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Assessing the influence of $PM_{2.5}$ and PM_{10} on subjective thermal comfort in university classrooms

***Hadjira Sakhri*[1,2,*]**

[1] Laboratory of Design and Modeling of Architectural Forms and Ambiances (LACOMOFA), Mohamed Khider University, Biskra, Algeria
[2] Institute of Architecture and Urbanism, University of Batna, Batna, Algeria

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CORRESPONDING AUTHOR:
hadjirasakhri@gmail.com
Tel : (+213) 33543160
Fax : (+213) 33543160

ABSTRACT

Introduction: Indoor air quality plays a significant role in students' health and productivity. The present study attempts to examine the impact of air pollution on subjective thermal comfort and explores how the interaction between thermal conditions and Particulate Matter (PM) affects students' thermal comfort and health.
Materials and methods: The data were collected through objective and subjective methods. The objective method consists the measurement of air pollution and meteorological parameters using the particle counter PCE-MPC 20. At the same time, subjective questionnaires were developed to obtain data relative to the students' sensations, preferences, and indoor environment during two periods of student occupancy and under two conditions: one with closed windows and one with natural ventilation.
Results: Findings show that the average indoor and outdoor PM concentrations exceed the World Health Organization (WHO) standard. These suggest that universities would benefit from upgrading their heating systems and providing humidifiers. Results also highlight the difference between Predicted Mean Vote (PMV) and Thermal comfort; Thermal Sensation Vote (TSV), Thermal Preference Vote (TPV) and the need for adopted strategies in the perceived thermal comfort assessments. Additionally, the static results indicated the significant impact of PM on both TSV and TPV (P values<0.05) regardless of whether the windows are open or closed.
Conclusion: To our knowledge, this is the first study conducted in Algeria to evaluate the effects of air pollution on students' perceived thermal comfort. The results underline the importance of addressing indoor air quality and prioritising natural ventilation strategies to enhance both student well-being and academic performance.

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Introduction

It is widely recognised that Indoor Environmental Quality (IEQ), including thermal conditions, acoustic comfort, Indoor Air Quality (IAQ) and visual comfort, directly affects the students' learning capacities and health [1, 3]. Since the COVID-19 pandemic, assessing classroom air quality has become a topic of attention worldwide [4-6]. The presence of pollutants, i.e. Carbon monoxide (CO), Nitrogen Oxides (NOx), and Particulate Matter (PM) generated by indoor and outdoor sources could contribute to poor indoor air quality in the classroom environment, leading to breathing difficulties, lost concentration, and productivity problems [7-9]. Among all indoor contaminants, particulate matter and carbon dioxide are the major indoor air pollutants. Particulate Matter (PM) comprises solid particles and liquid droplets suspended in the air, which differ in shape, size, chemical composition, and source. PM with diameters less than 2.5 μm and 10 μm are defined as $PM_{2.5}$ and PM_{10}, respectively [10]. The concentration of particulate matter in educational buildings is affected by various factors such as the building's geographical location, climate conditions, frequency of maintenance and cleaning materials [11, 12].

In recent years, numerous studies have focused on Indoor Air Quality (IAQ) and its relationship with thermal comfort [4, 13, 14]. The literature highlights the effects of poor IAQ on health and well-being, emphasising its impacts across various indoor environments, including residential, commercial, and educational buildings. While extensive research has been conducted on the effects of PM on thermal comfort in outdoor environments [15, 16], only a handful of studies investigate its impact on human thermal comfort within indoor environments [17, 18]. Research on indoor PM and thermal environments often lacks consideration of occupants' subjective experiences. Few studies assess the overall effects of thermal sensation and particulate matter in indoor classrooms [19]. In addition, there is no standard methodology to evaluate the impact between these two parameters.

University classrooms present distinct challenges regarding IAQ and thermal comfort. Despite the presence of Heating, Ventilation, and Air Conditioning (HVAC) systems designed to regulate indoor climates, the infiltration and accumulation of PM can significantly affect occupant comfort and health. Unlike outdoor spaces, where natural ventilation can mitigate pollutant concentrations. Compared to students in primary and secondary schools, university students are adults usually aged over 18, vary in thermal background and class types [20-22], which leads to difficulties in analysing their thermal perceptions and evaluating the indoor environmental quality at universities. Therefore, it is highly relevant to assess both subjective thermal comfort and air quality in university classrooms.

