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The investigation of carbon dioxide (CO_2) and particulate matter (PM) quantities in higher education buildings

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Abstract
Indoor air quality is one of the fundamental requirements that must be ensured for users of the buildings to be healthy and productive. As a result of poor indoor air quality, health problems could also arise in users. In educational buildings students spend most of their time in enclosed classrooms. Therefore, it is very important that the indoor air quality meets the health and comfort conditions of the students. In this study, the indoor air quality (IAQ) conditions (CO_2 and Particulate Matter/PM) of two higher education buildings in Edirne, Faculty of Architecture and Faculty of Engineering in Trakya University, were investigated. IAQ data were determined by measuring with the devices (Testo 480 for CO_2 and TSI Dusttrack 8532 for PM) during the use of the classrooms in the winter months. The results of the measurement were analyzed, then the results were compared with the values given in the standards. The values obtained by CO_2 and PM measurements are often found to be exceed the limit values determined by WHO and ASHRAE-62. In some cases, it has been observed that the CO_2 value has increased up to 2500 ppm in the classrooms. For PM measurements, values were obtained in the range of 71-151 µg/m^3 and where standard deviations varied between 6-34.

Keywords
Carbon dioxide, Educational buildings, Indoor air quality (IAQ), Particulate matter (PM).

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1. Introduction

The indoor comfort requirements and indoor air quality are very important for all buildings. However, this situation becomes more important for educational buildings due to consider children's health. In order to be healthy and productive, proper comfort and indoor air quality conditions must be provided for students, who spend most of their time in closed classrooms. Most students spend 30% of their time in school and 70% in classrooms (Kalimeri et al., 2016). The indoor comfort requirements are important factors on the cognitive processing speed and learning ability (Lee et al., 2012; Vilcekova et al., 2017). The comfort requirements include many subjects such as thermal comfort, indoor air quality, acoustics, and lighting. This study particularly focuses on indoor air quality in educational buildings.

In indoor air quality, it is primarily essential that the oxygen adequacy is ensured and CO_2 (carbon dioxide) and other pollutants (dust, carbon monoxide, etc.) should not exceed the allowed upper limits. Pollutants could be classified in different categories according to their source, phase, and effect. Pollutants might originate mainly from the external environment; some also might be originated from, the materials, hardware, furniture, cigarette, activity, chemical products used within the interior space and/or the building itself (Tham, 2016; Bari and Kindzierski, 2018). One of the most important environmental pollutants is CO_2. The maximum admissible level of CO_2 concentration is 350 ppm (parts per million) in outdoor, 1000 ppm in indoor environments (Apte et al., 2000; Abdul-Wahab et al., 2015).

The amount of CO_2 emission changes in accordance with the number of people and the activity in the environment. Especially in crowded spaces the use of oxygen will be much higher, and therefore the amount of CO_2 in the environment will increase, and the indoor air quality will be adversely affected. Concurrently, physiological changes could also be observed in people (Hess-Kosa, 2011; Can et al., 2015; Lee et al., 2015; Madureira et al., 2015). The growing amount of pollutants in the environment affects the users negatively and causes some health problems. Therefore, the air in the environment must be kept as clean as possible. The necessary level of oxygen in clean ideal air is 21%. This level should not fall below 19%, in a situation where the oxygen level drops below 15% health problems that cause permanent damage would occur (Peacock, 1998; WCBBC, 2008).

One of the other factors affecting the indoor air quality is the Particulate Matter (PM). PMs, known also as aerosol, are small particles and/or droplets such as solid and liquid acids that are suspended in air, organic chemicals, metals, earth, dust, soot or smoke (Amato et al., 2014; Mohammed et al., 2015; Yang et al., 2015). PM is measured in different sizes as PM_{10} (PM smaller than 10 μm in diameter) and $PM_{2.5}$ (PM smaller than 2.5 μm in diameter). PM_{10} sources consist of smoke and dust from industrial plants, agricultural emissions and roads. On the other hand, $PM_{2.5}$ is associated with volatile organic compounds (VOC), heavy metals, and traffic and forest fires. In terms of its health effects, $PM_{2.5}$ is more hazardous than PM_{10}. As the particle diameter becomes smaller its adverse effect on health is increased (Mohammed et al., 2015; Datta et al., 2017; Bari and Kindzierski, 2018).

