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Evaluating the Relationship Between Indoor Air Quality and Landscape Features in School Environments

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Abstract

Indoor air quality in schools is a fundamental component of a healthy indoor environment and significantly impacts students' health and well-being. Indoor air quality in schools stems from chemical pollutants, dust particles, and biological contaminants (bacteria, fungi, and viruses). Considering the effects of poor air quality in classrooms on the cognitive performance, health status, and overall learning experience of teachers and students, researching indoor air quality in schools and taking the necessary improvement measures is a critical requirement. It is well known that, in addition to measures taken within school buildings to improve indoor air quality, the landscaping areas belonging to schools also hold strategic importance. Indeed, outdoor environmental characteristics (physical factors such as plant design, shading elements, microclimate conditions, and airflow patterns) play a decisive role in shaping indoor air quality. In this context, improving the design of school outdoor spaces not only strengthens environmental sustainability but also contributes to creating a healthier and higher-quality indoor atmosphere in educational buildings.This study focuses on the effectiveness of landscape designs in reducing the negative effects of indoor air pollution by examining the changes in indoor air quality and the amount of carbon dioxide (CO2), one of the components affecting indoor air quality, in 10 different secondary schools selected as a sample in the city center of Isparta, along with relative humidity and temperature measurements. The study also found a significant relationship between air quality and the overall physical condition of the environment. This relationship is based on both statistical analyses and observational assessments. The research revealed that environmental design and physical environment quality affect not only outdoor but also indoor air quality. The findings highlight the need for a multidisciplinary approach to create healthy school environments.

Keywords: *School Gardens, Environmental Quality, Indoor Air Quality, CO2 Levels.*

Introduction

Today, societies are facing a global crisis linked to climate change and its effects, and these crises are causing various problems worldwide. One of the biggest problems in urban areas is air quality. In recent years, growing concern about the negative health effects of air pollutants has created a need for studies to monitor air pollution levels and develop and evaluate strategies. In line with sustainable development goals, the Action for Climate Empowerment (ACE) 2022-2032 framework was adopted at COP26 under Article 6 of the United Nations Framework Convention on Climate Change (UNFCCC), and the Action for Climate Empowerment Implementation Plan was adopted at COP27.

In terms of education policies, the ACE framework requires that climate change issues be integrated into the curriculum at all levels of education, that the climate literacy of teachers and students be increased, that sustainable behaviors be encouraged, and that school environments be organized in a way that supports climate action. Therefore, following the aforementioned international regulations and the COVID-19 pandemic, schools are now required to take an active role in the adaptation and mitigation process of the climate crisis. The primary purpose of schools is to provide children with the most suitable environment for learning and development (Mendell & Heath, 2005). Considering the amount of time children spend at school, they spend the majority of their time inside school buildings

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(approximately 30% at school and 70% in classrooms), exposing them to the negative effects of various pollutants (Shendell et al., 2004; Mendell & Heath, 2005; Children's Commissioner Report, 2024).

Overcrowded classrooms, shortened recess periods due to double-shift teaching, failure to ventilate classrooms during recess, insufficient ceiling heights, absence of mechanical ventilation systems, etc., lead to excessive pollution in classroom and school environments. It is emphasized that the deterioration of indoor air quality negatively affects individuals' comfort, peace of mind, and health (Çetin et al., 2019; Ghoma et al., 2022). Students breathe more air per unit weight than adults due to their developing lungs and immune systems, and they are more sensitive to heat/cold and humidity (Karaca, 2022). Students' exposure to pollution through various emissions in the air during their development causes structural and functional changes in them, affecting the health, performance, ability to concentrate on their lessons, and comfort of students and teachers (Meiboudi et al., 2016; Pulimeno et al., 2020; Chatzidiakou et al., 2023). In particular, CO_2 concentrations exceeding 1000 ppm cause lack of concentration, while headaches, dizziness, and fatigue complaints increase at concentrations above 1500 ppm (Myhrvold et al., 1996).

Mendell & Heath (2005) and Shendell et al. (2004) have demonstrated that indoor environmental quality in school buildings is generally inadequate and negatively impacts students' academic performance and attendance, particularly through the health effects caused by indoor pollutants. In addition, inadequate ventilation causes fatigue, impaired attention span, and loss of concentration (Dorizas et al., 2015) and an increase in illnesses (Meiboudi et al., 2016). Conversely, ensuring adequate ventilation in classrooms contributes to reduced absenteeism, limited spread of infectious diseases (Nazaroff, 2013), and improved cognitive task performance in both students and teachers (Shendell et al., 2004; Nazaroff, 2013).