The purpose of this research is to investigate the subjective thermal comfort of university students under different $PM_{2.5}$ and PM_{10} concentrations. The main objectives of this study are: 1) Analysing the effect of particulate matter on thermal perception in university classrooms. 2) Examining students' thermal comfort sensations and preferences under two conditions: with windows and doors closed and with natural ventilation (open windows). The results of this study offer empirical evidence and theoretical insights for creating a comfortable thermal environment in the indoor classroom, considering the interaction between thermal environment and particulate matter. This study provides valuable insights for improving environmental comfort in university classrooms and contributes to research on human subjective comfort in indoor educational buildings with similar characteristics.

Materials and methods

This study aims to investigate the impact of IAQ on subjective thermal comfort in university classrooms. The methodological process focused on a field survey (Fig. 1). Objective and subjective methods were applied simultaneously, through environmental measurements and a questionnaire survey. The objective methods consist of measurements of IAQ and physical parameters; temperature and humidity indoors and outdoors classroom. At the same time, subjective questionnaires were similarly developed to obtain data relative to the students' sensations, preferences, and environment acceptability. The methodological details for each step are described. The results are also presented.

Case study description

The measurements were conducted in one university classroom located in Banta (35°33′21N 6°10′26 E; altitude: 1037 m). Batna city is the capital of the Aures region in Algeria. It is located in the northeast part of Algeria and is known for its cold semi-arid climate. The classroom is located on the first floor of the Institute of Architecture and Urbanism, oriented northwest-southeast (Fig. 2). The classroom has a rectangular shape measuring 12.8 m in length and 7.8 m in width. It features three large windows, each 2.4 m in height and 2 m in width. Two of these windows are located on the southwest side, while the third is located on the southeast side. Additionally, there are four single windows, each 1.8 m in height and 0.8 m in width, positioned on the northeast side (Fig. 3).