As well as living in a healthy environment, it is significant for children to receive education in a healthy environment in order to get an efficient education. Thus, this study aims to evaluate indoor air quality, which is one of the parameters of indoor environmental quality for buildings, in educational buildings. In this context, two higher educational buildings belong to Trakya University (Faculty of Architecture and Faculty of Engineering) in Edirne are investigated as a case study in this research. To determine and analyze the indoor air quality of classrooms in the selected buildings, the amounts of CO_2 and PM were measured. The measurements were carried out simultaneously during winter months when classrooms are used. The selection of the classrooms was made due to considering different characteristics. The results obtained were examined comparatively for the two buildings and also evaluated based on the limit values in the literature.

2. Literature review

Recent studies on physical comfort in the literature emphasize the importance of indoor air quality. The studies examine the different aspects of indoor air quality from the effects of indoor air quality on user health to its relationship with pollutant sources. Furthermore, it is seen that the related studies in the literature are conducted for buildings of different scales and functions and in this regard, educational buildings are among the priority buildings.

In indoor spaces of schools, students are exposed to many air pollutants. The effects of indoor environmental quality on the health and success of students were investigated by Turunen et al. (2014). In the scope of the research, survey and indoor air quality measurements were carried out in schools of Finland. According to the assessments in the research, it is asserted that natural ventilation in schools is not sufficient on its own, and the physical conditions of the schools, materials that have been used, maintenance conditions also affect the indoor air quality. According to the data obtained by the survey, it has been found that students had health issues and in cases where the class presence is more than 15 people these health issues were increased (Turunen et al., 2014). Hreha (2007), in his doctorate thesis, investigated the effects of indoor air quality on the exam performance of the students. It is determined that, in a small space, because of the higher CO_2 exposure, students have not been able to perform well compared to students who had been tested in a larger space. This study demonstrates that in larger spaces, the level of CO_2 is significantly lower.

In the study that investigates the effects of traffic load on PM mass concentrations of indoor air in educational buildings, it was indicated that the high traffic intensity significantly increases the PM_{10} and $PM_{2.5}$ mass concentrations (Lee et al., 2015; Shakya et al., 2017; Zhang et al., 2017).

According to the ASHRAE 62 (2007) "Ventilation for Acceptable Indoor Air Quality" standard, a healthy indoor air quality is defined as, the air in which known pollutants are not to be at the level of harmful concentrations, which themselves determined by the qualified authorities, and that at least 80% of the people in this air should not be feeling any dissatisfaction with the quality of the air. ASHRAE 62-2001 standard recommends that the upper limit for clear outdoor air concentration should be around 300-400 ppm, while the indoor air concentration should be at most 700 ppm, the generally agreed margin is 1000 ppm (WHO, 1983). ASHRAE 62 and EPA (Environmental Protection Agency) state the average daily limit value of PM_{10} to be 150 µg/m^3 (ASHRAE, 2007; TSI, 2011).

One of the important parameters for determining indoor air quality is the air quality of the environment of the building. To increase the indoor air quality, a sufficient amount of fresh air should be introduced to the indoor space. In old buildings, this requirement was met due to the infiltration and the outside air was able to enter by natural ventilation. In the last 100 years, by the introduction of mechanical ventilation and curtain wall systems, buildings become resembling a thermos. Furthermore, without the proper mechanical ventilation systems, this could even cause people's deaths due to a lack of oxygen. In cases where there is a lot of outdoor pollution, natural ventilation to improve the indoor air quality acts in the reverse direction, resulting in even worse air quality. For effective ventilation, the oxygen concentration of the outdoor air must be high and the pollutant concentration must be low.

