Building Engineering 2024, 2(1), 1334.
https://doi.org/10.59400/be.v2i1.1334

Article

Field and intervention study on indoor environment in professional classrooms

Yue Lyu

School of Civil Engineering, Shaoxing University, Shaoxing 312000, Zhejiang Province, China; 2014000048@usx.edu.cn

CITATION

Lyu Y. Field and intervention study on indoor environment in professional classrooms. Building Engineering. 2024; 2(1): 1334. https://doi.org/10.59400/be.v2i1.1334

ARTICLE INFO

Received: 26 April 2024
Accepted: 24 May 2024
Available online: 5 June 2024

Abstract: To study the variation of environment in the professional classroom during lecture hours, multiple field experiments and intervention experiments on indoor and outdoor temperatures were conducted in a university professional classroom in Shaoxing during the spring. Environmental data, including indoor and outdoor temperatures, relative, and CO_2 concentrations, were recorded every 5 min. Volatile organic compounds (VOC) were sampled, and indoor air quality was evaluated repeatedly. Results showed that the classroom's average indoor air temperature ranged from 17.8–29.2 °C, the average indoor relative humidity from 34.5%–91.0%, the average CO_2 concentrations from 921.6–1805.2 ppmv, and total VOC concentrations from 330–682 ppbm. The subjective evaluation conducted during the intervention experiments indicated a significant increase in perceived odor intensity upon entering the classroom. When the CO_2 concentration reached 2000 ppmv, the satisfaction and acceptability of the air quality for the subjects and invitees decreased significantly. In the temperature range of 17–31 °C, the CO_2 emission rate of the human body was estimated to increase by 0.78 L/h for every 1 °C increase in temperature. To maintain the indoor CO_2 concentration at 1000 ppmv, the required ventilation rate for each person must be increased by 0.25 ± 0.3 L/s.

Keywords: classrooms; VOC; CO_2 concentration; CO_2 emission rate; intervention measurements

1. Introduction

Classrooms are the primary locations where students acquire knowledge, with students spending more than 40% of their time in these spaces [1,2]. Indoor pollutant levels of 2–5 are several times those of outdoor pollutants [3,4]. The reasons behind this include crowded classrooms, short break times, low ventilation during breaks, inadequacy in providing fresh air, absence of mechanical ventilation, unplanned construction of ventilation systems, factors bringing pollutants from the outdoors, and the existence of impermeable windows [5,6]. Almost all students are exposed to indoor air in school buildings during their educational lives. In these institutions, pollutants from several sources have a negative impact on the health, comfort, and performance of students and employees, especially affecting memory, concentration, and learning abilities. Therefore, the air quality inside the classroom is a key indicator for measuring students' learning comfort and learning efficiency. In schools, it is important to create a favorable teaching and learning environment. The air quality inside classrooms depends on air temperature, humidity, radiation, internal lighting, air flow, activities, clothing, and climate change and has a significant impact on the physical and mental health of students.

The deterioration of indoor air quality is caused by a combination of outdoor pollutants entering classrooms and indoor sources of pollutants [7,8]. In the research field of indoor environments, indoor CO_2 concentration, content, and concentration of volatile organic compounds (VOCs) can be regarded as a measure of indoor air quality affected by human pollutants [9].

Regarding CO_2 concentration studies, previous research has shown that the higher the CO_2 concentration, the worse the quality of brain work [10,11]. When the CO_2 concentration reaches 1000–2000 ppmv, people feel cloudy air and have difficulty breathing. When it exceeds 2000 ppmv, it may contribute to an increase in pulse rate, blood pressure, and skin temperature, causing headaches, drowsiness, fatigue, nausea, impaired concentration, and decreased mental and physical working capacity [12–14]. It is evident that there is no universally defined standard for indoor CO_2 concentration limits across countries. The US ASHRAE standard (2016) recommends a maximum daily mean indoor CO_2 concentration of 1000 ppmv and that the indoor-outdoor differential concentration should not exceed 700 ppmv. The UK BS EN 15251 standard (2008) stipulates indoor and outdoor CO_2 concentration limits for different indoor air quality levels. The German VDI 6022 Part 3 standard (2011) specifies a maximum CO_2 concentration of 1500 ppmv in classrooms. The Chinese GB/T18883 standard (2012) refers to the 1000 ppmv CO_2 concentration recommended by the ASHRAE standard.

Many previous studies have used ordinary classrooms as settings to illustrate the range of changes in indoor CO_2 concentrations. These studies encompassed various scenarios, including natural ventilation [15–18], mechanical ventilation [12,19], both ventilation modes combined [20–22] the utilization of air purifiers [23], and the implementation of a human respiratory heat model [24].

Most of these studies were conducted in summer or autumn; ordinary classrooms were selected as the study sites, and multiple classrooms were monitored simultaneously to obtain the maximum and minimum values of CO_2 concentration. Population density ranged from 0.01–0.59 (person/m^2), resulting in a wide range of CO_2 concentration fluctuations.

Regarding research on VOCs, numerous studies have shown that indoor exposure to VOCs can lead to significant adverse health effects and pathological architectural syndrome [25,26]. Particularly, pollutants emitted by building decorations, such as volatile benzene gases and aldehydes, can harm the human body for a long time. In addition, some buildings are not well ventilated, with limited pollutant dilution capacity, and long-term exposure or excessive inhalation of VOC can lead to malignant diseases, such as cancer and leukaemia, as well as obvious adverse effects on the human respiratory, cardiovascular, and nervous systems, causing irreparable damage to the human body. Apart from VOCs usually derived from indoor materials, furniture, and permeating air [27], VOCs originating from indoor spaces have also attracted new attention, especially in dense spaces, such as classrooms and lecture halls in education buildings, where human emissions may be an important source [28]. For example, VOC emissions produced by humans (from skin or breath) [29], clothing, personal possessions [30], and activities such as smoking and using personal care products [31]. In addition, the presence of humans in indoor environments reduces ozone concentration, and the reaction between ozone and human skin oil remaining on hair and clothing can contribute to indoor VOCs [32]. Many previous studies have analyzed VOC components in ordinary classrooms. For example, in the condition of natural ventilation [26,33], in the condition of mechanical ventilation [34,35], in the above two ventilation modes [36,37], the utilization of air purifiers [38], and in the condition of heating [39]. Most of these studies were mainly conducted in summer or winter, and ordinary classrooms were selected as the study site; multiple classrooms were monitored simultaneously to obtain the components of VOCs, while the detection interval was longer, usually before and after class.

In the study of indoor ventilation, good and effective ventilation methods can not only meet people's requirements for the indoor environment but also reduce the loss of indoor energy. Simultaneously, good ventilation can remove indoor pollutants and achieve clean indoor air. Therefore, ventilation is considered an important measure for improving indoor air quality. However, there is no standardization of the limit value of classroom ventilation rates. The US ASHRAE Standard [40] and Australia [41] provide ventilation rates corresponding to different age groups with different population densities. The UK BS EN 15251 standard [42] recommends the required ventilation rate for each individual at three indoor air quality levels. The German VDI 6022 Part 3 standard [43] indicates an average ventilation rate of 30 m^3/h for each person. The Chinese GB 50736 Standard [44] is based on the US ASHRAE standard and provides the corresponding value of required ventilation rates for each individual based on different population densities.

Previous studies have examined ventilation rates [6,7,14,15,45,46]. However, most of them recommend values of ventilation rates required to eliminate anthropogenic pollution in classrooms under a single temperature condition without considering the effect of temperature on human biological emissions. This approach has some limitations.

In summary, (1) Most previous studies focused on the measurement method, with a few combining it with a questionnaire. Evaluating indoor air quality grade is closely related to the impact of environmental pollution on human health, and the influence of the environment on the subjective perception of the human body should be considered. (2) Most studies represent the internal air quality of classrooms during specific seasons; based on test results from several classes in a certain season, only a few studies have conducted continuous monitoring of indoor air quality. To avoid the risk of environmental pollution, the relevant departments can timely and effectively control and rectify the unqualified air quality to ensure a safe and healthy environment; the air quality inside the classroom should be continuously monitored; (3) Previous studies have focused on ordinary classrooms, whereas there are few studies on professional classrooms (such as architectural classrooms). The class content in ordinary classrooms is primarily taught by teachers, whereas that in professional classrooms is relatively rich (e.g., teacher lectures, group discussions, program reports, drawings, and models). The different behaviors of indoor personnel have a significant impact on indoor air quality.

Therefore, the innovative points include 1) the real-world classroom scenarios with 100 min, 2) the combination of field and intervention studies; 3) the combination of objective measures and subjective surveys; 4) the continuous monitoring for sixteen weeks; and 5) the professional classroom with relatively rich classroom content. The scientific contributions are mainly reflected in that this study conducted field measurements in professional classrooms to investigate air quality during daily classroom lectures. Intervention experiments were also conducted to study the effects of temperature on indoor air quality in real-world classroom scenarios. The engineering application potential of this study includes: 1) This study aimed to supplement information on the environmental characteristics of professional classrooms and provide reference data for improving the relevant ventilation standards. 2) This study has certain reference value for the study of the indoor thermal environment and air quality of university professional classrooms. 3) This study will continuously promote the research and development of teaching environments and improvement countermeasures in university professional classrooms. In summary, this study's real-world classroom scenarios and comprehensive measurements will provide valuable data for improving ventilation standards and promoting research and development in professional classroom environments.

2. Experimental methodology

The study was conducted in a classroom at a university in Shaoxing, Zhejiang Province, for 16 consecutive weeks from 28th February to 20th June in 2022 (spring and summer). The classroom was naturally ventilated before each test, and all windows and doors were closed during the class. There are 16 experiments together, and they were completed in the same classroom from 8:00 a.m. to 9:40 a.m. every Monday. Indoor temperature, relative humidity, CO_2 concentration, and total volatile organic compound (TVOC) concentration were measured separately during class.