Studies showing the relationship between indoor environmental quality and school health (Chetoni et al., 2016; Holgate et al., 2020) indicate that good indoor air quality is a fundamental component of a healthy environment and is linked to students' physical and psychological health, comfort, and performance. According to the ASHRAE 62.1 (2010) standard: "air in which known pollutants are absent or do not exceed specified concentrations, and in which at least 80% of the people in that environment do not experience dissatisfaction (feeling of discomfort) related to air quality."

When students and teachers are present in the classroom, they release CO_2 into the classroom air at a relatively constant rate, causing CO_2 levels to rise above the background concentration. ASHRAE 62.1 states that whether an environment is adequately ventilated can be determined by measuring the CO_2 concentration created by the occupants in the indoor atmosphere. The American Society for Testing and Materials standard guide (ASTM D6245) states that CO_2 produced by people can be used as an indicator pollutant to evaluate indoor air quality and ventilation (Öztürk et al., 2013).

Although the studies focus on health and performance effects, the relationship between the health and performance effects of children in classrooms and school landscape spaces should be considered in a multifaceted manner. This study examines the indoor air quality and the change in the amount of carbon dioxide (CO_2), one of the components affecting indoor air quality, in 10 different secondary schools selected as a sample in the city center of Isparta, along with relative humidity and temperature measurements, focusing on the effectiveness of landscape designs in reducing the negative effects of indoor air pollution.

Indoor Air Quality and Components

Although CO_2 is a colorless, odorless, non-toxic gas, it can cause suffocation by reducing the oxygen level in the air when present in high concentrations. Carbon dioxide (CO_2) concentration is an indicator of human-generated biological waste emissions. Standards for CO_2 concentration vary from country to country. According to international standards, the maximum permissible CO_2 level is recommended to be 1500 ppm (Table 1). The World Health Organization (WHO) reports the recommended upper limit for CO_2 in indoor air as 1000 ppm, and many studies also consider CO_2 concentration to be fundamental for indoor air quality (Jones et al., 2020; Fisk, 2013; Sireesha, 2017; Korsavi & Montazami 2019; Haddad et al., 2021; Persily, 2020; Ranjbar, 2019).

Table 1. Standards for CO_2 concentrations

Country	Standard	CO_2 level
İreland	HSA 2023	<1000 -1400
England	EN16798—Annex A, 2019	C1 < 550 ppm,

	ESFA, 2016	C2 < 800 ppm, C3 < 1350 ppm, C4 < 1350 ppm. CO_2 < 1500 ppm
New Zealand	NZ Ministry of Education Guide 2017	CO_2 < 1500 ppm
Germany	DIN1946-2, 2005	1500 ppm
France	RSDT, 1978	<1000 ppm
Finland	Ministry of Health and Social Development Standard, 2003 Part D2, 2010	700-1200 ppm 1200 ppm
Portugal	Decreto-lei n.o 78, 2006a; Decreto-lei n.o 79, 2006b	< 984 ppm +/−10%
USA	ASHRAE 62-1989 U.S. Department of Health and Human Services Reference Guidelines for Indoor Air Quality in Schools	1000 ppm 1000 ppm
Estonia	Ministry of Social Affairs Standards	1000 ppm

The procedures and principles regarding air quality management in our country are determined by the “Air Quality Assessment and Management Regulation” which entered into force in 2008 (Official Gazette dated June 6, 2008, No. 26898) and was prepared in accordance with European Union (EU) environmental legislation. Within the scope of harmonizing the air quality legislation determined by the European Union with national legislation, the Ministry of Environment, Urbanization, and Climate Change published the “2013/37 Air Quality Assessment and Management Circular” in 2013. However, pollutant parameter standards related to indoor air quality have not been determined in our country. Outdoor air quality standards, on the other hand, have been revised in line with the European Union's Air Quality Directive (2008/50/EC), which came into force in 2008, with a phased reduction envisaged from that date onwards, and the process of updating the regulations is underway in a manner similar to the WHO guideline values (Kuula et al., 2022).