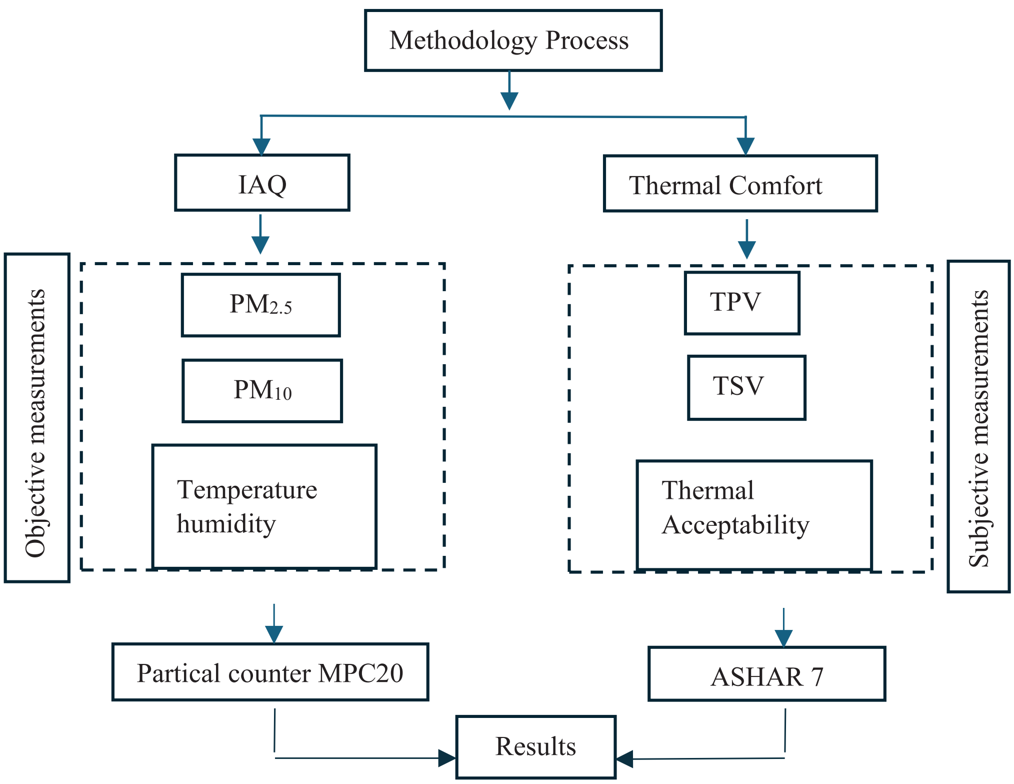


Fig. 1. Research methodology process

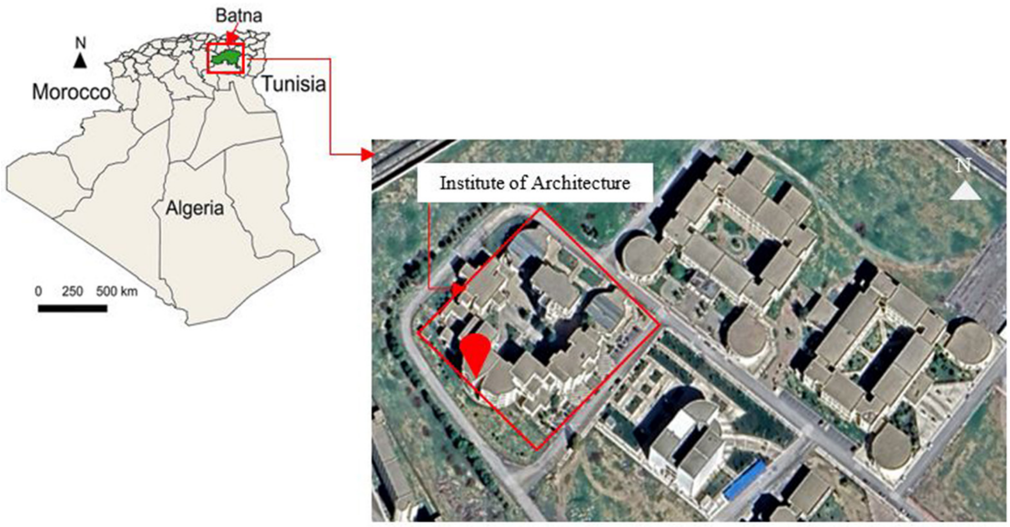


Fig. 2. Location of case study

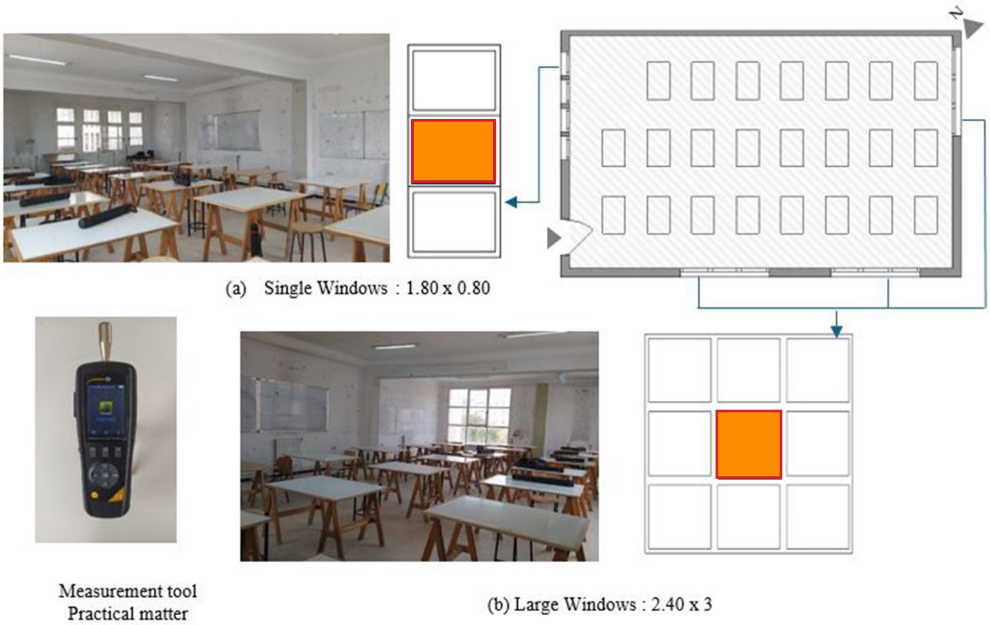


Fig. 3. Geometry of classroom and windows. The open windows in (a) and (b)

The classroom used for teaching studio design for architecture students, it is occupied by 22 students and 1 teacher. It does not have air conditioning or mechanical ventilation. However, it was heated by a central heating system using radiators. The main features of the classrooms are summarized in Table 1.

Table 1. The classroom characteristics

Space	Length /Height (cm)	Width (cm)	Orientation	Number
Classroom	1280	780	Northwest -southeast	23 occupants
Windows -type 1	180	80	Nord-East	4
Windows -type 2	240	200	South-East	1
	240	200	South-west	2
Windows open-type 1	70	90	South-west	1
Windows open -type 2	60	80	Nord-East	1
Door	240	120	Nord-East	1

Air pollution and meteorological measurements

Particulate Matter concentrations (PM) are used as an index to evaluate the air quality environment. Portable particle counter PCE-MPC 20(range 0-2000 ug/m^3, resolution 1ug/m^3) was placed in the centre of the classroom during spring on March, 5, at the height of 1 m vertically from the floor to measure $PM_{2.5}$ and PM_{10} simultaneously with temperatures between 0 and 50°C and humidity level between 0 and 20 %. Meteorological parameters (temperature and humidity level) were also taken simultaneously in the outdoor courtyard at the same height. Measurements were taken during two periods when the student occupied space, and under two conditions: Morning period (P1) between 8 a.m. and 12 p.m. with closed windows and door, and afternoon period (P2) between 12 p.m. and 2 p.m. with natural ventilation and open windows. The particle counter (PCE-MPC 20) was calibrated according to the manufacturer's specifications before data collection. Additionally, a calibration check was performed on-site to verify its accuracy before starting the measurements.