The purpose of 12 field measurements was to study the characteristics of the classroom's indoor environment and changes in the indoor air quality. The other 4 interventions (2 in spring and 2 in summer) were designed to provide a more thorough analysis of the impact of indoor air quality and students' comfort levels in the classroom. Therefore, the composition of indoor VOCs was determined, and the results of the subjective evaluation of the perceived air quality in the classroom were analyzed.

2.1. Experimental subjects

2.1.1. Experimental classroom

The classroom used in the experiment was located on the first floor of a teaching building on the Hexi Campus of Shaoxing University. As shown in **Figure 1**, the dimension of the classroom is 9.9 m × 7.2 m × 3.2 m (length × width × height). The classroom's south wall is an external wall, with three external windows of 1.80 m × 2.56 m, which were all closed during class, and the size of the inter-window wall is 1.125 m. The windowless north wall is adjacent to the corridor, and there are front and back doors with both 1.2 m wide in the north wall. The front and back doors were opened randomly during breaks. The corridor is 1.8 m wide, and the dimensions of the three windows in the corridor, the state of the window closure, and the size of the inter-window wall are the same as those on the south wall. The east and west walls are windowless interior walls. Floor-type air conditioners were placed in the southwest corner of the classroom for indoor temperature control. There were six ceiling fans in the classroom that were not opened during class, and there was no mechanical ventilation system. The size of the desk is 0.65 m × 0.4 m × 0.76 m (length × width × height); the transverse and longitudinal spacing between the desks is 0.66 m and 0.8 m, respectively. It should be noted that the four adjacent rooms were all architecture classrooms, which were refreshed in January 2022, and furniture such as desks and chairs was also replaced in January 2022.

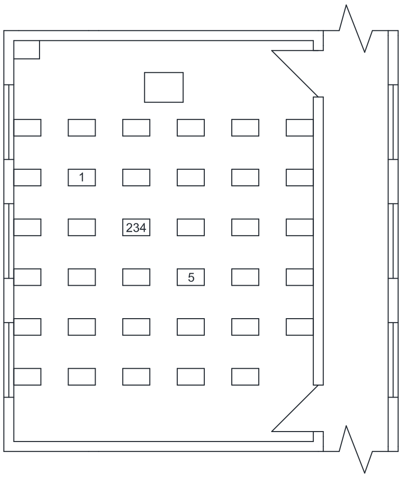

Figure 1. Classroom plan.

Note: the temperature, relative humidity and CO_2 concentration were measured in number '1, 2 and 5', TVOC was measured in number '3' and VOCs was measured in number '4'.

The front and back doors are randomly opened during recess and are all closed during class. The front and back doors are randomly opened during recess and are all closed during class. The front and back doors are randomly opened during recess and are all closed during class. There is a front door and a back door, both 1.2 m wide.

2.1.2. Characteristics of the subjects

Each lecture lasted 45 min, with a 10-min break. The classroom was exclusively for architectural students, designed specifically for architectural instruction. The course content for each class was tailored to meet the requirements of the major, as shown in **Table 1**.

Table 1. Course content for each week.

Number of weeks	Course content	
	0–45 min	55–100 min
1	TL, GD, RS, SD	TL, GD, RS, SD
2, 3, 5, 6, 7, 9, 10, 11, 13, 14, 15	TL	GD, SD
4, 8, 12, 16	GD, AF	RS

Teacher lecture (TL): When the teacher is lecturing, the teacher utilizes multimedia and a laser pointer together for teaching (the classroom is not equipped with chalk), walks back and forth at random sometimes, and talks. The students remained seated, listened to the lectures, and took notes. Random answers to questions.

Group discussion (GD): During the group discussion, the teacher walked back and forth and answered questions. Students sat in groups of 5–6, maintaining their positions while conversing.

Report on stage (RS): While reporting on stage, the teacher stood up, listened, and asked questions. Students stood on the platform, delivering presentations lasting 10 min each, with four students presenting each time. The other groups were also able to ask questions.

Student drawing designs (SD): For students drawing designs, the teacher walks back and forth randomly to answer questions. Students sit or stand to draw designs, and everyone uses a laptop to communicate with each other.

Analogue formation (AF): When creating the model, the teacher walked back and forth randomly to answer questions. Students sat or stood to create models and communicate with one another.

There were 26 students (20 males and 6 females) in this professional class in full attendance. The personal information of the 26 students is shown in **Table 2**. The students attending the class were 19 ± 1 year old, with an average skin surface area of 1.82 ± 0.17 m^2 and a body mass index of 20.77 ± 2.60 kg/m^2. All the students were in good health and did not engage in smoking and other bad habits. Furthermore, there was a female teacher and an experimenter in the classroom. Considering the absence of any students, the population density in the classroom should be 0.32–0.39 $persons/m^2$. However, not everyone left the classroom during the 10-minute break, and the study did not count how many students stayed in the classroom during the 10-minute break in the 16 experiments. The number of students in the classroom for each experiment is listed in **Table 3**.

Table 2. Personal information of subjects and invitees (mean value ± standard deviation).

Role	Number of persons	Height (m)	Weight (kg)	Age (years)	Average skin surface area (m^2)	Body mass index (kg/m^2)
Subjects	20 males/6 females	1.75 ± 0.16	70.7 ± 20.21	19 ± 1	1.82 ± 0.17	22.77 ± 2.60
Invitees	13 males/13 females	1.72 ± 0.07	70.1 ± 15.56	23 ± 1	1.76 ± 0.25	22.26 ± 5.50

Note. Skin surface area = 0.202 × $(\text{weight})^{0.425}$ × $(\text{height})^{0.725}$ [47], Body mass index = $\text{weight}/\text{height}^2$.

Table 3. Number of students and population density of classrooms during each measurement.

Number	Date	Total number of persons	Males	Females	population density ($person/m^2$)
1	28th, eb.	28	20	8	0.39
2	7th, Mar.	28	20	8	0.39
3	14th, ar.	28	20	8	0.39
4a	21st, ar.	27	20	7	0.38
5b	28th, Mar.	26	20	6	0.36
6	4th, Apr.	28	20	8	0.39
7	11th, pr.	28	20	8	0.39
8	18th, pr.	28	20	8	0.39
9	25th, pr.	27	20	7	0.38
10	9th, May.	25	19	6	0.35
11	16th, ay.	23	18	5	0.32
12	23rd, ay.	28	20	8	0.39
13	30th, ay.	27	20	7	0.38
14	6th, Jun.	28	20	8	0.39
15A	13th, un.	26	18	8	0.36
16B	20th, Jun.	28	20	8	0.39

Another group of 26 postgraduate students in a professional class were invited for sensory assessment in the intervention measurements. Their personal information is shown in **Table 3**. The invitees were 23 ± 1 years old, with an average skin surface area of 1.76 ± 0.25 m^2 and a body mass index of 22.26 ± 5.50 kg/m^2. All students were in good health, and the male-to-female ratio was 1:1. There were no significant differences in the anthropometric data.

2.1.3. Characteristics of the vocational class studied

The architectural design course of architecture major has the following characteristics: the lecture is taught by the teacher in the first 45 min, then the students draw with a laptop, and they could communicate with others in the second 45 min. At the same time, the teacher could arrange for the students to report the drawing content irregularly in the second 45 min. The architectural design courses are taught in this form in universities in China. The architectural design is the main course for architecture major, consisting of architectural design (1) to (8), with one architectural design course per semester.

2.2. Experimental procedures

The detailed steps of the basic and interventional measurements are shown in **Figure 2**. Before the basic measurement, the students entered the classroom successively, and the environmental measurements began at 8 a.m. (i.e., 0 min for the lecture). These measurements included an unceasing monitor of the air temperature, relative humidity, and CO_2 concentration. The TVOC concentration was recorded intermittently every 5 min at 0, 20, 40, 55, 75, and 95 min during class. There was a 10-minute break between classes from 8:45 a.m. to 8:55 a.m., allowing students to enter and exit the classroom freely through the front and back doors. At other times, the classroom doors and windows were closed.

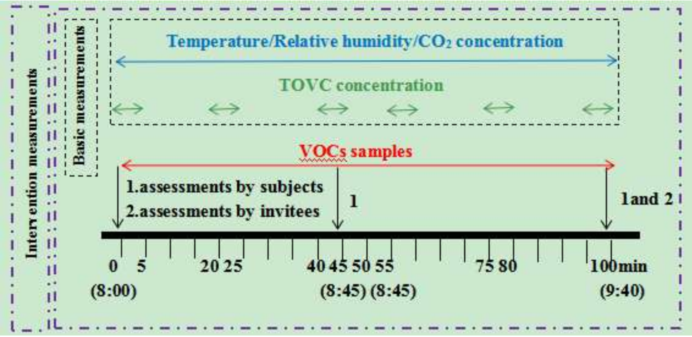

Figure 2. Procedures for basic and intervention measurements.

The intervention measurements and the basic measurement process were essentially the same, but with some differences. (1) For the intervention group (tests 5 and 16), the indoor temperature was maintained at 25 ± 1.5 °C using an air conditioner, while for the control group (tests 4 and 15), the indoor temperature changed naturally without an air conditioner. (2) Volatile organic compound sampling was conducted for 100 min before and during the class in all four intervention measurements. (3) Subjective evaluations of classroom air perception quality were collected from the subjects and invitees during the class in the four intervention measurements. The subjects were in class all the time, and they completed the questionnaires three times at 0, 45, and 100 min; the invitees came in at 0 and 100 min, and they completed the questionnaires twice at 0 and 100 min, respectively.