Natural ventilation is the most common type of ventilation system used in educational buildings. However, low classroom ventilation rates may be a possible cause of observed effects, as when classroom temperatures are too high, students may be unable to concentrate or become distracted, leading to negative consequences for an effective learning process. Increased classroom temperatures also prevent teachers and children from attending school due to suboptimal classroom conditions. ASHRAE 55 (Thermal Environmental Conditions for Human Occupancy) indoor air temperature values are based on air exchange rates and specify temperatures of 23–26 ºC in winter and 20–24 ºC in summer, with humidity limits of 30–60% relative humidity. The MDPH (Massachusetts Department of Public Health) recommends an indoor air temperature of 21.11-26.67 ºC and an indoor relative humidity of 40-60%. TS 12281 (Environmental Health - Measures Related to Indoor Air) dated April 1997 states that the indoor temperature should be between 18 ºC and 24 ºC, and for very young children and the elderly, this value is given as 20 ºC. Furthermore, studies have concluded that lowering the temperature from 20-25°C to 18°C increases academic performance in students by 2-4% (Seppanenen et al., 2006; Bako'-Biro' et al., 2007; Wargocki & Wyon, 2007). Furthermore, it has been stated that buildings ventilated by natural means provide energy savings of up to 90% compared to similar buildings with mechanical ventilation (Yüksek & Esin, 2011).

Increased relative humidity in enclosed spaces facilitates the proliferation of microorganisms such as bacteria and mold fungi, thereby increasing the bioaerosol load and accelerating the release of toxins and microbial volatile organic compounds into the environment. This situation demonstrates that mechanical or natural ventilation alone is not a sufficient solution and that air taken from outside must be purified before being released into the indoor environment. Therefore, since indoor air quality is directly related to outdoor air quality, the ecological quality and plant arrangements of school gardens play a complementary and critical role in improving indoor air conditions.

Effects on Indoor Air Quality in School Garden

Various findings support that landscaping activities carried out in school gardens positively affect the quality of outdoor air transported into indoor spaces through natural ventilation (Zhang et al., 2019).

Studies in the literature reveal that plant arrangements, in particular, cause significant changes in the microclimate and play a regulatory role in environmental parameters such as temperature, wind regime, particulate matter retention, and moisture balance. Therefore, the arrangements implemented in school gardens not only enhance outdoor comfort but also indirectly yet significantly contribute to creating healthy indoor air conditions.

Plant cover is generally the most effective and least costly solution for reducing the urban heat island effect and improving environmental quality. The use of plants in school gardens contributes to lowering indoor air temperatures during summer months and, consequently, reducing cooling loads (Simpson & McPherson, 1998). In their study, Lin et al. (2023) stated that vegetation contributes to improving indoor thermal comfort by lowering indoor air temperature by 3.4°C on hot days through shading and blocking solar radiation. They also noted that heat loss can be reduced in winter months through the selection of plant species and their placement.

The seasonal permeability characteristics of tree species also determine indoor thermal behavior. The effects of different tree species on indoor thermal behavior vary depending on the species' morphology and leaf characteristics. Deciduous species provide coolness by blocking sunlight in summer, while allowing sunlight to enter in winter through leaf fall, thereby reducing heating requirements. In contrast, coniferous species act as a protective barrier throughout the year and have the potential to reduce heat loss in winter (Darvish et al., 2021). This is particularly important when using species that transmit sunlight at different rates depending on the season. Furthermore, studies on the effects of tree shade on thermal performance show that shading reduces cooling requirements in summer (Simpson & McPherson, 1998; Hu et al., 2020; Park & Guldmann, 2021). Morakinyo et al. (2016) showed in their study that indoor temperatures are lower and indoor relative humidity is higher in buildings with tree shade due to tree transpiration. The percentage of shade cover and the amount of solar radiation received by the building's exterior walls directly affect indoor temperature (Berry et al., 2013). Trees with broad leaves and dense crowns create a high-quality shade effect (Antoszewski et al., 2020).

Viecco et al. (2021) found that plants used on exterior walls and roofs can improve urban air quality by trapping particulate matter. However, it has also been noted that trees and green facades can reduce wind speed, potentially leading to a local increase in particulate matter concentrations in some cases. A well-designed plant arrangement, both on its own and as part of a system, can provide a noticeable net reduction in particulate matter and act as a buffer against the concentration of other environmental pollutants (Diener & Mudu, 2025). These findings indicate that the air quality-improving effect of plant design in school gardens should be evaluated in conjunction with environmental parameters.

Materials and Methods

The study's material consists of 10 different secondary schools located in the city center of Isparta (Mehmet Köse Secondary School, Iyaş Selçuklu Secondary School, Atatürk Secondary School, ITO Şehit Mustafa Gözütok Secondary School, TED Isparta Secondary School, Şehit Burhan Açıkkol Secondary School, Mustafa Şener Secondary School, Kadir Boylu Secondary School, Halıkent Secondary School, Yaşar Ulucan Imam Hatip Secondary School. Schools were selected for the sample based on their location, building characteristics, number of students, and willingness to participate in the research.