Subjective measurements

Subjective questionnaires were developed simultaneously with environment measurements according to the ISO 28802 standard [23]. The questionnaire consists of two parts. The first part consists of students' demographic information, such as age and gender. The second part consisted of the evaluation of the thermal environment. For the present study, only thermal sensation, thermal preference, and thermal acceptability questions are studied. Students answer the following questions:

-How do you feel in this precise moment?

-At this moment, how would you prefer to feel?

-How do you judge this environment (thermal environment)?

Students were asked to evaluate their thermal sensation; at a seven-point Likert scale ranging between "very cold" (− 3) to "very hot" (+3), and their thermal preference at a seven-point Likert scale ranging between "much color (− 3) to "much warmer" (+3). Thermal Acceptability Vote (TAV): ranging between "Unacceptable (0) and "Acceptable" (1). The frequency distribution of the questionnaires was divided into two periods, P1 and P2. In each period, students were asked to complete the questionnaire 1 h after entering the class (P1a, P2a) and 15 min before leaving the class (P1b, P2b) to assess their adaptation to the indoor environment (Fig. 4).

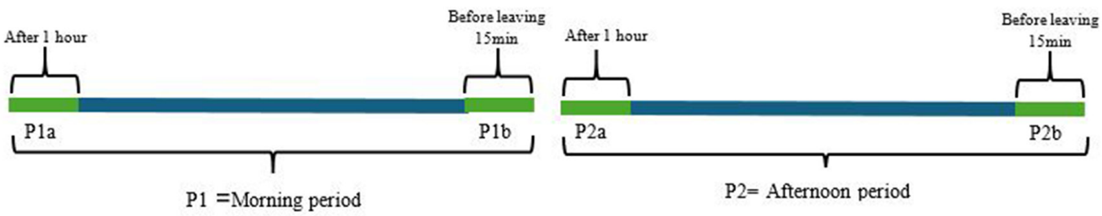


Fig. 4. Distribution and completion of questionnaires during the class

Table 2. Average particulate matter concentration and meteorological variables indoor and outdoor classroom

		Temperature (°C)	Humidity (%)	$PM_{2.5}$ (µg/m³)	PM_{10} (µg/m³)	$PM_{2.5}$ Indoor/Outdoor	PM_{10} Indoor/Outdoor
Indoor	P1	21.35	37.1	60	248.5	0.86	1.62
	P2	24	27.65	4	16		
Outdoor	P1	13.65	51.55	69.5	153	0.14	0.99
	P2	26.7	27.1	28	154		

P1 =Morning period
P2= Afternoon period

Results and discussion

Particulate matter concentration

$PM_{2.5}$ and PM_{10} are used as an evaluation index of air quality environmental. Table 2 shows the indoor and outdoor average of meteorological data (air temperature and relativity humidity) and air quality index ($PM_{2.5}$ and PM_{10}) of the study area. In the indoor, the measurement results show that the $PM_{2.5}$ and PM_{10} concentrations in close condition (P1) were higher with an average of 60 µg/m³ and 248.5 µg/m³ respectively, then in open condition (P2) with an average of 4 µg/m³ and 16 µg/m³ respectively. Compared to the outdoor measurements, the results show that the $PM_{2.5}$ averages of 69.5 µg/m³ outdoors and 60 µg/m³ indoors in P1, and 28 µg/m³ outdoors and 4 µg/m³ indoors in P2. However, in P1, indoor PM_{10} levels were higher at 248.5 µg/m³ compared to 153 µg/m³ outdoors. In P2, outdoor PM_{10} levels were higher at 154 µg/m³, while indoor levels were only 16 µg/m³. It is interesting to note that the highest concentrations of PM 2.5 and PM_{10} levels were observed on the closed windows while the lowest concentration was observed on the opening windows. This suggests that poor ventilation significantly contributes to the accumulation of particulate matter, which can have serious health implications for students.