2.3. Environmental element measurements

The instruments and parameters used for these 16 measurements are listed in **Table 4**. The indoor CO_2 concentration, temperature, and relative humidity were continuously recorded using a TR-76 Ui-s instrument at 1-min intervals. Prior to formal measurements, all instruments were calibrated by certified quality inspection agencies. The TVOC concentration was measured using a portable VOC detector (TSI EMV-7) calibrated with isobutylene as the standard gas before using the instrument. TVOC concentrations were recorded intermittently every 5 min at 0, 20, 40, 55, 75, and 95 min during class with data recording intervals of 1 s. Finally, the average value at 5 min was considered the indoor TVOC concentration value of the corresponding period. The three measurement points shown in **Figure 1** as 1, 2, 3, 4, and 5 were arranged on a desk along the room diagonal at equal intervals in the horizontal direction. The table is 0.76 m high. Considering that students sit in class, we can avoid blocking the sight with instrument shelves. Obtain a more complete representation of the temperature, relative humidity, and CO_2 concentration distributions in the classroom. The TVOC concentration had only one measurement point, located at the centre of the student. As shown in **Figure 1**, the temperature, relative humidity, and CO_2 concentration were measured in numbers '1, 2, and 5'; TVOC was measured in number '3'; and VOCs were measured in number '4'. It should be noted that, owing to the needs of the experiment, the three desks were empty; that is, no students were sitting there during class.

Table 4. Instrument specifications.

Measured parameters	Instruments	Manufacturers	Measurement range	Measurement accuracy	Recording interval
Temperature (°C)	TR-76 Ui-s	T&D	0–55	± 0.5	1 min
Relative humidity (%)			10–95	± 2.5%	1 min
CO_2 (ppmv)			0–9999	± (50 ppmv + 5% reading)	1 min
TVOC (ppbm)	TSI EMV-7	TSI	0–500000	± 5%	1 s

In addition to these parameters, VOCs were also sampled from the intervention measurements (Tests 4, 5, 15, and 16). An automatic sampler GSP-400FT (GASTEC) and an activated carbon tube 258A-20-20 (GASTE) were selected as the sampling devices. Samples were taken before class, when nobody was present, and during that class for a duration of 100 min. All samples were stored in a −5 °C reservoir and later sent to a specialized laboratory for processing and analysis. After pretreatment in the laboratory, all samples underwent gas chromatography-mass spectrometry (GC Orbitrap, Thermo Fisher Scientific). Full-scan MS acquisition was performed using an m/z range of 30–400 with a resolution of 60,000 FWHM. The outlet and inlet temperatures were set at 230 °C and 280 °C, respectively, and the shunt samples were ionized by EI with a shunt ratio of 10:1. The MS transmission line temperature was 230 °C, the temperature of the electronic ionization source was 260 °C, and the obtained data were processed using Trace Finder 5.1 data processing software. Finally, the detected compounds, their corresponding retention times, and chromatographic peak intensity values were determined.

It should be noted that the indoor and outdoor measurements were conducted simultaneously, which included outdoor relative humidity, outdoor temperature, and outdoor CO_2 concentration. The data were collected by the instrument TR-76Ui-s placed on the windowsill outside the classroom at a 1-min interval.

2.4. Questionnaire survey

In addition to personal information such as sex, age, height, weight, health status, and bad habits, the questionnaire survey also included information on the perception of air quality in the classroom, such as odor intensity, acceptability, and satisfaction with air quality [48]. Odor intensity was assessed using 6 points of consecutive grades, namely, no odor (0), slight odor (1), moderate odor (2), strong odor (3), very strong odor (4), and overwhelming odor (5). The air quality acceptability was two consecutive grades: from obviously unacceptable (−2) to just unacceptable (−1), from just acceptable (0) to fully acceptable (1); Air quality satisfaction was assessed by consecutive grades with two ends, with dissatisfaction (0) and satisfaction (1).

2.5. Calculation of the CO_2 emission rate of the members in the classroom

As the main source of CO_2 in the classroom were the classroom members, the mean CO_2 emission rate of the members was calculated after measuring the indoor CO_2 concentration. Each 100-min measurement was divided into two cycles with a 10-minute break, and the interval in which the concentrations of CO_2 increased steadily in every cycle was truncated for calculating. According to the indoor CO_2 mass balance equation in Equation (1), the formula for calculating the personnel CO_2 emission rate can be obtained using the integral conversion method of Equation (2).

$$\frac{d(C_iV)}{dt} = GN + C_{out}Q - C_iQ \tag{1}$$

$$G = 10^{-6} \times \frac{Q}{N} \times \left(\frac{C_1 - C_2}{e^{-\frac{Q}{V}\Delta t} - 1} + C_1 - C_{out}\right) \tag{2}$$

where C_i is the measured indoor CO_2 concentration (C_1 is the indoor CO_2 concentration which is recorded at 10 and 60 min of class, C_2 is the CO_2 concentration which is recorded at 30 and 80 min of class, ppmv), V is the classroom volume (228 m^3), t is the time of C_i (minute), G is the human CO_2 emission rate (L/h per person), N is the number of students remaining in the classroom, and C_{out} is the outdoor CO_2 concentration, with 470 ± 26 ppmv as measured by the TR-76 Ui-s instrument. Q is the ventilation rate of the classroom with all the windows and doors closed, and 26.0 L/s as measured using the tracer gas (CO_2) concentration decay method [49]. Δt is the time interval (20 min) of the calculation period.

The uncertainty of the CO_2 emission rate Equation (3) was calculated following the uncertainty analysis in JJF 1059.1–2012 'Evaluation and expression of measurement uncertainty' [48].

$$U_c\,(y) = \sqrt{\sum_{i=1}^{n} \left[\frac{\partial f}{\partial x_i}\right]^2 u^2(x_i)} \tag{3}$$

where the derivative term $\frac{\partial f}{\partial x_i}$ is the sensitivity coefficient of the input variable x_{i}, and $u^2\,(x_{\mathrm{i}})$ is the standard uncertainty of the input variable x_{i}.

The uncertainty in the CO_2 emission rate includes the following variables: (1) Uncertainty in the measurement of the CO_2 concentration due to an indication error, calculated as $u(x) = \frac{a}{k}$ where a is the instrument precision specified by the manufacturer. That is, the CO_2 concentration measured by the TR-76 Ui-s instrument is 50 ppmv, and k has a confidence factor of 1.732; (2) The CO_2 concentration uncertainty is caused by multiple measurements, which are calculated by the range method. The expression is $u(x) = \frac{R}{C\sqrt{n}}$, where R is the difference range, C is the confidence factor equal to 1.64, and n is the number of measurements, which was three in this study. (3) Uncertainty in the ventilation rate gained by the CO_2 concentration decay method and (4) uncertainty in the classroom volume were considered. The change in the net classroom volume caused by the number of members in the classroom was estimated to be less than 0.12 m^3; therefore, the uncertainty caused by volume could be ignored.

3. Results

3.1. Thermal environment in the field measurement

3.1.1. Temperature

Figure 3 shows the changes in indoor and outdoor temperatures during the measurement process. (1) The change in outdoor temperature: the average outdoor temperature gradually increased from 11.4 °C to 30.1 °C due to seasonal changes from spring to summer. Additionally, the outdoor temperatures also increased by 1.5–3.3 °C during each 100-min measurement, especially in test 16 on 20th June with the fastest rise.

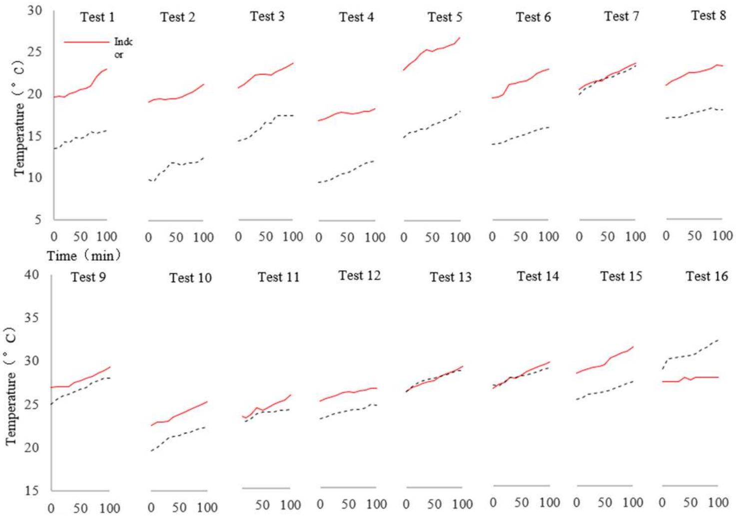

Figure 3. Indoor and outdoor air temperature in 16 tests.

(2) The change of indoor temperature: the average indoor temperature showed an upward trend from February to June, with the lowest being 17.8 °C and the highest being 29.2 °C, also influencing seasonal changes. An air conditioner was used to control the indoor temperature for the intervention measurements in tests 5 and 16. The measurement results indicated that the indoor temperature was 25 ± 1.5 °C, which showed that the indoor temperature was well controlled with the air conditioner in the classroom and could meet the conditions of the experiment. At the same time, during the 100-minute measurement period, the indoor temperature gradually increased by 1.0–4.0 °C because the doors and windows were closed during the class, and the indoor temperature was mainly affected by the various behaviors of the members in the classroom. In test 1, the teacher arranged four course contents, and the students were very active, resulting in an increase of 3.4 °C in the indoor temperature of the classroom within 100 min. In tests 2, 3, 5, 6, 7, 9, 10, 11, 13, 14, and 15, the intervention measurements were conducted during the 0–45 min and 55–100 min intervals. In test 5, which took place in spring, the classroom temperature increased by 4.0 °C, the highest among all test groups, due to the air conditioner heating. While comparing 0–45 min and 55–100 min, the amplitude of the temperature increases also differed from the different behaviors of the members in the classroom. Overall, the magnitude of the increase in the indoor temperature within 0–45 min was less than that within 55–100 min. In tests 4, 8, 12, and 16, the intervention measurements were conducted during 0–45 min and 55–100 min intervals. In test 16, which took place in summer with the air conditioner refrigeration, the indoor temperature decreased by 1.0 °C within 100 min. While comparing 0–45 min and 55–100 min, test 16, the amplitude of the temperature change was not obvious under the influence of air conditioning. For Tests 4, 8, and 12, the magnitude of the indoor temperature increases within 0–45 min is greater than that within 55–100 min. In addition, there was a 10-min break for the 16 test groups; although the front and back doors were randomly opened at this time, the indoor temperature was not significantly affected by the short opening time.