The efforts to reduce the energy losses in buildings resulted in a rise in the levels of building airtightness and a reduction in the transmission rates between the indoor-outdoor air, thus, degrading the indoor air quality. Inadequate thermal resistance on sections of the building envelope results in low internal surface temperatures, causing unhealthy conditions such as chills, moulds on the interior surfaces (Sarafis et al., 2010). Accompanying these issues, the term "Sick Building" emerges. Since 1983, the indoor environmental issues experienced by the users were defined by the World Health Organization (WHO) as sick building syndrome (SBS) (WHO, 1983).

In the 21st century 'green buildings' become the main focus. Although energy and resource conservation is of primary concern, healthy buildings have gained importance. And green buildings have begun to be synonymous with healthy buildings. In connection with green buildings, product emission tests and green product certificates come into prominence and, by 2009; standards were introduced on the indoor air quality for high-performance buildings. "The indoor air quality" occupies an important place inside the green building certificate systems. For example, in the American LEED certification, The Indoor Air Quality Management Plan is considered to achieve a minimum score of 6 points in a 21-point evaluation (Hess-Kosa, 2011).

The effects of poor indoor air quality on health depend on many factors. The relevant factors that determine the potential health effects on the population depend on the concentration density of each air pollutants, the duration of exposure, and the susceptibility of the individual (Hess-Kosa, 2011). According to a study by NIOSH (The National Institute for Occupational Safety and Health), the basis of complaints in buildings is given in Figure 1. One of the primary complaints is inadequate ventilation and indoor pollutants.

3. Material and methods

In the scope of this study, in the buildings, during the 45 minutes of course time, the amount of CO_2 in the indoor environment of the classrooms was recorded each minute using the Testo 480. The Testo 480 is a multifunctional measuring device with built-in differential pressure and absolute pressure sensors and measures the indoor air quality, temperature, humidity, pressure, airspeed, radiant heat, turbulence by connecting external probes. Also, the outdoor environment measurement was made by recording every minute for 10 minutes. In the measurement of dust Particulate Matter, instant measurements were taken in diameters of 2,5µm and 10µm by using the TSI Dusttrack 8532. The device is used for measuring concentrations of dust (aerosol, dust, mist, fume, etc.) in 0.1 ... 10-micron dimensions. The amount of dust contained in 1 m^3 of air is given in mg. Measurements were taken every day at the same time and position and, according to the features of the device, determined within the 1 to 3 minutes interval. The range of the device's measurement is between 0.001 ... 150 mg/m^3 and its accuracy is ± 5%.

To determine which classes to measure, the selection criteria were set according to the different directions, stories, dimensions and user numbers of the classrooms. Accordingly, three classrooms were selected from the buildings of the Faculty of Architecture and the Engineering. The measurement schedule was realized in the Faculty of Architecture in November, in the Faculty of Engineering in December 2015, on weekdays (from Monday to Friday) between 10:30 am and 03:30 pm during the ongoing education.

3.1. Case study

The study was realized in Edirne, which has the characteristics of a mild moist climate region. The features of the climate are the moderate summers and mild winters. When the five-year meteorological data of Edirne are examined, the mean monthly temperature is 4.55 °C in the winter season (heating season) and monthly average highest and lowest temperatures are 13.7 °C and -2.7 °C respectively. The mean relative humidity is 84.25% and