Temperature and humidity interactions

The measurements of indoor air temperature and Relative Humidity (RH) are necessary to evaluate their influence on the simultaneous recording of PM mass concentrations (Table 2). The average air temperature in P2 is higher, at 24°C, compared to P1, which is 21°C. However, the Relative Humidity (RH) in the classroom is higher in P1, at 37%, than the P2, at 27.6%. Despite a cooler temperature in P1 (21°C), the higher relative humidity (37%) contributed to some thermal discomfort levels. This relationship indicates that humidity can exacerbate feelings of warmth, especially when PM levels are elevated. According to American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard [24], the relative humidity levels should be maintained between 40 and 60 % and temperatures ranging from 21°C to 23°C. In P2, while temperatures are higher (24°C) with lower humidity (27.6%) and reduced particulate matter, creating a more comfortable environment in the classroom, these findings illustrate the benefit of natural ventilation inside the classroom and how the air quality can mitigate thermal discomfort even at slightly warmer temperatures.

Subjective responses

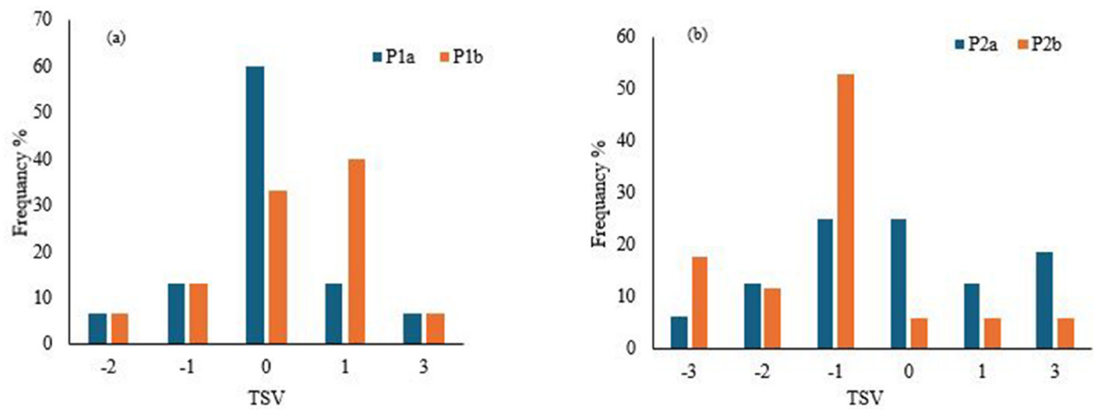
A total of 84 responses were collected during the two periods; 21 questionnaires were excluded from the statistical analyses due to the incompleteness of the responses. As a result, a total of 63 were completed and analysed using IBM SPSS Statistics 22. The demographic information of participants is presented in Table 3.

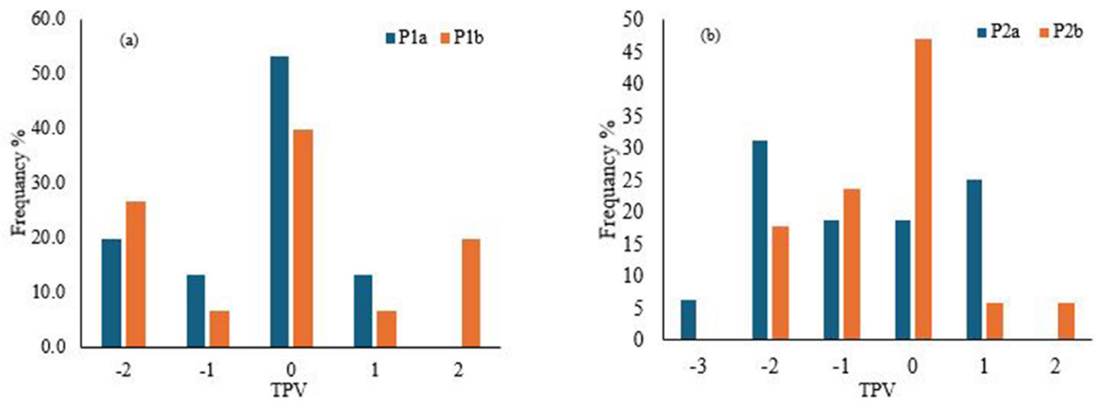
Table 3. The demographic data of participants

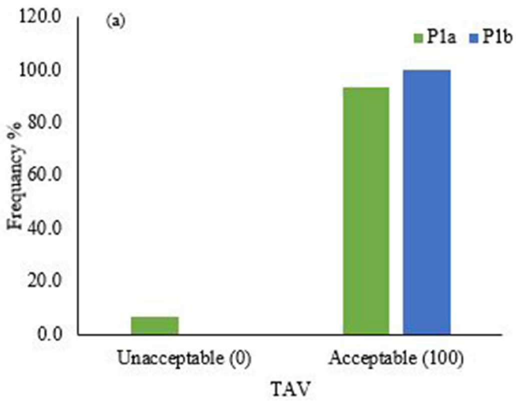
	Time	Total	Male (%)	Female (%)	Age (years)
Period 1	P1a	15	60	40	20-23
	P1b	15	33.3	66.7	20-23
Period 2	P2a	17	37.5	62.5	20-23
	P2b	16	41.2	58.8	20-23