(3) Comparison of the indoor and outdoor temperature: the temperature difference between indoor and outdoor was 0.9–6.4 °C, which may be due to the influence of the building envelope making the indoor temperature higher than that of the outdoor temperature.

It is worth mentioning that the indoor and outdoor temperatures in Test 7 were essentially the same before class, and similar conditions were found in Tests 11, 13, and 14. This was because the doors and windows of the classroom were open before class in these four tests. After confirming with the logistics staff of the teaching building, the students who used the classroom the night before forgot to close the doors and windows, which led to the above results.

3.1.2. Relative humidity

Figure 4 shows the calculation results for the indoor and outdoor relative humidity. It can be seen that: (1) The change of outdoor relative humidity: the average outdoor relative humidity was 35.7%–93.6%, and the outdoor relative humidity increased with the outdoor temperature. In addition to seasonal factors, this could be because the experimental classroom is near the Fengze River, and a higher outdoor temperature could lead to more water vapor in the air, which, in turn, increases the relative humidity outside. However, regardless of the outdoor temperature, the outdoor relative humidity exceeded 80% on rainy days, as shown in Tests 3, 4, 9, 10, 12, 13, 15, and 16. This shows that the relationship between the outdoor relative humidity and temperature on rainy days is not obvious. Meanwhile, the outdoor relative humidity remained in a relatively stable state during the 100-minute measurement, ranging from 0.0–1.5%. This may be because the outdoor temperature increased from 1.5–3.3 °C, but did not increase enough to cause excessive changes in the outdoor relative humidity.

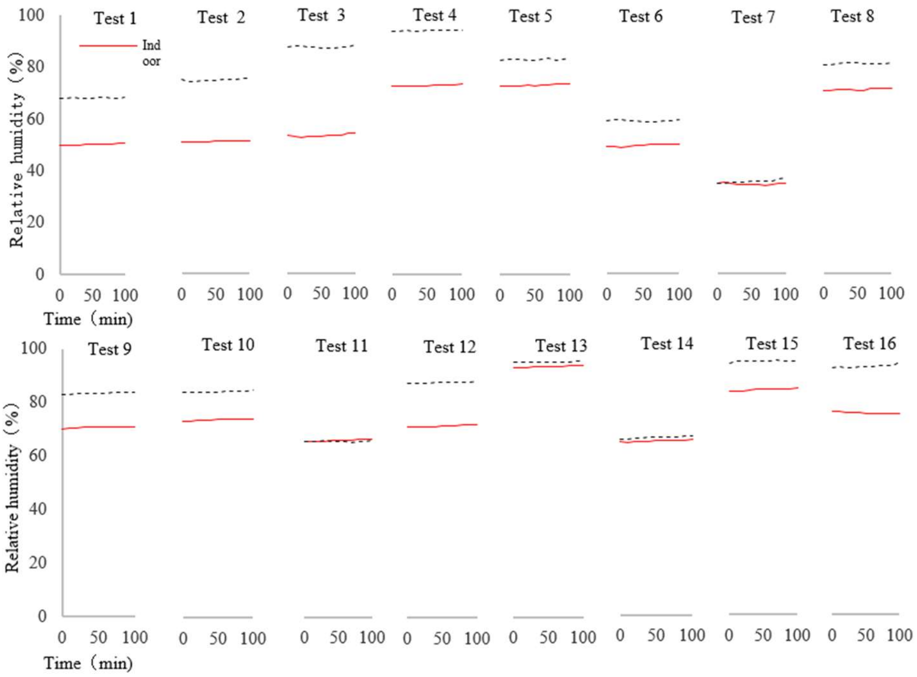

Figure 4. Indoor and outdoor relative humidity in 16 tests.

(2) Change in the indoor relative humidity: the average indoor relative humidity ranged from 34.5%–91.0%. Meanwhile, the indoor relative humidity fluctuated slightly in the range of 0.0%–1.0% during the 100-minute measurement. The doors and windows were closed during class; therefore, the indoor relative humidity was mainly affected by the indoor temperature and indoor members' breathing. However, the indoor relative humidity did not change much, which may be due to the following: first, the increase in the indoor temperature was not sufficient to cause a change in the indoor relative humidity; second, the population density of 0.32–0.39 people/m^2 in the classroom was too low to affect the indoor relative humidity. Meanwhile, the indoor relative humidity increased by 0.5% for intervention measurement 5 and decreased by 0.8% for intervention measurement 16 within 100 min, indicating that the intervention measurement did not have a significant impact on the indoor relative humidity. In addition, the indoor relative humidity was not significantly affected by the short door-opening time during a 10-min break.

(3) Comparison of indoor and outdoor relative humidity: the relative humidity difference between indoors and outdoors was 1.1%–26.0%. The indoor and outdoor relative humidities in Test 7 were basically the same before class, and similar

conditions were found in Tests 11, 13, and 14.

Except for the mean values, the measured indoor temperature and relative humidity uncertainties were calculated in this study, as listed in **Table 5**. The uncertainty for the indoor temperature and indoor relative humidity was 0.5 ± 0.1 ℃ and 1.6 ± 0.2%, respectively. The relative errors were below 3% and 4%, respectively.

Table 5. Uncertainty for the three measurement points: indoor temperature, relative humidity and CO_2 concentration.

	(Mean value ± standard deviation)	**Ranges**
Indoor temperature (℃)	0.5 ± 0.1	0.4–0.7
Indoor relative humidity (%)	1.6 ± 0.2	1.4–2.0
CO_2 concentration (ppmv)	99 ± 7	80–110

3.2. CO_2 concentration measurement

The indoor CO_2 concentration measured in the classroom was shown in **Figure 5** and was 500–887 ppmv at the beginning of the lecture. During class, the indoor CO_2 concentration gradually increased because of the accumulation of CO_2 produced by classroom members when the doors and windows were closed. The opening of the front and back doors during a 10-min break resulted in a transient decrease in the indoor CO_2 concentration. Subsequently, the CO_2 concentration continued to increase, reaching 2100–3600 ppmv by the end of the class. The average indoor CO_2 concentration was 1176.9–2031.7 ppmv during the 16 tests, and the real-time CO_2 concentration above 1000 ppmv was about 90% of the class duration. Overall, the trend in the CO_2 concentration was consistent with that of the indoor temperature. In tests 1, 2, 3, 5, 6, 7, 9, 10, 11, 13, 14, and 15, test 5 exhibited the fastest increase in CO_2 concentration within 100 min. The increase of 0–45 min in the CO_2 concentration was less than that at 55–100 min CO_2 concentration. In tests 4, 8, 12, and 16, there was no significant difference in the magnitude of the CO_2 concentration rise within 100 min for test 16. At tests 4, 8, and 12, the 0–45 min CO_2 concentration increases were greater than the 55–100 min CO_2 concentration increases.

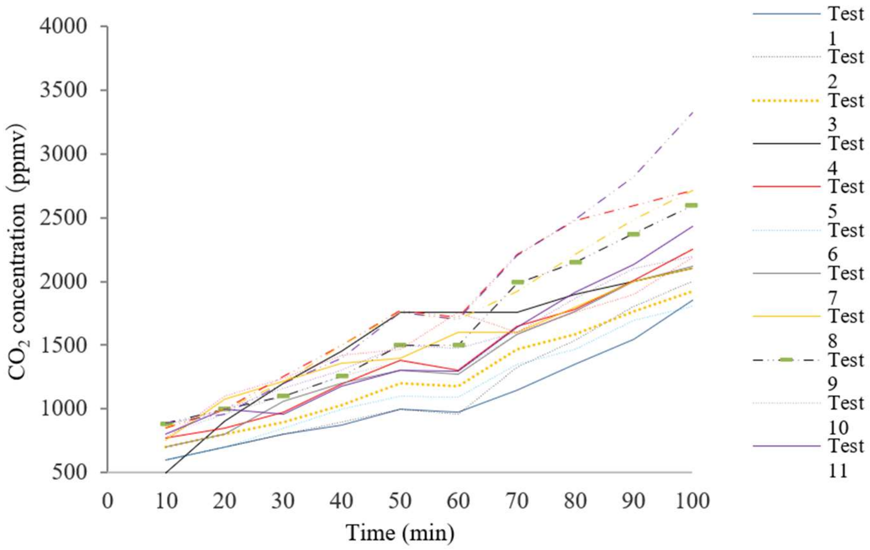

Figure 5. Measured indoor CO_2 concentration during 100-min class.

The average indoor temperature during the corresponding period was calculated in this study. **Figure 6** shows the calculated average CO_2 emission rates and indoor temperatures. The average emission rate of CO_2 was 22.76 ± 3.26 L/h for each person, with an uncertainty for the average emission rate of CO_2 of 2.6 L/h for each person approximately. The resulting relative error was less than 7%. It is evident that there is a positive correlation between human CO_2 emission rate and indoor temperature ($p < 0.05$), namely, the increased indoor temperature would cause an increase in human CO_2 emission rate. Based on the regression analysis, it can be estimated that the human CO_2 emission rate increases by 0.78 L/h for each person when the temperature increases by 1 ℃ with the range of 17 ℃–31 ℃. According to ASHRAE 62.1 [50], the CO_2 emission rate of adult males in standard sedentary and reading states was approximately 15.48 L/h. Therefore, the human CO_2 emission rate increased by approximately 4.5% for every 1 ℃ increase in temperature.

