number of students in the classrooms, and cross ventilation should be performed with a sufficient total opening area (>3 m^2).

Based on the findings of this research, it was concluded that good IAQ can be maintained by developing a proper ventilation protocol for schools, but the impact of ventilation on indoor thermal conditions must be taken into account. Future research steps could investigate the adaptive thermal comfort of students.

Abbreviations

IAQ: Indoor air quality
TC: Thermal comfort
TSV: Thermal sensation vote
MTSV: Mean thermal sensation vote
NV: Natural ventilation
FR: Free-running.

Data Availability

Data are available on request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Authors' Contributions

Sen Miao was responsible for the conceptualization, methodology, investigation, data curation, formal analysis, and visualization; wrote the original draft; and wrote, reviewed, and edited the manuscript. Marta Gangolells was responsible for the conceptualization, methodology, resources, supervision, project administration, and funding acquisition and wrote, reviewed, and edited the manuscript. Blanca Tejedor was responsible for the conceptualization, methodology, resources, and supervision and wrote, reviewed, and edited the manuscript.

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References

[1] S. Mohamed, L. Rodrigues, S. Omer, and J. Calautit, "Overheating and indoor air quality in primary schools in the UK," *Energy and Buildings*, vol. 250, article 111291, 2021.

[2] L. Jia, J. Han, X. Chen, Q. Li, C. Lee, and Y. Fung, "Interaction between thermal comfort, indoor air quality and ventilation energy consumption of educational buildings: a comprehensive review," *Buildings*, vol. 11, no. 12, p. 591, 2021.

[3] R. Sadrizadeh, R. Yao, F. Yuan et al., "Indoor air quality and health in schools: a critical review for developing the roadmap for the future school environment," *Journal of Building Engineering*, vol. 57, article 104908, 2022.

[4] V. V. Tran, D. Park, and Y. C. Lee, "Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality," *International Journal of Environmental Research and Public Health*, vol. 17, no. 8, p. 2927, 2020.

[5] Z. S. Zomorodian, M. Tahsildoost, and M. Hafezi, "Thermal comfort in educational buildings: a review article," *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 895–906, 2016.

[6] S. S. Korsavi, A. Montazami, and D. Mumovic, "Indoor air quality (IAQ) in naturally-ventilated primary schools in the UK: occupant-related factors," *Building and Environment*, vol. 180, article 106992, 2020.

[7] V. Faye McNeill, R. Corsi, J. Alex Huffman et al., "Room-level ventilation in schools and universities," *Atmospheric Environment: X*, vol. 13, article 100152, 2022.

[8] ASHRAE, *ASHRAE 62.1: Ventilation and acceptable indoor air quality*, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2022.

[9] CEN, *EN 16798-1: 2019, Part 1: Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics*, European Committee for Standarization (CEN), 2019.

[10] E. Ding, D. Zhang, and P. M. Bluyssen, "Ventilation regimes of school classrooms against airborne transmission of infectious respiratory droplets: a review," *Building and Environment*, vol. 207, article 108484, 2022.

[11] G. Remion, B. Moujalled, and M. El Mankibi, "Review of tracer gas-based methods for the characterization of natural ventilation performance: comparative analysis of their accuracy," *Building and Environment*, vol. 160, p. 106180, 2019.

[12] M. Díaz, M. Cools, M. Trebilcock, B. Piderit-Moreno, and S. Attia, "Effects of climatic conditions, season and environmental factors on CO_2 concentrations in naturally ventilated primary schools in Chile," *Sustainability*, vol. 13, no. 8, p. 4139, 2021.

[13] C. C. Vassella, J. Koch, A. Henzi et al., "From spontaneous to strategic natural window ventilation: improving indoor air quality in Swiss schools," *International Journal of Hygiene and Environmental Health*, vol. 234, article 113746, 2021.

[14] C. Cai, Z. Sun, L. B. Weschler, T. Li, W. Xu, and Y. Zhang, "Indoor air quality in schools in Beijing: field tests, problems and recommendations," *Building and Environment*, vol. 205, article 108179, 2021.

[15] A. Monge-Barrio, M. Bes-Rastrollo, S. Dorregaray-Oyaregui et al., "Encouraging natural ventilation to improve indoor environmental conditions at schools. Case studies in the north of Spain before and during COVID," *Energy and Buildings*, vol. 254, article 111567, 2022.