The analytical framework of this study focuses on examining the role and effectiveness of secondary school landscape designs in reducing the negative effects of environmental pollution. In the first phase of the study, a literature review was conducted to evaluate existing information on air quality in school spaces, current indoor air quality guidelines, and indoor air quality indices developed by previous researchers. In the second phase, CO_2, temperature, and relative humidity measurements were taken in the indoor spaces of schools located in different areas of Isparta city center. These parameters were then correlated with environmental characteristics and spatial conditions to develop spatial strategies for reducing CO_2 levels in schools.

Before measurements were taken in schools, the necessary permissions were obtained from the school administration, and measurements of carbon dioxide, temperature, and relative humidity levels affecting indoor air quality were taken in real time at breathing height using measuring devices in classrooms approved by the relevant school administrations during class time. Throughout the measurement process, factors such as classroom occupancy (number of students) and user behavior and activities (e.g., opening windows during class, movement, frequency of talking, etc.) were also recorded and included in the evaluation. This approach ensured a healthier analysis of indoor air quality and environmental conditions.

Within the scope of the study, temperature, humidity, and CO_2 levels were measured in selected secondary school facilities in December 2023 and May 2024. Measurements were taken during class hours using a portable precision measurement device called the "Carbon Dioxide, Temperature, and Humidity Recording Device." The measurement device used is a simple, mobile, sensor-based device that measures temperature and relative humidity values. The device's measurement ranges are -10 °C to +60 °C for temperature, 5.0% Rh to 95.0% Rh for humidity, and 0 to +10000 ppm for CO_2.

The first measurements were taken between December 11-15, 2023, and the second measurements were taken between May 13-17, 2024. Care was taken to ensure that the classrooms selected for the study were similar in terms of spatial size. After the classroom measurements, measurements were taken in the school corridors. Measurements were taken during class hours to observe the effects of user density, classroom size, and ventilation conditions. Carbon dioxide measurements were taken twice in each classroom in the morning, between 11:00 a.m. and 2:00 p.m., at the beginning and end of the class, for 5 minutes each, and the averages were recorded. During the measurements, the sensor was placed at a height of 1.0-1.5 m (ISO 16000-2; EN ISO 7726:2001) above the floor, at the breathing level of seated students, at a distance of 1.2 m, at least 0.5 m away from walls and windows, and the measurement was repeated.

To ensure the measurement process is carried out systematically, a school information form was created, and an inventory form was developed for schools. The inventory form includes the physical condition of the schools, the construction date of the school, the ventilation system, the heating system, and the number of students and staff. In addition, the current status of the landscaping features of school gardens has been evaluated, and their effects on environmental comfort have been analyzed. In this way, the relationship between the indoor and outdoor air conditions of schools and their spatial and environmental characteristics has been addressed with a holistic approach.

Data Evaluation Criteria

In the evaluation of carbon dioxide measurements, indoor air quality parameters measured in schools were compared with other country standards, and the measured CO_2 value was evaluated using the maximum acceptable CO_2 concentration level of 1000 ppm recommended by the World Health Organization (WHO) and many international standards (ASHRAE 62.1, EN 13779) as the maximum acceptable CO_2 concentration level for indoor environments (Table 2).

Table 2. CO_2 Concentration Level Assessment Scale

CO_2 Level (ppm)	Evaluation
<600 ppm	Excellent air quality
600 -1000 ppm	Acceptable
1001 -1500 ppm	Low ventilation, attention needed
>1500 ppm	Poor air quality, ventilation should be increased

In addition to the measurements, a Pearson analysis was performed to evaluate the relationship between indoor air quality parameters, namely indoor temperature and carbon dioxide levels. The Pearson correlation coefficient (r) is a statistical measure that assesses the linear relationship between two numerical (continuous) variables.

$$r = \frac{\sum(xi - x^{-})(yi - y^{-})}{\sqrt{(\mathrm{xi} - \mathrm{x}^{-})^2 . \sum(yi - y^{-})^2}}$$

xi: CO_2 data, yi: Temperature data, x^{-},y^{-}: Represent the average values.

r Value Range	Type of Relationship
r = 1	Perfect positive relationship
$0.7 \leq r < 1$	Strong positive relationship
$0.3 \leq r < 0.7$	Moderate positive relationship
0 < r < 0.3	Weak positive relationship

r Value Range	Type of Relationship
r = 0	No relationship
r < 0	Negative relationship

Findings and Discussion

Increases in carbon dioxide levels indoors depend on outdoor carbon dioxide levels, indoor space size, ventilation systems, and the number of students. Students' physical activity, the opening of windows and doors in classrooms, and ventilation options cause CO_2 levels to fluctuate. CO_2 measurement devices measure not only carbon dioxide levels but also environmental variables such as temperature and relative humidity, enabling a more comprehensive assessment of indoor air quality. When these three parameters are considered together, a more accurate and comprehensive picture of the physical conditions in the classroom environment is obtained. Therefore, measurements provide more meaningful and reliable data for both improving air quality and optimizing educational environments.