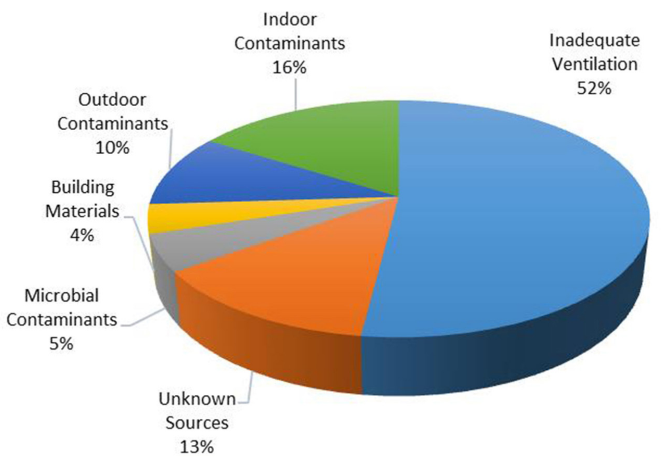

Figure 1. *Source of complaints in the buildings assessed by NIOSH study (Hess-Kosa, 2011).*

Figure 2. *The location of the Faculty of Architecture and the Faculty of Engineering inside the city center.*

the highest and lowest values of monthly average are 91.6% and 72.1%. While the highest wind speed is 2.4 m/s, the lowest wind speed is 1.6 m/s and the mean wind speed is also 2.03 m/s in Edirne (TSMS, 2015). Furthermore, it is seen that PM values (PM_{10}) in the atmosphere of Edirne changes between 32.57 and 116.71 μg/m^3 (Güler and İşçi, 2016).

The construction elements (roof, window, wall, floor, etc.) and their properties which form the building envelope were determined by acquiring drawings and documents about the settlement, location, plan, and sections of the educational buildings. The locations of the buildings within the city are shown in Figure 2. The Faculty of Architecture building is located in the city center and was constructed in 1871 as masonry while the Faculty of Engineering is located at the intersection of City Bus Terminal and the belt highway outside the city center and was built on reinforced concrete (RC) frame system.

During the wintertime, a central gas heating system is used in both buildings. Through the summer conditions, no air conditioning system is used. The buildings are ventilated naturally. The characteristics of the classrooms in which the measurements were done are given in Table 1. Figure 3 and Figure 4 show the indoor environment of the classrooms.

Table 1. *The characteristics of the classrooms in the buildings.*

Faculty	Faculty of Architecture			Faculty of Engineering		
Classroom Name	A104	D204	A201	D102	D206	L304
Floor	Ground Floor	1st Floor	1st Floor	Ground Floor	1st Floor	2nd Floor
Direction	West	East	North	South	North	Northwest
Area (m^2)	89.20	58.90	138.98	90.50	90.50	90.33
Height (m)	4.30	4.50	4.50	3.35	3.35	3.25
Volume (m^3)	382.66	265.05	638.48	301.36	301.36	293.58
Window Size (m^2)	17.85	6.62	5.45	14.58	14.58	10.08
No. of People	60	40	90	78	40	104
No. of Measurement (Indoor)	10	10	10	10	10	10
No. of Measurement (Outdoor)	10			10		
Construction System / Date	Masonry / 1871			RC Frame / 2006		
Operating Time	Day-time			Day-time + Night-time		
Location	City Center			Outside City Center at the intersection of City Bus Terminal and the belt highway		

Figure 3. *The classrooms in the Faculty of Architecture.*

4. Results and discussion

The results of the surveyed classrooms of the two higher education buildings are given in the graphs and tables below. The measurements were done initially in the Faculty of Architecture then in the Faculty of Engineering. The numbers of measurements in the faculties are different from one another. However, to be able to evaluate both of the faculties together, 10 measurements for each classroom were provided within the scope of this study.

The relation between the number of users, the indoor air temperature, the amount of CO_2 and the relative humidity in the classrooms of the Faculty of Engineering and the Faculty of Architecture are shown in Figure 5. Classrooms of the Faculty of Engineering provide thermal comfort conditions in D102 and D206 when evaluated in terms of temperature and relative humidity. In the L304, these values were obtained at minimum comfort limit values (Figure 5). Although both the D206 and L304 classrooms have a north-facing facade, the L304 classroom has two facades (north and west), which makes this classroom more disadvantageous. The results for the measurement of CO_2 in the classrooms D102 and D206 of the Faculty of Engineering are often above the 1000 ppm limit. The classrooms' volume is very close to each other in the Faculty of Engineering. Therefore, the greatest impact on the amount of CO_2 difference is due to the number of users. Thus, in L304, all of the measurements taken exceed the 1000 ppm limit and the average is in the range of 2000-2500 ppm (Figure 5) because of the high occupancy ratio.