[16] M. K. Singh, R. Ooka, H. B. Rijal, S. Kumar, A. Kumar, and S. Mahapatra, "Progress in thermal comfort studies in classrooms over last 50 years and way forward," *Energy and Buildings*, vol. 188-189, pp. 149–174, 2019.

[17] ASHRAE, *ASHRAE 55: Thermal Environment Conditions for Human Occupancy*, American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), 2020.

[18] ISO, *EN ISO 7730: Ergonomics of the Thermal Environment - Analytical Determination and Interpretation of Thermal Comfort using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria*, ISO, 2005.

[19] P. Aparicio-Ruiz, E. Barbadilla-Martín, J. Guadix, and J. Muñuzuri, "A field study on adaptive thermal comfort in Spanish primary classrooms during summer season," *Building and Environment*, vol. 203, article 108089, 2021.

[20] B. Yang, T. Olofsson, F. Wang, and W. Lu, "Thermal comfort in primary school classrooms: a case study under subarctic climate area of Sweden," *Building and Environment*, vol. 135, pp. 237–245, 2018.

[21] H. Al-Khatri, M. Alwetaishi, and M. B. Gadi, "Exploring thermal comfort experience and adaptive opportunities of female and male high school students," *Journal of Building Engineering*, vol. 31, article 101365, 2020.

[22] J. Jiang, D. Wang, Y. Liu, Y. Di, and J. Liu, "A field study of adaptive thermal comfort in primary and secondary school classrooms during winter season in Northwest China," *Building and Environment*, vol. 175, article 106802, 2020.

[23] M. Shrestha, H. B. Rijal, G. Kayo, and M. Shukuya, "A field investigation on adaptive thermal comfort in school buildings in the temperate climatic region of Nepal," *Building and Environment*, vol. 190, article 107523, 2021.

[24] C. Heracleous and A. Michael, "Experimental assessment of the impact of natural ventilation on indoor air quality and thermal comfort conditions of educational buildings in the Eastern Mediterranean region during the heating period," *Journal of Building Engineering*, vol. 26, article 100917, 2019.

[25] F. Ma, C. Zhan, X. Xu, and G. Li, "Winter thermal comfort and perceived air quality: a case study of primary schools in severe cold regions in China," *Energies*, vol. 13, no. 22, p. 5958, 2020.

[26] T. G. Theodosiou and K. T. Ordoumpozanis, "Energy, comfort and indoor air quality in nursery and elementary school buildings in the cold climatic zone of Greece," *Energy and Buildings*, vol. 40, no. 12, pp. 2207–2214, 2008.

[27] L. D. Pereira, D. Raimondo, S. P. Corgnati, and M. Gameiro da Silva, "Assessment of indoor air quality and thermal comfort in Portuguese secondary classrooms: methodology and results," *Building and Environment*, vol. 81, pp. 69–80, 2014.

[28] A. Alonso, J. Llanos, R. Escandón, and J. J. Sendra, "Effects of the COVID-19 pandemic on indoor air quality and thermal comfort of primary schools in winter in a Mediterranean climate," *Sustainability*, vol. 13, no. 5, p. 2699, 2021.

[29] S. Kumar, M. K. Singh, R. Kukreja, S. K. Chaurasiya, and V. K. Gupta, "Comparative study of thermal comfort and adaptive actions for modern and traditional multi-storey naturally ventilated hostel buildings during monsoon season in India," *Journal of Building Engineering*, vol. 23, pp. 90–106, 2019.

[30] B. Tejedor, M. Casals, M. Gangolells, M. Macarulla, and N. Forcada, "Human comfort modelling for elderly people by infrared thermography: evaluating the thermoregulation system responses in an indoor environment during

winter," *Building and Environment*, vol. 186, article 107354, 2020.

[31] N. Mahyuddin and H. Awbi, "A review of CO_2 measurement procedures in ventilation research," *International Journal of Ventilation*, vol. 10, no. 4, pp. 353–370, 2012.

[32] ASTM, *ASTM D6245-18. Standard Guide for using Indoor Carbon Dioxide Concentrations to Evaluate Indoor Air Quality and Ventilation*, American Society for Testing and Materials (ASTM), 2018.