Analysis of Schools' Physical Characteristics

The physical characteristics of schools serve as a positive factor in the learning process, not only by providing physical comfort but also by encouraging attention and concentration. Physically, schools experience problems with the quality of the physical environment, which can be related to temperature regulation and air quality (Sogol & Holliday, 2018). All schools where the study was conducted have central heating systems powered by natural gas. These systems support students' thermal comfort by maintaining indoor temperatures at a certain level during the winter months. However, schools do not have mechanical ventilation systems (Table 3).

Table 3. Physical Characteristics of Schools

School	Date of Construction	Heating System	Ventilation System	Number of Students	Number of Staff
Mehmet Köse Secondary School	1991	Central heating	Natural ventilation	170	14
Iyaş Selçuklu Secondary School	1976	Central heating	Natural ventilation	755	57
Atatürk Secondary School	1982	Central heating	Natural ventilation	338	32
ITO Şehit Mustafa Gözütok Secondary School	2012	Central heating	Natural ventilation	848	56
TED Isparta Secondary School	2001	Central heating	Natural ventilation	400	100
Şehit Burhan Açıkkol Secondary School	2000	Central heating	Natural ventilation	254	34
Mustafa Şener Secondary School	1998	Central heating	Natural ventilation	506	43
Kadir Boylu Secondary School	2014	Central heating	Natural ventilation	637	56
Halıkent Secondary School	2018	Central heating	Natural ventilation	562	61

Yaşar Ulucan İmam Hatip Secondary School	2018	Central heating	Natural ventilation	93	14

The open space and landscape features of each school were evaluated, including the total area covered by the schools, building area, hard surface ratio, presence and ratio of open and green spaces, and the state of plant design (Table 4). This analysis was conducted to determine the indirect effects of landscape arrangements on indoor air quality and to identify improvement strategies. The findings of this study reveal that school gardens have indirect but significant effects on both outdoor air quality and indoor air conditions.

Table 4. Current Status of School Gardens

School	Total area (m^2)	Hard surface area (m^2)	Building area	Landscape area	Green space per person (m^2)
Mehmet Köse Secondary School	5889	4471	418	1000	5,5
Iyaş Selçuklu Secondary School	5422	4300	922	200	0,3
Atatürk Secondary School	4084	2988	896	200	0,5
ITO Şehit Mustafa Gözütok Secondary School	7836	5800	1486	550	0,6
TED Isparta Secondary School	40000	23600	5400	11000	15,7
Şehit Burhan Açıkkol Secondary School	7900	5500	1800	600	2,1
Mustafa Şener Secondary School	7711	6666	745	300	0,6
Kadir Boylu Secondary School	4978	3437	1341	200	0,3
Halıkent Ortaokulu	6674	4800	1577	297	0,5
Yaşar Ulucan İmam Hatip Ortaokulu	3871	3352	469	50	0,4

The assessment of school garden areas revealed that open and green spaces and plant designing are limited in public schools (Figure 1). In schools, the preference for hard surfaces over natural vegetation, which is an important component of the natural ecosystem that has a decisive impact on students' healthy lives and general well-being, combined with inadequacies in maintenance, renewal, and improvement efforts, constitutes a significant problem area. Therefore, enhancing plant arrangements in school open spaces creates a holistic effect that improves not only the outdoor microclimate but also indoor environmental conditions through natural ventilation.

Findings regarding the indirect effects of landscaping on air quality:

- Wooded areas can reduce the direct transfer of traffic-related pollutants to classroom windows.
- Heat accumulation and environmental stress factors increase in school gardens with a high proportion of hard surfaces.

Figure 1. Images of school gardens

In terms of garden usage rate and garden size, taking into account the current student potential, the most suitable schools are TED Isparta Secondary School, Mehmet Köse Secondary School, and Şehit Burhan Açıkkol Secondary School. These schools' gardens, with their spacious areas and usage capacities suitable for the student population, offer students more play and recreation space, enabling the effective use of the gardens.