The temperature and relative humidity values at the Faculty of Architecture show that all three classes (A104, A201 and D204) provide almost the same comfort conditions (Figure 5). When the classrooms in the Faculty of Architecture are compared, it is seen that the highest CO_2 concentration is in the A104 although the A201 has the highest occupancy ratio (Figure 5). It can be said that the spatial dimension of A201 leads to this situation (Table 1). Due to the increased volume, it was found that the CO_2 concentration did not increase at the same rate within the increase in the number of users. The CO_2 measurements in the Faculty of Architecture also determined that the 1000 ppm limit was exceeded. However, the maximum exceeding values were recorded in A104. The average measurements range between 1000-1500 ppm (Table 2).

In both buildings, changes in the measurements are generally linked to the number of users. When the number of users increases, the amount of CO_2 is also seen to increase apart from A201. However, in all circumstances, the amounts of CO_2 in the classrooms of the Faculty of Engineering are higher comparing to the Faculty of Architecture. Although the Faculty of Architecture classrooms, which have the features of masonry building system, are close in areas to the classrooms of the Faculty of Engineering, they are quite different in volume due to their floor heights (Table 1). When the measurements for the classrooms with similar volumes but different areas were examined in two buildings, it is seen that the average number of users in Architecture D204 is 20 while in Engineering L304, it is 50. While the average CO_2 measurement for Architecture D204 is 980 ppm and for Engineering L304 it is 2500 ppm. This clearly shows the effect of the number of users in indoor air quality. Nevertheless, measurements that have been taken with fewer users, seems to also over exceed the CO_2 limit. This situation can be linked to the classroom not being ventilated for a long time and to the long duration of its usage (Figure 5).

In Table 2 the CO_2 measurements, taken in the outdoor environment together with the Faculty of Engineering and the Faculty of Architecture classrooms, are given with maximum, minimum, mean values and their standard division. In Table 2, when comparing the average amount of CO_2 for the Faculty of Engineering and the Architecture classrooms, there is no significant difference between the Faculty of Architecture classrooms with different areas, volumes and number of users. In the Faculty of Engineering classrooms which have similar areas and volumes but have a very different number of users, especially in L304 the average

Figure 4. The classrooms in the Faculty of Engineering.

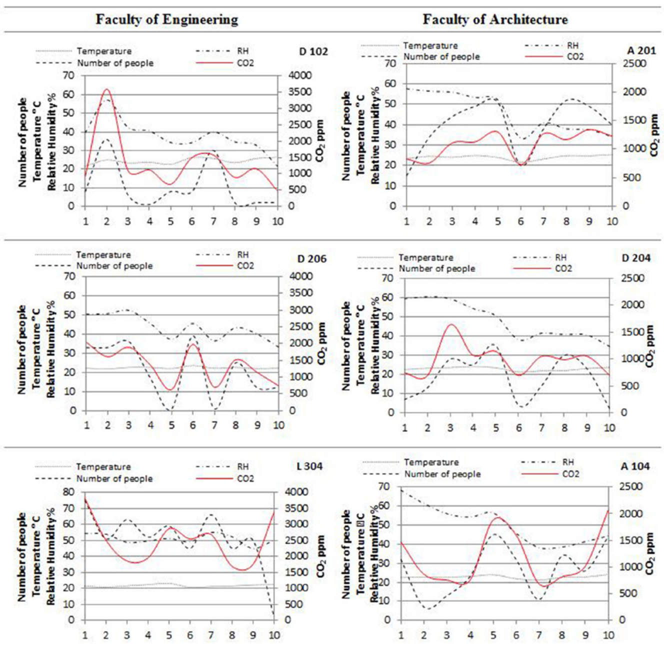

Figure 5. The number of users in the faculty of engineering and the faculty of architecture classrooms, changes in CO_2 in relation to indoor air temperature and relative humidity.