P1a, P2a: After 1 h of entering
P1b, P2b: 15 min before leaving the class

Fig. 5 shows the overall distribution of students' thermal comfort votes. During the first period, when the windows
were closed, the Thermal Sensation Vote (TSV) results indicate that approximately 60% of students rated their thermal sensation as Natural after entering the classroom (P1a). By the end of the class (P1b), about 40% of students felt that the indoor environment was Slightly Warm. In the second period (P2) with the same group of students and with natural ventilation (open the windows), after entering the class (P2a) most students felt that the indoor environment was Slightly Cool and Neutral about 25% on both scales, while before leaving the class, they found the indoor environment Natural about 52.9% and Cool about 17.6%. The overall distribution of the occupant's thermal preference (TPV) shows that with windows closed, over 53% of occupants, after 1 h of starting the course in P1a and before leaving the class in P1b, 40% of students prefer No Change in the indoor thermal environment. With the windows open in P2a, over 31% of occupants preferred a Cooler environment, while 25% preferred it Slightly Warmer. In P2 b, over 47% of students preferred No change, and over 23% preferred Slightly Cooler. Concerning the thermal acceptability vote (TAV), students found the indoor thermal environment Acceptable in P1a and P2b with more than 90% and 100%, respectively, as well as in P2a and P2b with more than 80% and 75% respectively.







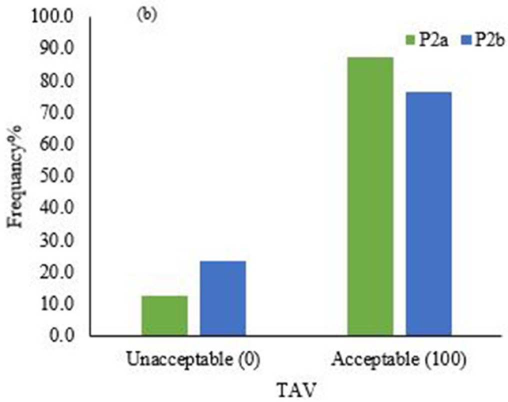


Fig. 5. Subjective thermal comfort responses according to frequency distribution: (a) in closed condition, (b) in open condition. (1) Thermal sensation votes, (2) Thermal preference votes, (3) Thermal acceptability votes

Table 4. Meteorological parameters and indoor thermal comfort assessment

Time	Temperature (°C)	Humidity (%)	T_r (°C)	V_{ar} (m/s)	PMV
P1a	22.1	32.4	22.1	0.1	0
P1b	20.6	41.8	19.6	0.1	-0.4
P2a	20	33.4	21	0.1	-0.3
P2b	28	21.9	27	0.1	1.1

P1a, P2a: After 1 h of entering

P1b, P2b: 15 min before leaving the class

Thermal comfort

A thermally comfortable classroom environment is essential for students' health, well-being, and academic performance. The Predicted Mean Vote (PMV) index, defined in ISO 7730 [25] and aligned with ASHRAE 55, was used in this study to estimate students' thermal sensation. PMV considers environmental variables such as air temperature (Ta), relative humidity (RH), mean radiant temperature (Tr), and air velocity (Var), along with personal factors like metabolic rate (1.0 Met) and clothing insulation (1.0 Clo), following ASHRAE 55 guidelines (Table 4). While PMV is typically applied in mechanically conditioned spaces, it was applied in this study to provide a consistent method for assessing thermal comfort. Additionally, the study acknowledges the importance of the ASHRAE 55 adaptive comfort model, which reflects how occupants naturally adjust to thermal conditions in naturally ventilated environments.

The aim is to compare the PMV index, with the results obtained from the questionnaire survey. The results show that the indoor environment is Natural (PMV=0 and T<25) in P1a, 60% of students voted feeling Natural and more than 50% prefer No change. In P1b, the Ta <25°C and PMV< -1, the indoor environment is slightly cool, while a significant part of students voted feeling Slightly Warm 40%, and prefer No change 40%. In the P2a, with the same environmental condition (Ta <25°C, PMV <-1), students voted varied between Slightly cool and Neutral, with 25%, while over 31% of students preferred Cooler (-2) and 25% Slightly Warmer (+1). In the P2b, the air temperature was higher than 25ºC,1 <PMV. More than 50% of the students perceived the indoor environment as Natural than expected from the calculated PMV; they did not perceive the environment as Slightly Warmer, and they preferred No change more than 45%. The findings indicated that the PMV mode tended to overestimate students' sensitivity, which is consistent with findings from other studies [26, 27]. These results underscore the need for adaptive strategies in the perceived thermal comfort assessments.