The schools with the richest variety of plants used in the landscape design of their school gardens are TED Isparta Secondary School and ITO Şehit Mustafa Gözütok Secondary School. The garden areas owned by educational institutions play a vital role not only in contributing to the physical and mental development of students but also in raising environmental awareness. However, the study found that the majority of school gardens included in the study have concrete or asphalt surfaces and lack sufficient plant design. The high proportion of hard surfaces in school gardens, the neglected, worn, and compacted soil surfaces, and the poor quality of landscape plants limit the educational and ecological functionality of these areas.

Air Quality Measurement Values in Schools

The daily class schedules of the schools included in the study vary according to the level of education. In public schools, classes start at 08:30 and end at 15:30. In private schools, these hours can extend until 17:00. There is a one-hour lunch break in the middle of the day. Additionally, depending on the school, students may sometimes have to go to another classroom for music, art, or sports classes as part of their daily schedule. The academic year in the selected schools runs from the beginning of September to the end of June.

Measurements taken at schools were conducted at two different times during the day: in the morning and in the afternoon. The schools' initial CO_2, temperature, and relative humidity measurements were taken on December 11-15, 2023 (Tables 5-6), and repeat measurements were taken on May 13-17, 2024 (Tables 7-8). Measurements were taken in two different classrooms in each school, and the averages of the values obtained for these two separate classrooms were calculated.

Table 5. Morning Measurements İn Schools (11:00-12:00) December 11-15, 2023

School	CO_2 (ppm)			Temperature (C^0)	Humidity (%)
	Min.	Max.	Corridor		
Mehmet Köse Secondary School	1951	2020	1017	20.2	59
Iyaş Selçuklu Secondary School	1868	1885	762	21	38.4
Atatürk Secondary School	884	925	950	22.7	38.5

ITO Şehit Mustafa Gözütok Secondary School	1868	1880	1181	20.6	57
TED Secondary School	885	1100	850	19.4	62
Mustafa Şener Secondary School	678	686	951	17	55
Kadir Boylu Secondary School	1100	1260	750	20.1	57.4
Halıkent Secondary School	1610	1685	930	18.6	60.3
Yaşar Ulucan İmam Hatip Secondary School	1203	1289	1068	18.9	54
Şehit Burhan Açıkkol Secondary School	1788	1806	835	21	43.8

Table 5 covers the morning measurements taken at schools between December 11 and 15, 2023. It was determined that the indoor carbon dioxide concentrations at schools ranged from a minimum of 678 ppm to a maximum of 2020 ppm. This variation depends on various factors such as whether there is activity in the classrooms, whether the windows are closed, etc.

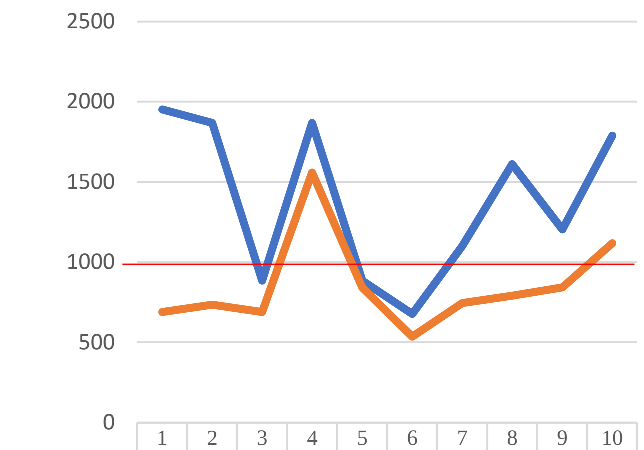
Table 6. Afternoon Measurements (1:00 PM To 2:00 PM) İn Schools From December 11 To 15, 2023

School	**CO_2 ppm**			**Temperature C^0**	**Humidity %**
	Min.	**Max.**	**Corridor**		
Mehmet Köse Secondary School	690	711	900	20.2	34
Iyaş Selçuklu Ortaokulu	735	776	668	20.3	36.8
Atatürk Secondary School	690	703	881	20.9	38.7
ITO Şehit Mustafa Gözütok Secondary School	1558	1627	1170	20	49
TED Secondary School	840	854	700	18.8	58
Mustafa Şener Secondary School	535	543	905	18.2	56
Kadir Boylu Secondary School	744	959	550	19.4	52.5
Halıkent Secondary School	790	805	900	20.2	48.8
Yaşar Ulucan İmam Hatip Secondary School	842	884	1010	19	53
Şehit Burhan Açıkkol Secondary School	1117	1167	760	19	52

It has been determined that carbon dioxide levels decreased somewhat during the midday break due to ventilation in the classrooms (Table 6). Problems with effective ventilation have been encountered due to reasons such as windows not being opened during breaks in cold weather out of concern for thermal comfort in the classrooms, restrictions on opening classroom windows for safety reasons, and the short duration of breaks.