amount of CO_2 was recorded as the highest. This condition is the result of the high occupancy ratio in that classroom. However, in the other classrooms, the average number of users during the measurement is an average of 10 persons in D102 and 20 persons in D206, and the average CO_2 values are very close to each other.

When similar studies in the literature were to be examined; in a study conducted in 116 schools in Korea, the average CO_2 value in the classrooms was measured as 827 ppm (Yang et al., 2015). After the analysis of the data obtained by the Faculty of Architecture and the Faculty of Engineering, the evaluation results depending on CO_2 can be summarized as below:

Although some measures are exceeding the limit value of 1000 ppm in all classrooms in the Faculty of Architecture, there are also values below the limit value. The number of users and the fact that the windows were open during measurements are seen as factors in changing this value (Huang, 2017). Besides, as expected, the CO_2 values in the outdoor environment are lower than the indoor environment.

In the Faculty of Engineering, all classrooms exceeded the limit value of 1000 ppm in terms of CO_2 values. Especially in a certain classroom (L304), data exceeded above the limit values of all measurements. This may be due to the physical characteristics of the classroom (low ceiling height), the high occupancy ratio and the fact that the classroom was not adequately ventilated.

Table 2. *CO_2 measurements for the Faculty of Engineering and the Faculty of Architecture.*

		Faculty of Engineering				Faculty of Architecture			
		D 102	D 206	L 304	Outdoor	A 201	D 204	A 104	Outdoor
CO_2 (ppm)	mean	1303,4	1362,0	2505,2	489,0	1199,8	1095,5	1102,7	529,7
	min	477,5	631,1	1691,4	377,0	628,6	663,5	568,9	394,1
	max	3600,0	2039,1	3808,9	686,0	1692,3	1911,9	2069,1	682,4
	s.d.	**873,3**	**537,6**	**713,6**	**100,4**	**303,9**	**364,5**	**460,6**	**93,8**

Table 3. *PM measurements for the Faculty of Engineering and the Faculty of Architecture.*

		Faculty of Engineering				Faculty of Architecture			
		D 102	D 206	L 304	Outdoor	A 201	D 204	A 104	Outdoor
2.5µm	mean	86	95	85	78	97	99	119	112
	min	78	87	75	71	91	93	113	103
	max	110	112	111	131	110	129	128	141
	s.d.	**14**	**10**	**15**	**27**	**8**	**16**	**6**	**16**
10µm	mean	90	96	90	79	99	99	120	116
	min	81	87	75	71	92	92	114	104
	max	141	114	151	146	114	124	137	132
	s.d.	**26**	**11**	**33**	**34**	**9**	**13**	**10**	**11**

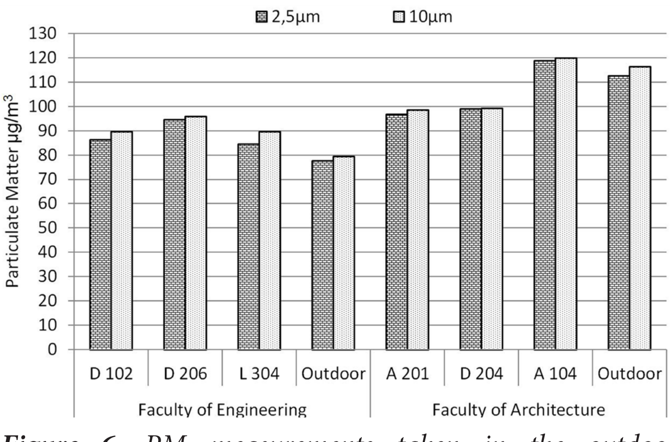

Figure 6. *PM measurements taken in the outdoor environment together with the Faculty of Engineering and the Faculty of Architecture classrooms.*