Effect of $PM_{2.5}$ and PM_{10} on TSV and TPV

To obtain reliable and comparable data on subjective perceptions. The data collected from the questionnaire were used to calculate the mean of thermal perception and preference votes using the following Eq. 1:

$$Mean = \frac{(n_1 \times x_1) + (n_2 \times x_2) + (n_3 \times x_3)}{N} \quad (1)$$

n = Number of students x = Value of vote
N = Total number of students

Table 5 shows the mean value of survey results and PM concentrations. The data analysis of TSV in close conditions shows some discomfort reported by students, the average students were feeling Slightly Warm (mean 0.00 <TSV< 1). Students reported tended to accept the thermal environment but preferred a Slightly Cooler environment (-1 <TPV< 0). The PM concentrations are higher in this period, which indicates that poor air quality directly correlates with a decrease in thermal comfort. In open conditions, averages of students were feeling Slightly Cooler (mean -1 <TSV< 0), student tended to accept the thermal environment and preferred a Slightly Cooler environment (-1 <TPV< 0). The PM concentrations decrease in this period; this suggests that improved air quality enhances perceived comfort.

Table 5. The mean values of TSV, TPV, $PM_{2.5}$ and PM_{10} during the two separate periods

		Mean	Range	*P -values*
Close windows and door	TSV	0.17	0.07≤ TSV ≤0.27	0.004
	$PM_{2.5}$	60	59 ≤ PM2.5 ≤61	
	PM_{10}	248.5	248≤ PM10 ≤249	0.0005
	TPV	-0.265	-0.4 ≤ TPV ≤ -0.13	
Natural ventilation	TSV	-0.15	-0.19 ≤ TSV ≤ -0.9	*0.002*
	$PM_{2.5}$	4	PM2.5 ≤ 4	
	PM_{10}	16	15 ≤ PM10 ≤17	0.02
	TPV	-1.08	-0.75≤ TPV ≤ -1.41	

Table 6. Correlation matrix between air quality, environmental parameters, and thermal comfort

	$PM_{2.5}$	PM_{10}	Temperature	Humidity	TSV	TPV
$PM_{2.5}$	1					
PM_{10}	0,999735	1				
Temperature	0,88895	0,889301	1			
Humidity	0,680537	0,666787	0,78900541	1		
TSV	0,917823	0,910159	0,701722195	0,713734	1	
TPV	0,85516	0,848026	0,945850779	0,94281	0,783652	1

The aim is to compare the subjective thermal comfort with the air pollution in the indoor classroom and see if there is an influence impact between them under the two conditions. The hypothesis is to see if the mass concentration of $PM_{2.5}$ and PM_{10} indoors the classroom has a significant effect on both thermal sensation and preference. In this context, T-test and correlation analysis were applied to examine the relationships between indoor air quality, subjective thermal comfort, and environmental conditions. As shown in Table 6, there is a strong relationship between air quality indicators, environmental parameters, and subjective thermal comfort responses. A very strong positive correlation is observed between $PM_{2.5}$ and PM_{10} (r^2=0.9997), indicating that these pollutants likely originate from similar sources.

Regarding environmental conditions, both $PM_{2.5}$ and PM_{10} show strong correlations with air temperature, with r^2 = 0.889 for each. This suggests that elevated temperatures may be associated with increased particulate concentrations, potentially due to seasonal influences or ventilation-related factors. In terms of thermal comfort, the findings reveal that $PM_{2.5}$ and PM_{10} are also strongly correlated with TSV (Thermal Sensation Vote), with r^2 = 0.918 and r^2=0.910, respectively. Furthermore, significant correlations are noted with TPV (Thermal Preference Vote), with r^2 = 0.855 for $PM_{2.5}$ and r^2 = 0.848 for PM_{10}. All relationships are statistically significant with p-values < 0.05. These results suggest that higher levels of indoor air pollution are associated with heightened sensations of thermal discomfort and a stronger desire for thermal change. When focusing on thermal preferences, TPV shows a very strong correlation with temperature (r^2=0.946), whereas TSV shows a moderate to strong correlation (r^2=0.702). This indicates that as indoor temperature increases, occupants not only feel warmer but also increasingly prefer a cooler environment. Additionally, humidity is strongly associated with TPV (r^2=0.943) and shows a moderate correlation with TSV (r^2=0.714). Notably, TSV and TPV are significantly correlated (r^2=0.784), indicating that thermal sensation and thermal preference are not independent variables but are instead interconnected and jointly influenced by environmental conditions. Overall, these findings confirm that occupants' thermal sensations and preferences are strongly linked to both environmental parameters (temperature and humidity) and indoor air quality levels. The results highlight that particulate matter significantly affects students' subjective comfort and this relationship is mediated by indoor meteorological conditions. As a result, enhancing indoor air quality through strategies such as natural ventilation and air exchange can improve thermal comfort perception and contribute to a healthier and more comfortable indoor environment.