Measurements taken in 10 schools revealed that carbon dioxide (CO_2) concentrations exceeded 1000 ppm in 7 schools, particularly during the winter months, due to inadequate ventilation. According to the measurement results, approximately 70% of students are in classrooms where the CO_2 level in the ambient air is above 1000 ppm. The remaining 30% are exposed to CO_2 concentrations of at least

500 ppm. Measurements taken in the afternoon revealed that the carbon dioxide (CO_2) concentration exceeded 1000 ppm in 2 schools (Figure 2). This indicates that adequate ventilation in classrooms improves indoor air quality, thereby enhancing students' health and learning performance.



	1	2	3	4	5	6	7	8	9	10
Series1	1951	1868	884	1868	885	678	1100	1610	1203	1788
Series2	690	735	690	1558	840	535	744	790	842	1117

Figure 2. Change in CO_2 Levels in Schools during the Winter Season

Between December 11-15, 2023, the morning CO_2 measurements (11:00-12:00) and temperature C^0 values in schools showed a moderate positive correlation with a Pearson correlation coefficient of r = 0.3179. The afternoon measurement values in schools (1:00 PM–2:00 PM) showed a weak positive correlation with r = 0.0656 (Figure 3).

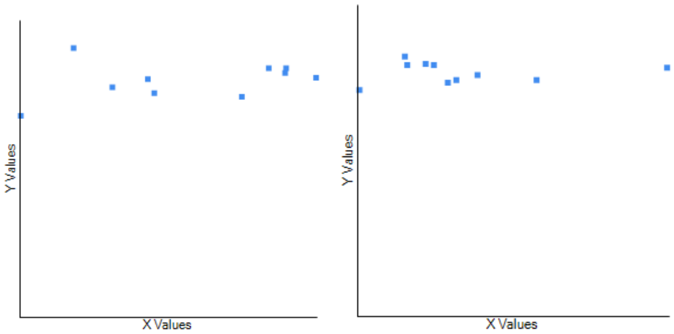


Figure 3. Relationship between indoor temperature and carbon dioxide levels in schools (December 11-15, 2023)

Inadequate ventilation leading to increased carbon dioxide (CO_2) levels in indoor environments quickly exceeds acceptable limits in schools (Coley & Beisteiner, 2002; Çetin & Şevik, 2016). Gil-Baez et al. (2017) stated in their study that CO_2 concentrations can reach levels of approximately 4000 ppm during periods of classroom occupancy. Particularly as a result of consecutive classes in classrooms, the amount of carbon dioxide released into the indoor environment by students through respiration can exceed 5000 ppm towards the end of the last class if ventilation is not provided. Sınanmış (2021), on the other hand, reported that in classrooms with an average of 30 students in Istanbul, the CO_2 level rose to 2600 ppm at the end of a 40-minute class period. Furthermore, he noted that ventilation achieved by opening windows on one side during breaks was insufficient to always achieve acceptable indoor air quality levels. This situation stems from the fact that in schools with natural ventilation, windows are generally kept closed during class hours to block outside noise and reduce airflow. Although classroom environments and climates vary worldwide, studies conducted in many countries (Greece, Kalimeri et al., 2016; Serbia, Jovanović et al., 2014; USA, Godwin & Batterman, 2007) reveal the common point that classroom ventilation is relatively poor.

During the spring term measurements in schools (Table 7), CO2 levels in classrooms reached 1182 ppm starting at 8:30 AM as students arrived, due to the accumulation of CO_2. Then, with the opening of windows during lunch break, the afternoon measurements (Table 8) showed a decrease to 516 ppm.

Table 7. Schools' Morning Measurements (11:00-12:00) May 13-17, 2024

School	CO_2 ppm			Temperature C^0	Humidity %
	Min.	Max.	Corridor		
Mehmet Köse Secondary School	1117	1167	1182	25.4	39.5
Iyaş Selçuklu Secondary School	950	931	728	25.2	41
Atatürk Secondary School	960	980	820	24.8	35
ITO Şehit Mustafa Gözütok Secondary School	1257	1308	728	26.4	42.1
TED Secondary School	750	790	510	25.6	38
Mustafa Şener Secondary School	1110	1065	895	27.2	32
Kadir Boylu Secondary School	1117	1167	1182	25.4	39.5
Halıkent Secondary School	656	672	532	24.2	42.4
Yaşar Ulucan İmam Hatip Secondary School	931	950	883	25.9	40.0
Şehit Burhan Açıkkol Secondary School	1182	1782	735	26.4	37.3