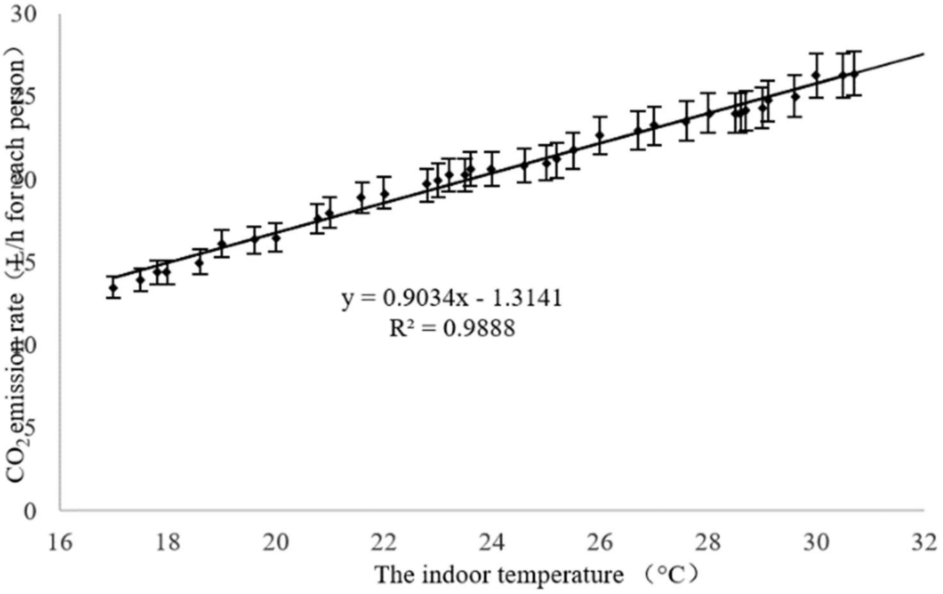

Figure 6. The CO_2 emission rate at different temperature.

3.3. TVOC concentration measurement

Figure 7 shows the results of TVOC concentration measurements conducted in the classroom. The mean TVOC concentration varied widely across 16 measurements, with the maximum and minimum values being 1026 ± 13 ppbm and 520 ± 7 ppbm, respectively. The mean TVOC concentration across the 16 measurements was 706 ± 276 ppb. Comparatively, TVOC concentrations in Tests 9 and 15 were higher from 0 min than the other test groups because of the higher indoor temperatures of the two groups from the beginning. The TVOC concentration in test 5 showed an obvious upward trend with air conditioner heating, and the indoor temperature rose rapidly, leading to a rapid rise in the TVOC concentration; however, it remained stable in test 16, also utilizing an air conditioner, alongside a consistent indoor temperature.

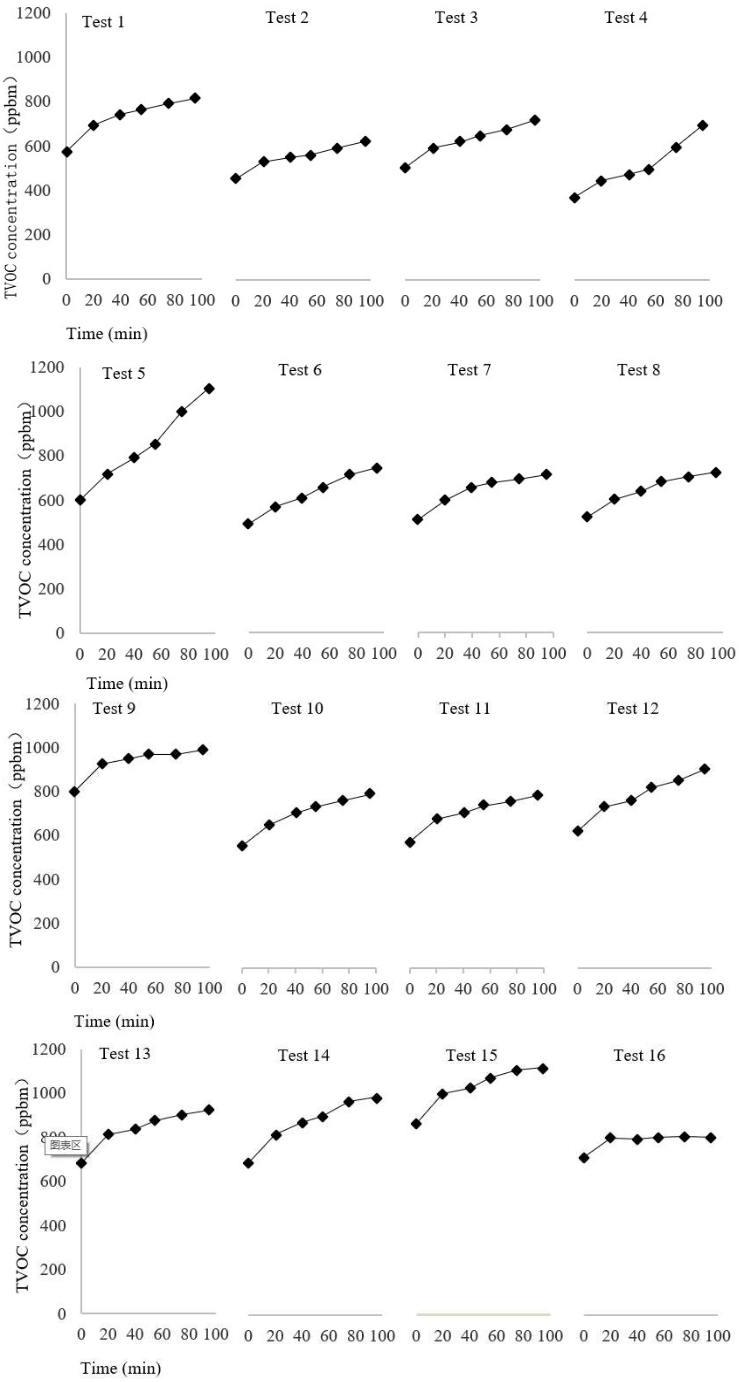

Figure 7. Measured indoor TVOC concentration during 100-min class.

Zheng et al. [51] and Jia et al. [28] showed that the indoor TVOC concentration change exhibited a trend similar to that of the CO_2 concentration, both rising slowly, which is consistent with the results of this study. However, their study also indicated that the average indoor TVOC concentration in spring and summer was 400.5 ± 26 ppbm and 296 ± 30 ppbm, respectively, which was inconsistent with the average TVOC concentration (706 ± 276 ppbm) in this study. This may be because, although the number of indoor personnel, the typical activity of personnel, the opening or closing of doors and windows, and the function of the classroom were different in spring and summer, the average indoor TVOC concentration was also different.

3.4. Indoor VOCs composition

Eight air samples were collected before and during the four intervention experiments (tests 4, 5, 15, and 16), and 40 common compounds were detected, which is shown in **Table 6**. Most of the VOCs detected were exogenous.

Table 6. The volatile organic compounds detected in the surveyed classrooms.

No.	Component name	CAS No.	No.	Component name	CAS No.
1	Benzonitrile	100-47-0	21	Benzene, 1,3-dichloro-2-isocyano-(9CI)	6697-95-6
2	2-Methylthiophene	554-14-3	22	Ethylbenzene	100-41-4
3	1-Ethyl-3-methylbenzene	620-14-4	23	Naphthalene	91-20-3
4	Mesitylene	108-67-8	24	Isoprene	78-79-5
5	Dodecane	112-40-3	25	1,3-Butanediol	107-88-0
6	Butylated Hydroxytoluene	128-37-0	26	Thiophene	110-02-1
7	Benzene	71-43-2	27	Heptanal	111-71-7
8	2,4-Dithiapentane	1618-26-4	28	Benzothiazole	95-16-9
9	2-methyl-5-(1-methylethyl) bicyclo [3.1.0] hex-2-ene	2867/5/2	29	Styrene	100-42-5
10	4-Isopropylbiphenyl	7116-95-2	30	p-Xylene	106-42-3
11	o-Xylene	95-47-6	31	1,4-Dichlorobenzene	106-46-7
12	Acetone	67-64-1	32	3,4-Dimethylbenz	5973-71-7
13	Dimethyldisulfide	624-92-0	33	Formaldehyde	50-00-0
14	Methyl propyl trisulfide	17619-36-2	34	(1-Butyloctyl) benzene	2719-63-3
15	(1-Methylethyl) benzene (Cumene)	98-82-8	35	Propylbenzene	103-65-1
16	Methyl propyl disulfide	2179-60-4	36	1-Ethyl-2-methylbenzene	611-14-3
17	Tetrachloroethylene	127-18-4	37	Toluene	108-88-3
18	1,6-Dimethyl-4-(1-methylethyl) naphthalene	483-78-3	38	Phenol	108-95-2
19	m-Xylene	108-38-3	39	1-Ethyl-4-methylbenzene	622-96-8
20	Isophyllocladene	511-85-3	40	1,1′-Biphenyl, 3,4-diethyl-	61141-66-0

For a more detailed understanding of the differences in the indoor VOC composition at different temperatures before (0 min) and during (100 min) classes, two air samples collected in each intervention experiment were analyzed in this study. The results of Tests 4 and 16 (**Figure 8**), and Tests 5 and 15 (**Figure 9**) were generally consistent. The relative concentration difference of the same component was qualitatively determined from the chromatogram.

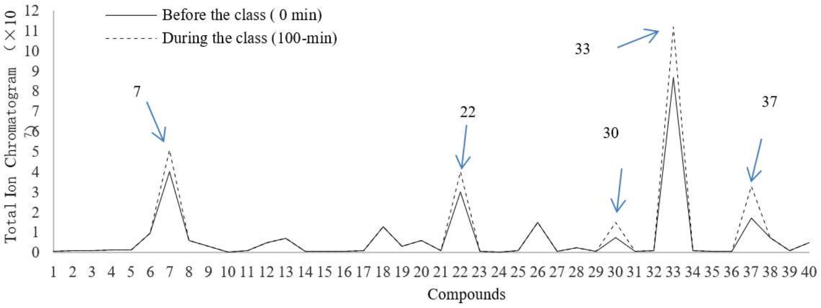

Figure 8. Chromatography comparison of sampling results before and after Class (Test 4 and 16).