In Table 3 and Figure 6 PM measurements were given for the classrooms of both buildings and the outdoor environment of these buildings. When PM changes with diameters of 2.5µm and 10µm are examined in the Faculty of Engineering classrooms, the highest values are found at D206. In the Faculty of Architecture classrooms, PM amounts are highest at A104. The outdoor environment measurements in the Faculty of Engineering are lower comparing to the Architecture. The highest measurement in the outdoor environment of the Faculty of Architecture has been detected as 10µm. This is because of the urban location of the buildings, the measured PM values can increase at the points where the city traffic is high (Bucur et al., 2010). Thus, the value of PM measurements in the classrooms and the outdoor environment of the Faculty of Architecture at the city center was determined to be higher than the Faculty of Engineering which is located outside the city center (Table 3).

In classrooms in Athens, $PM1_0$ levels were found to be 229 µg/m³ in indoor and 166 µg/m³ in outdoor environments (Diapouli et al., 2008). In a study conducted by Alves et al. (2013) in schools, concerning the number of users in the classroom, the average PM_{10} concentration was found to be 111-362 µg/m³ and the average $PM_{2.5}$ was 44-117 µg/m³. Particularly in studies where the effect of traffic is emphasized; Ekmekçioğlu and Keskin (2007) found the level of $PM_{2.5}$ to be 13.3 – 95.2 and PM_{10} to be 27.9 and 289 µg/m^3 in schools, while Lee and Chang (2000) found that the PM_{10} concentration exceeded the average level of 180 µg/m^3, which is the 24-hour average value set forth by the local legislation in Kong.

As a result of PM measurements in this study, PM of different diameters appeared to show similar changes for both buildings. $PM_{2.5}$ values for the Faculty of Engineering vary between 85 and 95 µg/m^3, while for the Faculty of Architecture vary between 97 and 119 µg/m^3 (Table 3). $PM_{2.5}$ values for the Faculty of Engineering are similar to other studies in the literature. However, the values obtained at the Faculty of Architecture are above the results in other educational building studies. It can be said that this situation is caused by the use of tools and equipment which are necessary for the education of architecture. However, for PM_{10}, both buildings had lower values than the data in the literature.

5. Conclusion

In this study, the aim was to investigate the indoor air quality in naturally ventilated classrooms (three samples each) at two higher education buildings (Faculty of Architecture and Faculty of Engineering) which were taken as a case study. For this purpose, CO_2 and PM measurements of the indoor spaces were carried out in winter, during the usage of the classrooms. When the results found in this study were compared with similar studies in the literature, despite some differences when considering the various variables such as location, structural and spatial characteristics, the number of users, etc. similar results were obtained depending on average values.

In terms of indoor air quality, although CO_2 measurements have sometimes exceeded the limits at the Faculty of Architecture, it was found well above the limit values at the Faculty of Engineering. This situation was caused by the physical characteristics of the classrooms in the Faculty of Engineering (low ceiling height), the excessive number of users and the fact that the classrooms are used for longer periods due to the evening education and are not ventilated adequately. Especially in the Faculty of Engineering, ventilation must be controlled to ensure the indoor air quality and to enable the education to be carried out more efficiently. Classrooms should be ventilated in the morning before the usage of the space and also afterward, if necessary, mechanical ventilation should be utilized.

People who spend most of their time indoors spend about a third of their days in educational buildings. These and similar studies on indoor air quality, which are known to have a significant impact on students' efficiency and productivity, provide important inputs both for the improvement of existing buildings and for the planning of new buildings. This study aimed to emphasize the importance of indoor air quality issues, but future studies can be conducted to determine the effects of indoor air quality on learning by applying learning tests to students simultaneously with the measurements in buildings.

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