[33] ISO, *EN ISO 7726: Ergonomics of the Thermal Environment–Instruments for Measuring Physical Quantities*, International Organization for Standardization (ISO), 2001.

[34] N. Mahyuddin, H. B. Awbi, and M. Alshitawi, "The spatial distribution of carbon dioxide in rooms with particular application to classrooms," *Indoor and Built Environment*, vol. 23, no. 3, pp. 433–448, 2014.

[35] N. Ma, D. Aviv, H. Guo, and W. W. Braham, "Measuring the right factors: a review of variables and models for thermal comfort and indoor air quality," *Renewable and Sustainable Energy Reviews*, vol. 135, article 110436, 2021.

[36] F. Ma, C. Zhan, and X. Xu, "Investigation and evaluation of winter indoor air quality of primary schools in severe cold weather areas of China," *Energies*, vol. 12, no. 9, p. 1602, 2019.

[37] A. Asif and M. Zeeshan, "Indoor temperature, relative humidity and CO_2 monitoring and air exchange rates simulation utilizing system dynamics tools for naturally ventilated classrooms," *Building and Environment*, vol. 180, article 106980, 2020.

[38] M. Gil-Baez, J. Lizana, J. A. Becerra Villanueva, M. Molina-Huelva, A. Serrano-Jimenez, and R. Chacartegui, "Natural ventilation in classrooms for healthy schools in the COVID era in Mediterranean climate," *Building and Environment*, vol. 206, article 108345, 2021.

[39] M. Shrestha, H. B. Rijal, G. Kayo, and M. Shukuya, "An investigation on CO_2 concentration based on field survey and simulation in naturally ventilated Nepalese school buildings during summer," *Building and Environment*, vol. 207, article 108405, 2022.

[40] E. Papazoglou, K. P. Moustris, K. P. Nikas, P. T. Nastos, and J. C. Statharas, "Assessment of human thermal comfort perception in a non-air-conditioned school building in Athens, Greece," *Energy Procedia*, vol. 157, pp. 1343–1352, 2019.

[41] S. S. Korsavi and A. Montazami, "Children's thermal comfort and adaptive behaviours; UK primary schools during non-heating and heating seasons," *Energy and Buildings*, vol. 214, article 109857, 2020.

[42] A. Martinez-Molina, P. Boarin, I. Tort-Ausina, and J. L. Vivancos, "Post-occupancy evaluation of a historic primary school in Spain: Comparing PMV, TSV and PD for teachers' and pupils' thermal comfort," *Building and Environment*, vol. 117, pp. 248–259, 2017.

[43] C. M. Rodriguez, M. C. Coronado, and J. M. Medina, "Classroom-comfort-data: a method to collect comprehensive information on thermal comfort in school classrooms," *MethodsX*, vol. 6, pp. 2698–2719, 2019.

[44] S. Sivanantham, C. Dassonville, A. Grégoire, L. Malingre, O. Ramalho, and C. Mandin, "Coexposure to indoor pollutants in French schools and associations with building characteristics," *Energy and Buildings*, vol. 252, article 111424, 2021.

[45] L. Bai and J. Liang, "The k-modes type clustering plus between-cluster information for categorical data," *Neurocomputing*, vol. 133, pp. 111–121, 2014.

[46] M. Gangolells, M. Casals, J. Ferré-Bigorra et al., "Office representatives for cost-optimal energy retrofitting analysis: a novel approach using cluster analysis of energy performance certificate databases," *Energy and Buildings*, vol. 206, article 109557, 2020.

[47] Catalonia, "Clima," 2022, Accessed on 15 February 2022, https://www.catalunya.com/clima-9-1-9?language=es.

[48] M. Kottek, J. Grieser, C. Beck, B. Rudolf, and F. Rubel, "World map of the Köppen-Geiger climate classification updated," *Meteorologische Zeitschrift*, vol. 15, no. 3, pp. 259–263, 2006.

[49] Spain, *Royal Decree 2429/1979. Basic building standard NBE-CT-79*, Official State Gazette of Spainish government (BOE, Spain), 1979.

[50] M. Gangolells and M. Casals, "Resilience to increasing temperatures: residential building stock adaptation through codes and standards," *Building Research & Information*, vol. 40, no. 6, pp. 645–664, 2012.