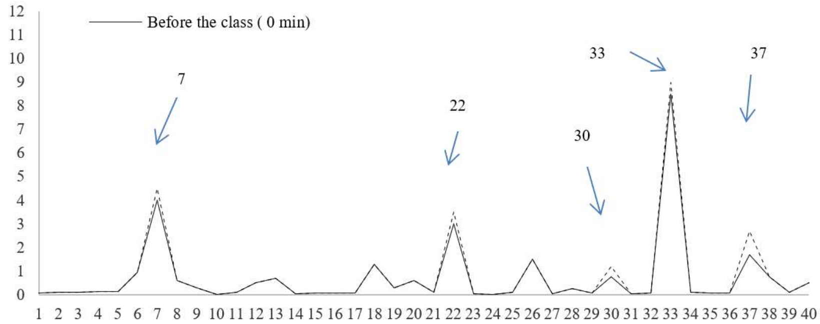

Figure 9. Chromatography comparison of sampling results before and after class (Test 5 and 15).

In tests 4 and 16, the concentrations of benzene (No. 7), ethylbenzene (No. 22), *p*-xylene (No. 30), formaldehyde (No. 33), and toluene (No. 37) increased significantly, whereas the levels of the other 35 components remained unchanged. In tests 5 and 15, the trends were similar, but the five compounds increased less than those in tests 4 and 16. This difference could possibly be attributed to the fact that in Tests 4 and 16, the building materials for the models were kept in the classroom with the doors and windows closed during classes. In Tests 5 and 15, there was no model in the class; therefore, there were no other building materials in the classroom.

3.5. Air quality assessment in the classroom in the intervention experiments

The subjective perceptions of indoor air quality by subjects experiencing adaptation in the classroom and by invitees upon entering the intervention experiment are shown in **Figure 10**. The results demonstrated that the air quality satisfaction and acceptability of Tests 5, 15, and 16 were significantly lower than those of Test 4, and the odor intensity was significantly stronger than that of Test 4. Furthermore, this difference persisted with an increase in stay time. Since the mean indoor temperature for tests 4, 5, 15, and 16 was 17.8 °C, 25.2 °C, 29.2 °C and 27.3 °C, respectively (seen analysis in 3.1 above), it could be concluded that there was a reduced perceived air quality along with the increased temperature and stay time.

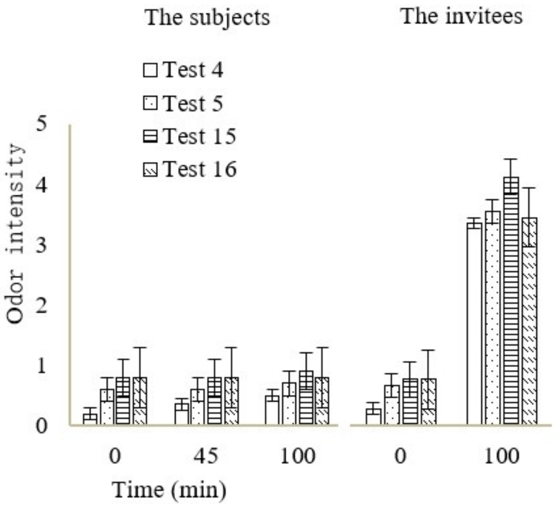

Figure 10. (*Continued*).

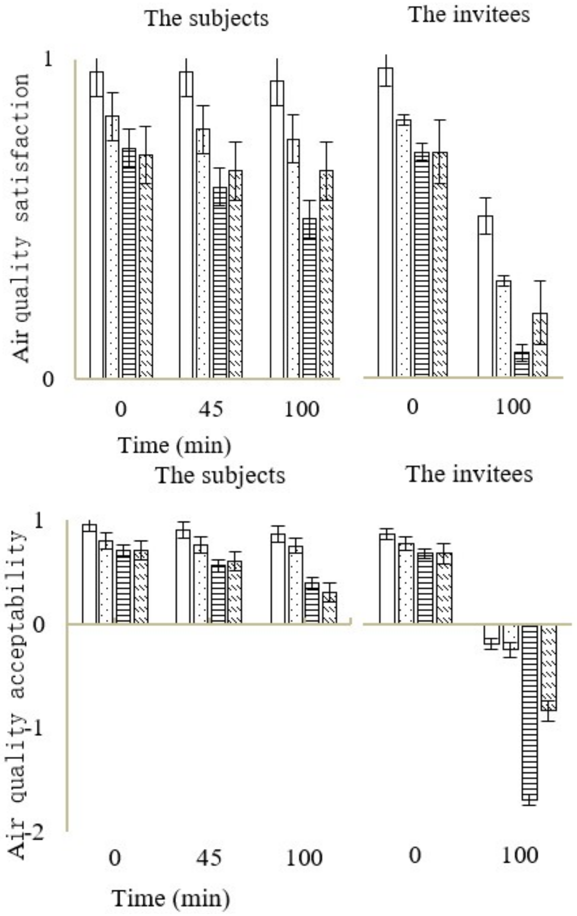

Figure 10. Air quality assessment performed by subjects and invitees in the intervention experiments.

Note: L represents the CO_2 concentration (ppmv) corresponding to the 0, 45 and 100 min of the test group. From **Figure 5**, A-D values were 500, 776, 887, 876, E-H values were 1760, 1380, 1760 and 1500, and I-L values were 2200, 2595, 3600 and 2430, respectively.

From the analysis in Section 3.2, the CO_2 concentrations in tests 4, 5, 15, and 16 were 500, 776, 887, and 876 ppmv at 0 min, 1760, 1380, 1760, and 1500 ppmv at 45 min, and 2200, 2595, 3600, and 2430 ppmv at 100 minutes, respectively. Therefore, the premise of the air quality assessment in this study was that the CO_2 concentration should be 500–3600 ppmv.

According to the odor intensity results, the evaluation of tests 4, 5, 15, and 16 at 0, 45, and 100 min was between no odor and a slight odor, and test 4 was closer to no odor. For the invitees, the evaluation of the four groups ranged between no odor and slight odor at 0 min. There was greater variation at 100 min, with a strong odor in tests 4, 5, and 16, and a very strong odor in test 15.

Based on the results of air quality satisfaction and acceptability, the evaluation of Test 4 was the highest among the four tests of the corresponding test times for both the subjects and invitees. The evaluations of the two groups were very similar at 0 min; however, when the CO_2 concentration was above 2000 ppmv at 100 minutes, the evaluation value of the invitees was lower than that of the subjects. The invitees were more dissatisfied with air quality satisfaction on tests 4, 5, 15, and 16. In tests 4, 5, and 16, the evaluation range of air quality acceptability for the invitees was between just unacceptable and just acceptable. In Test 15, the corresponding evaluation results were almost unacceptable.

The above analysis shows that the subjects had a better perception of air quality than the interviewees, with lower perceived odor intensity and higher satisfaction and acceptability of air quality. This difference seems reasonable, considering that the subjects stayed continuously in the classroom and had strong olfactory adaptation. The results of this study were inconsistent with those of Liu et al. [9], who indicated that respondents' acceptance of indoor air quality was mainly influenced by thermal sensations, independent of the CO_2 concentration. This may be because 1) Liu's study focused on the winter semester, whereas this study focused on spring and summer. 2) Liu's study investigated students' thermal comfort and perceived air quality in naturally ventilated university classrooms while the doors and windows were closed during class.

4. Discussion

4.1. Influence of indoor temperature on the CO_2 emission rate of the human body

The average CO_2 emission rate ranged from 19.5–26.02 L/h per person, which was higher than that reported in previous studies. Qi et al. [52] showed experimentally that the CO_2 emission rate in sedentary was 13.57 L/h for Chinese males and 11.13 L/h for females at 22–24 ℃, respectively. Similarly, Wang [53] explained that the CO_2 emission rate for Chinese males and females in the sitting reading state was 16.2 L/h and 13.2 L/h, respectively, at a temperature of 26 ℃. This may be because in the 16 tests, the status of the subjects pointed out in previous studies was sedentary, whereas the status of the subjects in this study had many changes. Therefore, the average CO_2 emission rate obtained in this study was high.

Previous studies have suggested that the CO_2 emission rate depends mainly on the metabolic rate [54], which is determined by temperature [55]. Thus, an increase in temperature leads to a higher metabolic rate, subsequently resulting in higher CO_2 emission rates. Based on the results of the present study, it could be concluded that the human CO_2 emission rate increases by 0.78 L/h for each person when the temperature increases by 1 ℃ within the range of 17–31 ℃. This result is similar with that of Zhang [54], where the human thermal sensation ranged from neutral to warm between the temperatures at 26 ℃–32 ℃, resulting in a significant increase in CO_2 emissions. These results suggest that, compared to thermal neutrality, people emit more CO_2 when they feel thermal warmth. Similar findings have also been reported by Liu et al. [9], Luo et al. [56], and Kuga et al. [11], indicating a higher CO_2 emission rate occurred at higher temperatures when subjects were warm.

4.2. Modified ventilation rate corresponding to the human CO_2 emission rate

In this study, the trace gas (CO_2) concentration is used to measure the ventilation capacity in the classroom Equation (4). The trace gas method follows the principle of mass conservation and is calculated as follows:

$$\frac{dC}{dx} = \frac{Q}{V}(C_{out} - C_x)\frac{V_{co_2}}{V} \tag{4}$$

where $\frac{dC}{dx}$ is the outdoor airflow rate for each person (L/s); V is the classroom volume (228 m^3); C_x is the indoor CO_2 concentration (ppmv); C_{out} is the outdoor CO_2 concentration (470 ppmv); Q is the ventilation rate (L/S); and V_{co_2} is the human emission rate (L/s). To maintain the indoor CO_2 concentration at 1000 ppmv, the required ventilation rate per person was 6.75 L/s according to Equation (3). This result is largely consistent with ASHRAE 62.1 criteria [40]. In general, to maintain 1000 ppmv of indoor CO_2 concentration, the calculated ventilation rate for each person needs to increase by 0.25 ± 0.3 L/s to account for the increased human CO_2 emission because of the temperature rise.