Conclusion

The research above focuses on the impact of $PM_{2.5}$ and PM_{10} concentrations on subjective thermal sensation and preference in university classrooms. At present, numerous studies have been conducted on thermal and air quality environments, but there is limited research on the interaction between subjective comfort and particulate matters; $PM_{2.5}$ and PM_{10}. This study aims to further investigate the interaction between the change in particulate matter concentration and human subjective comfort, and provide a reference for follow-up studies on multi-environment interactions. Air temperature (T) and Relative humidity (RH) greatly affect PM mass concentrations and thermal comfort, as shown in section 3.2. PM concentration can be transferred from outside environments; the findings confirm that PM decreases during opening windows (P2). In this research, the $PM_{2.5}$ and PM_{10} concentrations are obtained during the occupied period of the classroom. Average mass concentrations of indoor $PM_{2.5}$ and PM_{10} are 60 $\mu g/m^3$ and 248.5 $\mu g/m^3$, respectively, in P1, and 4 $\mu g/m^3$ and 16 $\mu g/m^3$ in P2. The average measurements of outdoor $PM_{2.5}$ and PM_{10} are 69.5 $\mu g/m^3$ and 153 $\mu g/m^3$, respectively in P1. In P2, the average measurements of $PM_{2.5}$ are 28 $\mu g/m^3$ and 154 $\mu g/m^3$ for PM_{10}. As a result, the highest PM 2.5 concentrations were found when the windows were closed (P1), while the lowest levels were noted when the windows were open (P2). Furthermore, the highest PM_{10} levels were recorded outside the classroom, whereas the lowest $PM_{2.5}$ concentrations were found inside. Currently, there is no indoor or outdoor particulate matter concentration standard in Algeria. However, the World Health Organisation (WHO) Air Quality Guidelines (2021) establish a limit of 25 $\mu g/m^3$ for 24-h average concentrations of ambient $PM_{2.5}$ to offer enhanced protection against health effects associated with both long-term and short-term exposures. This air quality guideline value can also be applied to the indoor environment. The obtained results show that the average indoor and outdoor $PM_{2.5}$ concentrations in the classroom exceed the WHO standard. These results suggest that universities would benefit from upgrading their heating systems, adjusting thermostats, and providing humidifiers to create a thermally comfortable classroom environment. In terms of evaluation of the thermal environment, assessing thermal comfort using the PMV index where compared with the obtained results from the questionnaire survey. Findings highlight the difference between PMV and actual thermal comfort (TSV, TPV). These confirm that individual perceptions are more influenced by immediate air quality and highlight the need for adopted strategies in the perceived thermal comfort assessments. In the context of the effect of air quality on thermal sensation and preference, the results of TSV indicated that students' perceptions change with air quality. In P1, students felt "Slightly Warm," likely due to the combination of high PM levels and humidity, while in P2, students voted between "Slightly Cool" and "Natural." This correlation emphasises that air quality impacts thermal sensations. The TPV responses support the idea that students preferred cooler conditions in environments with lower PM levels, which highlighted the influence of air quality on thermal preferences.

The statically results indicated the significant impact of $PM_{2.5}$ and PM_{10} on both TSV and TPV (P values < 0.05), as PM levels rise, the comfort level decreases. Overall, these findings underline the importance of addressing indoor air quality to create a healthy, comfortable learning environment. Universities should prioritise natural ventilation strategies to enhance both student well-being and academic performance.

One of the key limitations of this study is that it was conducted in a single classroom. While this allowed for in-depth analysis under controlled conditions, factors such as building design, orientation, and ventilation can vary significantly across different classrooms. Future research will explore the long-term impacts of indoor air quality on subjective thermal comfort, including a larger number of classrooms across multiple buildings or campuses to validate and extend the findings.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethical considerations

Ethical issues (Including plagiarism, Informed Consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, redundancy, etc.) have been completely observed by the authors. Informed consent was obtained from all participants, and their confidentiality was maintained throughout the study.

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