[51] Spain, *Royal Decree 314/2006. The Spanish Technical Building Code*, Official State Gazette of Spainish government (BOE, Spain), 2006.

[52] Spain, *Royal Decree 1027/2007. Regulation of technical installations in buildings RITE*, Official State Gazette of Spainish government (BOE, Spain), 2007.

[53] IDAEA, "Ventilation guide for indoor spaces," 2021, Accessed on 10 February 2022, https://www.idaea.csic.es/wp-content/uploads/2021/12/Ventilation-guide-of-indoor-environments.pdf.

[54] Spain, *Royal Decree 486/2004. The minimum safety and health provisions in the workplace*, Official State Gazette of Spainish government (BOE, Spain), 2004.

[55] Google, "Google Colab," 2023, Accessed on 10 April 2023, https://colab.research.google.com/.

[56] C. R. Harris, K. J. Millman, S. J. van der Walt et al., "Array programming with NumPy," *Nature*, vol. 585, no. 7825, pp. 357–362, 2020.

[57] W. McKinney, "Data structures for statistical computing in python," *Proceedings of the 9th Python in Science Conference*, vol. 445, pp. 51–56, 2010.

[58] S. Seabold and J. Perktold, "Statsmodels: econometric and statistical modeling with Python," in *Proceedings of the Python in Science Conference*, pp. 92–96, Austin, Texus, USA, 2010.

[59] N. J. de Vos, "Kmodes categorical clustering library," 2021, Accessed on 20 June 2023, https://github.com/nicodv/kmodes.

[60] V. Satopaa, J. Albrecht, D. Irwin, and B. Raghavan, "Finding a "Kneedle" in a haystack: detecting knee points in system behavior," in *2011 31st International Conference on Distributed Computing Systems Workshops*, pp. 166–171, Minneapolis, MN, USA, 2011.

[61] J. D. Hunter, "Matplotlib: a 2D graphics environment," *Computing in Science & Engineering*, vol. 9, no. 3, pp. 90–95, 2007.

[62] M. L. Waskom, "Seaborn: statistical data visualization," *Journal of Open Source Software*, vol. 6, no. 60, p. 3021, 2021.

[63] A. Meiss, H. Jimeno-Merino, I. Poza-Casado, A. Llorente-Álvarez, and M. A. Padilla-Marcos, "Indoor air quality in naturally ventilated classrooms. Lessons learned from a case study in a COVID-19 scenario," *Sustainability*, vol. 13, no. 15, p. 8446, 2021.

[64] A. Persily and L. Jonge, "Carbon dioxide generation rates for building occupants," *Indoor Air*, vol. 27, no. 5, pp. 868–879, 2017.

[65] A. Jindal, “Thermal comfort study in naturally ventilated school classrooms in composite climate of India,” *Building and Environment*, vol. 142, pp. 34–46, 2018.

[66] M. T. Miranda, P. Romero, V. Valero-Amaro, J. I. Arranz, and I. Montero, “Ventilation conditions and their influence on thermal comfort in examination classrooms in times of COVID-19. A case study in a Spanish area with Mediterranean climate,” vol. 240, 2022.

[67] S. Miao, M. Gangolells, B. Tejedor, and P. Pujadas, “Indoor air quality, thermal comfort, and energy consumption trade-off for educational buildings,” in *Proceedings from the 26th International Congress on Project Management and Engineering, 02-010*, pp. 353–364, 2022.

[68] F. Babich, G. Torriani, J. Corona, and I. Lara-Ibeas, “Comparison of indoor air quality and thermal comfort standards and variations in exceedance for school buildings,” *Journal of Building Engineering*, vol. 71, article 106405, 2023.

[69] S. Kumar and M. K. Signh, “Seasonal comfort temperature and occupant's adaptive behaviour in a naturally ventilated university workshop building under the composite climate of India,” *Journal of Building Engineering*, vol. 40, article 102701, 2021.

[70] S. Kumar, M. K. Singh, A. Mathur, J. Mathur, and S. Mathur, “Evaluation of comfort preferences and insights into behavioural adaptation of students in naturally ventilated classrooms in a tropical country, India,” *Building and Environment*, vol. 143, pp. 532–547, 2018.