4.3. Characteristics of the VOCs in the classroom

This study points out that the substances with the highest detection frequency were benzene, formaldehyde, toluene, *p*-xylene, and ethylbenzene. This result is similar to those of previous studies [15,57], which also identified benzene, *p*-xylene, ethylbenzene, and toluene as the most frequently detected in experimental classrooms. Benzene primarily originates from paint, adhesives, plates, foam plastics, etc.; formaldehyde from wood, glass glue, latex paint, paint, etc.; toluene and *p*-xylene from paint, plywood, foam filler, etc.; and ethylbenzene from paint, spray paint, adhesives, etc. Indoor concentrations of these substances are related to fatigue values [15], and excessive exposure to these substances increases the risk of cancer [57]. In conclusion, related research should focus on the pollutants released by various indoor building materials.

However, the VOC components detected in this study differed from those detected by Fu et al. [26], Kang et al. [58], and Liu et al. [59]. This may be because of different factors, including occupied conditions, season and function, classroom type, types of items inside the classroom, quality of furniture, and possible factors correlated with human-related items.

Furthermore, this study is inconsistent with the Zhang et al. [22] study, which indicated that the real-time difference of indoor VOC composition is more obvious when the indoor temperature is between 16 °C and 24 °C, and there is basically no difference in real-time of indoor VOC components when the indoor temperature is between 24 °C and 30 °C. Several factors contribute to these differences. First, regarding objective factors, the architecture classroom was renovated in January 2022, and furniture such as desks and chairs were also replaced. The renovations were completed in February 2022, but the windows were kept open for extended periods to ensure ventilation. Since it was winter, the effect of scattered taste was not the best. Second refers to subjective factors, that is, the content of the classroom is different. In tests 4 and 16, model-making activities were arranged, and the students brought a large quantity of building materials into the classroom; therefore, the concentration of some VOCs increased significantly over 100 min. Hence, it can be seen that the concentration of indoor VOCs is not only related to temperature but also to the above objective and subjective factors.

4.4. Deficiencies

The results of the current study contribute to the field of indoor air quality, but some shortcomings still remain. First, this experiment only covered spring and summer, and the data obtained did not reflect the actual conditions in autumn and winter. Therefore, future experiments should include at least two semesters covering all four seasons. Second, this study only performed a simple correlation analysis between the indoor air temperature and CO_2 emission rate. To further elucidate the association mechanism between air temperature and CO_2 emission rates, a wider temperature range should be investigated. Third, the experiment was conducted in a single classroom setting. If the experimental conditions permit, multiple classrooms with different orientations should be selected to conduct future experiments. Fourth, the current participants and invitees were only students from one class, and the number of students could be expanded in the future. Fifth, to ensure environmental safety, it is necessary to predict the long-term concentrations of VOCs, taking into account the effects of temperature changes. Simultaneously, source apportionment can be conducted to quantify the contribution rates of various sources of these targeted VOCs under actual conditions. Sixth, there are some difficulties encountered during data collection; a few subjects and invitees would be late. In several experiments, the teacher also delayed sometimes. As a result, the questionnaire may not be completed at a very precise time. Moreover, in the 16 experiments, students were absent some times, which cannot ensure the same number of students in each experiment.

5. Conclusion

In the spring semester of university, the average outdoor temperature ranged from 11.4 °C–30.1 °C, and the average outdoor relative humidity was 35.7%–93.6%. The average indoor temperature ranged from 17.8 °C–29.2 °C and the average indoor relative humidity was 34.5%–91.0%. In the 100-minute period, the indoor temperature generally increased by 1.0 °C–4.0 °C, and the indoor relative humidity fluctuated slightly in the range of 0.0%–1.0%.

Before and after the class, the average indoor CO_2 concentration was 500–887 ppmv and 2100–3600 ppmv, respectively. Across 16 tests, the average indoor CO_2 concentration was 1176.9–2031.7 ppmv. The average minimum and maximum concentrations of indoor TVOC were 520 ± 7 ppbm and 1026 ± 13 ppbm, respectively, and the average indoor TVOC concentration across the 16 tests was 706 ± 276 ppbm. The environmental results indicated that the thermal conditions in the surveyed classrooms were acceptable, but indoor air quality required improvement.

An increase in the indoor temperature has a negative effect on the perception of air quality. When the average classroom temperature increased from 17.8 °C to 26.3 °C, the subjects reported that the intensity of odors they experienced ranged between no odors and slight odors, while the invitees indicated a strong intensity. When the CO_2 concentration reached 2000 ppmv at 100 min, the air quality satisfaction and acceptability of the participants and invitees decreased significantly, and the evaluation value of the invitees was lower than that of the participants.

There was a significant positive correlation between the human CO_2 emission rate and indoor temperature. The human CO_2 emission rate was estimated to increase by 0.78 L/h for every 1 °C increase in temperature in the range of 17 °C–31 °C. To maintain an indoor CO_2 concentration of 1000 ppmv, the required ventilation rate per person must be increased by 0.25 ± 0.3 L/s.

A total of 16 universities in China offer architecture majors; the architectural design courses are taught in this form in universities in China. The architectural design is the main course for architecture major, consisting of architectural design (1) to (8), with one architectural design course per semester. Therefore, the results can be applicable to the same vocational classes in other universities.

Future research directions should include the following aspects, for example: further exploration of VOC sources, long-term monitoring in four seasons, expanded sample size and settings, recommendations for mitigation strategies, and educational outreach and policy implications. The above research content could help advance our understanding of IAQ management.

Funding: The authors of this paper would like to express their gratitude to Historical and cultural city research center (NO:13012001009027) for their financial support.

Conflict of interest: The author declares no conflict of interest.

References

1. Gao XY. Experimental Analysis of the Effect of Natural Ventilation on the CO_2 Concentration in Campus Classroom. Chongqing University; 2016. doi: CNKI:CDMD:2.1016.732242
2. Marchetti N, Cavazzini A, Pasti L, et al. A campus sustainability initiative: Indoor air quality monitoring in classrooms. In: Proceedings of the 2015 XVIII AISEM Annual Conference; 3-5 February 2015; Trento, Italy. doi: 10.1109/aisem.2015.7066774
3. Deng SH, Lau J. Seasonal variations of indoor air quality and thermal conditions and their correlations in 220 classrooms in the Midwestern United States. Building and Environment. 2019; 157: 79-88. doi: 10.1016/j.buildenv.2019.04.038
4. Shendell DG, Barnett C, Boese S. Science-Based Recommendations to Prevent or Reduce Potential Exposure to Biological, Chemical, and Physical Agents in Schools. Journal of School Health. 2004; 74(10): 390-396. doi: 10.1111/j.1746-1561.2004.tb06603.x
5. Clausen G, Carrick L, Fanger PO, et al. A Comparative Study of Discomfort Caused by Indoor Air Pollution, Thermal Load and Noisec. Indoor Air. 1993; 3(4): 255-262. doi: 10.1111/j.1600-0668.1993.00006.x
6. Kabirikopaei A, Lau J. Uncertainty analysis of various CO_2-based tracer-gas methods for estimating seasonal ventilation rates in classrooms with different mechanical systems. Building and Environment. 2020; 179: 107003. doi: 10.1016/j.buildenv.2020.107003
7. Rajagopalan P, Andamon MM, Woo J. Year long monitoring of indoor air quality and ventilation in school classrooms in Victoria, Australia. Architectural Science Review. 2021; 65(1): 1-13. doi: 10.1080/00038628.2021.1988892
8. Yu YZ, Wang B, You SJ, et al. The Effects of Manual Airing Strategies and Architectural Factors on the Indoor Air Quality in College Classrooms: A Case Study. Air Quality, Atmosphere & Health. 2021; 15(1): 1-13. doi: 10.1007/s11869-021-01074-y
9. Liu JL, Yang X, Jiang QW, et al. Occupants' thermal comfort and perceived air quality in natural ventilated classrooms during cold days. Building and Environment. 2019; 158: 73-82. doi: 10.1016/j.buildenv.2019.05.011
10. Coley DA, Beisteiner A. Carbon Dioxide Levels and Ventilation Rates in Schools. International Journal of Ventilation. 2002; 1(1): 45-52. doi: 10.1080/14733315.2002.11683621
11. Kuga K, Ito K, Wargocki P. The effects of warmth and CO_2 concentration, with and without bioeffluents, on the emission of CO_2 by occupants and physiological responses. Indoor Air. 2021; 31(6): 2176-2187. doi: 10.1111/ina.12852
12. Haddad S, Synnefa A, Ángel Padilla Marcos M, et al. On the potential of demand-controlled ventilation system to enhance indoor air quality and thermal condition in Australian school classrooms. Energy and Buildings. 2021; 238: 110838. doi: 10.1016/j.enbuild.2021.110838
13. Haverinen-Shaughnessy U, Shaughnessy RJ, Cole EC, et al. An assessment of indoor environmental quality in schools and

its association with health and performance. Building and Environment. 2015; 93: 35-40. doi: 10.1016/j.buildenv.2015.03.006

14. Mendell MJ, Eliseeva EA, Davies MM, et al. Do classroom ventilation rates in California elementary schools influence standardized test scores? Results from a prospective study. Indoor Air. 2015; 26(4): 546-557. doi: 10.1111/ina.12241
15. Korsavi SS, Montazami A, Mumovic D. Ventilation rates in naturally ventilated primary schools in the UK; Contextual, Occupant and Building-related (COB) factors. Building and Environment. 2020; 181: 107061. doi: 10.1016/j.buildenv.2020.107061
16. Mutmainnah N, Mulyadi R, Hamzah B. Air Quality Characteristics in Junior High School Classroom with Natural Ventilation in Pangkep Regency. EPI International Journal of Engineering. 2019; 2(2): 157-161. doi: 10.25042/epi-ije.082019.11
17. Shrestha M, Rijal HB, Kayo G, et al. An investigation on CO_2 concentration based on field survey and simulation in naturally ventilated Nepalese school buildings during summer. Building and Environment. 2022; 207: 108405. doi: 10.1016/j.buildenv.2021.108405
18. Taemthong W. Selecting Ventilation Fan Capacity for University Classroom Based on Empirical Data. International Journal of Environmental Science & Sustainable Development. 2019; 4(1): 13-21. doi: 10.21625/essd.v4i1.487
19. Chan WR, Li X, Singer BC, et al. Ventilation rates in California classrooms: Why many recent HVAC retrofits are not delivering sufficient ventilation. Building and Environment. 2020; 167: 106426. doi: 10.1016/j.buildenv.2019.106426
20. Cai CR, Sun ZW, Weschler LB, et al. Indoor air quality in schools in Beijing: Field tests, problems and recommendations. Building and Environment. 2021; 205: 108179. doi: 10.1016/j.buildenv.2021.108179
21. Sahu V, Gurjar, BR. Spatial and seasonal variation of air quality in different microenvironments of a technical university in India. Building and Environment. 2020; 185: 107310. doi: 10.1016/j.buildenv.2020.107310
22. Zhang D, Ding E, Bluyssen PM. Guidance to assess ventilation performance of a classroom based on CO_2 monitoring. Indoor and Built Environment. 2022; 31(4): 1107-1126. doi: 10.1177/1420326x211058743
23. Choe Y, Shin JS, Park J, et al. Inadequacy of air purifier for indoor air quality improvement in classrooms without external ventilation. Building and Environment. 2022; 207: 108450. doi: 10.1016/j.buildenv.2021.108450
24. Kierat W, Ai Z, Melikov A, et al. Towards enabling accurate measurements of CO_2 exposure indoors. Building and Environment. 2022; 213: 108883. doi: 10.1016/j.buildenv.2022.108883
25. Chi CC, Chen WD, Guo M, et al. Law and features of TVOC and Formaldehyde pollution in urban indoor air. Atmospheric Environment. 2016; 132: 85-90. doi: 10.1016/j.atmosenv.2016.02.043
26. Fu N, Wei P, Jia YB, et al. Indoor volatile organic compounds in densely occupied education buildings of four universities: Target list, concentration levels and correlation analysis. Building and Environment. 2021; 191: 107599. doi: 10.1016/j.buildenv.2021.107599
27. Huang LH, Qian H, Deng SX, et al. Urban residential indoor volatile organic compounds in summer, Beijing: Profile, concentration and source characterization. Atmospheric Environment. 2018; 188: 1-11. doi: 10.1016/j.atmosenv.2018.06.009
28. Jia YB, Zheng X, Guan J, et al. Investigation of indoor total volatile organic compound concentrations in densely occupied university buildings under natural ventilation: Temporal variation, correlation and source contribution. Indoor and Built Environment. 2020; 30(6): 838-850. doi: 10.1177/1420326x20914000
29. Sun X, He J, Yang X. Human breath as a source of VOCs in the built environment, Part I: A method for sampling and detection species. Building and Environment. 2017; 125: 565-573. doi: 10.1016/j.buildenv.2017.06.038
30. He J, Sun X, Yang X. Human respiratory system as sink for volatile organic compounds: Evidence from field measurements. Indoor Air. 2019; 29(6): 968-978. doi: 10.1111/ina.12602
31. Yang T, Xiong J, Tang X, et al. Predicting Indoor Emissions of Cyclic Volatile Methylsiloxanes from the Use of Personal Care Products by University Students. Environmental Science & Technology. 2018; 52(24): 14208-14215. doi: 10.1021/acs.est.8b00443
32. Xiong JY, He ZC, Tang XC, et al. Modeling the Time-Dependent Concentrations of Primary and Secondary Reaction Products of Ozone with Squalene in a University Classroom. Environmental Science & Technology. 2019; 53(14): 8262-8270. doi: 10.1021/acs.est.9b02302
33. Duan JH, Wang LX, Zhuo SH, et al. Seasonal variation of airborne phthalates in classroom and dormitory, and its exposure assessment in college students. Energy and Buildings. 2022; 265: 112078. doi: 10.1016/j.enbuild.2022.112078
34. Vallecillos L, Borrull A, Marcé RM, et al. Passive sampling to control air quality in schools: Uptake rate determination and

application. Indoor Air. 2020; 30(5): 1005-1017. doi: 10.1111/ina.12684

35. Vornanen-Winqvist C, Alapieti T, Mikkola R, et al. Volatile organic compounds in school buildings with indoor air quality problems. In: Proceedings of Joint annual meeting of the International Society of Exposure Science and the International Society for Environmental Epidemiology; 2019.
36. Fong ML, Lin Z, Fong KF, et al. Evaluation of thermal comfort conditions in a classroom with three ventilation methods. Indoor Air. 2011; 21(3): 231-239. doi: 10.1111/j.1600-0668.2010.00693.x
37. Gohara T, Iwashita G. Field study on the indoor air quality in elementary schllos in Kagoshima city: Part 1 VOCs concentrations in elementary schools. Journal of Architecture & Planning. 2002; 67(553): 63-70. doi: 10.3130/aija.67.63_2
38. Zhou JQ, Deng BQ, Kim CN. Numerical Simulation of VOCs Distribution with an Air Cleaner in a Classroom. International Symposium on Heating, Ventilating and Air Conditioning; 2009.
39. Can E, Özden Üzmez Ö, Döğeroğlu T, et al. Indoor air quality assessment in painting and printmaking department of a fine arts faculty building. Atmospheric Pollution Research. 2015; 6(6): 1035-1045. doi: 10.1016/j.apr.2015.05.008
40. ASHRAE. Standard 62.1., 2016. Ventilation for Acceptable Indoor Air Quality. American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.; 2016.
41. Committee ME-062, Ventilation and Air conditioning. Australian Standard, AS 1668.2-2012. The Use of Ventilation and Air Conditioning in Buildings, Part 2: Mechanical Ventilation in Buildings. Committee ME-062, Ventilation and Air Conditioning; 2012.
42. British Standards Institute. S. EN15251., 2008. Indoor Environmental Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment Lighting and Acoustics. British Standards Institute; 2008.
43. Verein Deutscher Ingenieure. VDI 6022 Part 3., 2011. Ventilation and Indoor Air Quality-Assessment of Indoor Air Quality. Verein Deutscher Ingenieure; 2011.
44. Ministry of Housing and Urban-Rural Development of the People’s Republic of China. GB, GB 50736. Design Code for Heating Ventilation and Air Conditioning of Civil Buildings. China Architecture & Building Press; 2012.
45. Park S, Park H, Seo J. Analysis on the Exhaust Air Recirculation of the Ventilation System in Multi-Story Building. Applied Sciences. 2021; 11(10): 4441. doi: 10.3390/app11104441
46. Rastogi K, Lohani D, Acharya D. Context-Aware Monitoring and Control of Ventilation Rate in Indoor Environments Using Internet of Things. IEEE Internet of Things Journal. 2021; 8(11): 9257-9267. doi: 10.1109/jiot.2021.3057919
47. Zhang XJ, Zhao CX, Zhang TY, et al. Association of indoor temperature and air quality in classrooms based on field and intervention measurements. Building and Environment. 2023; 229: 109925. doi: 10.1016/j.buildenv.2022.109925
48. The state bureau of quality and technical supervision of the People’s Republic of China. B/T, GB/T 18204.18-2000., 2000. Method for Determination of Air Change Flow of Indoor Air in Public Places. The State Bureau of Quality and Technical Supervision of the People’s Republic of China; 2000.
49. Jindal A. Investigation and analysis of thermal comfort in naturally ventilated secondary school classrooms in the composite climate of India. Architectural Science Review. 2019; 62(6): 466-484. doi: 10.1080/00038628.2019.1653818
50. Persily AK, Jonge LD. Carbon Dioxide Generation and Building Occupants. ASHRAE Journal. 2017; 59(7): 64-66.
51. Zheng X, Jia YB, Guan J, et al. Impact analysis of human emission on total volatile organic compound concentration in university classrooms: A field study. Heating Ventilating & Air Conditioning. 2020; 50(1): 115-121.
52. Qi MW, Li XF, Weschler LB, et al. CO_2 generation rate in Chinese people. Indoor Air. 2014; 24(6): 559-566. doi: 10.1111/ina.12110
53. Wang XN. Experimental Study of Human Carbon Dioxide Generaton Rate at Different Activity Levels. Xi’an University of Architecture and Technology; 2021.
54. Zhang YJ. The Experimental Research into the Influence of Temperature and Carbon Dioxide to Human Comfort in Small Space. Chongqing University; 2018.
55. Robinson WR, Peters RH, Zimmermann J. The effects of body size and temperature on metabolic rate of organisms. Canadian Journal of Zoology. 1983; 61(2): 281-288. doi: 10.1139/z83-037
56. Luo MH, Zhou X, Zhu YX, et al. Revisiting an overlooked parameter in thermal comfort studies, the metabolic rate. Energy and Buildings. 2016; 118: 152-159. doi: 10.1016/j.enbuild.2016.02.041
57. Li KW, Shen JD, Zhang X, et al. Variations and characteristics of particulate matter, black carbon and volatile organic compounds in primary school classrooms. Journal of Cleaner Production. 2020; 252: 119804. doi:

10.1016/j.jclepro.2019.119804

58. Kang J, Liu JJ, Pei JJ. The indoor volatile organic compound (VOC) characteristics and source identification in a new university campus in Tianjin, China. Journal of the Air & Waste Management Association. 2017; 67(6): 725-737. doi: 10.1080/10962247.2017.1280561
59. Liu S, Li R, Wild RJ, et al. Contribution of human-related sources to indoor volatile organic compounds in a university classroom. Indoor Air. 2015; 26(6): 925-938. doi: 10.1111/ina.12272