Table 8. Afternoon Measurements At Schools (1:00 PM–2:00 PM) May 13–17, 2024

School	CO_2 ppm			Temperature C^0	Humidity %
	Min.	Max.	Corridor		
Mehmet Köse Secondary School	850	900	649	25.2	38.4
Iyaş Selçuklu Secondary School	628	656	598	25.9	40.0
Atatürk Secondary School	540	586	410	25.1	38.2
ITO Şehit Mustafa Gözütok Secondary School	883	950	704	24.9	37.3
TED Secondary School	703	730	728	24.3	36.4
Mustafa Şener Secondary School	910	1000	735	26.3	43
Kadir Boylu Secondary School	634	680	586	26.4	37.3
Halıkent Secondary School	516	598	482	24.2	42
Yaşar Ulucan İmam Hatip Secondary School	703	730	728	25.6	38
Şehit Burhan Açıkkol Secondary School	634	680	506	25.4	39.5

Although an increase in CO_2 levels was observed in the early morning hours in schools due to staff and student usage, indoor CO2 levels were found to be quite stable and low in the same areas in the afternoons under different ventilation conditions (e.g., opening windows, activities involving higher air exchange rates) (Figure 4). Therefore, the data obtained highlights the behavior and management of window opening and closing in each school's classrooms.

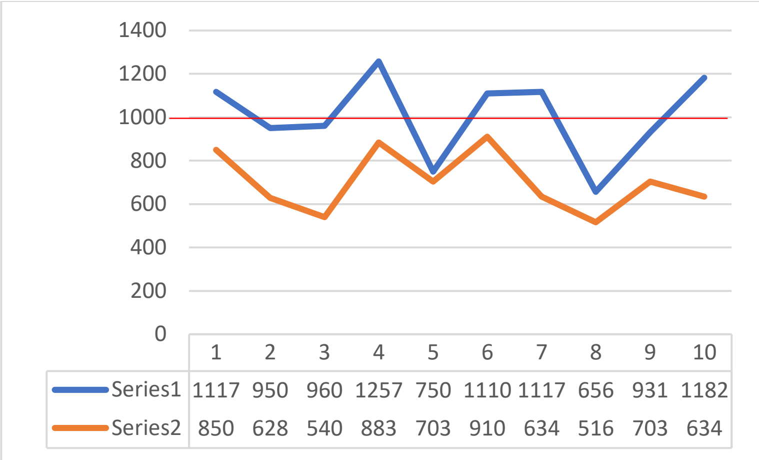


Figure 4. Change İn CO_2 Levels İn Schools During The Spring Semester

From May 13-17, 2024, the morning CO_2 measurements (11:00-12:00) and temperature C0 values at schools showed a moderate positive correlation with a Pearson correlation coefficient of r = 0.5632. The afternoon measurement values for schools (1:00 PM to 2:00 PM) showed a weak positive correlation with r = 0.2297 (Figure 5).

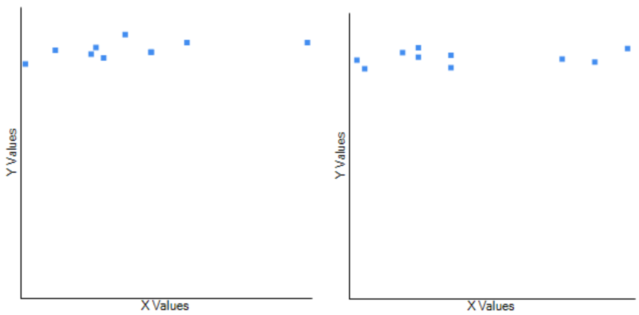


Figure 5. Relationship Between İndoor Temperature And Carbon Dioxide Levels İn Schools (May 13-17, 2024)

Studies using data recorded in schools in the UK also show that classroom ventilation rates are generally lower during the winter months, typically about half the values obtained during the spring months (Vouriot et al., 2021; Burridge et al., 2021) and that classroom ventilation changed significantly during different periods of the COVID-19 pandemic (Burridge et al., 2021). ASHRAE Standard 62.1 (2010) states that an indoor CO_2 level up to 700 ppm higher than the outdoor level is acceptable. This means that, assuming the outdoor level is approximately 400 ppm, the indoor limit of 1100–1200 ppm should not be exceeded.

The study determined that, thanks to the natural gas central heating system present in all schools, classroom temperatures generally remained within an acceptable range. However, the absence of mechanical ventilation and insufficient air circulation in classrooms that remained constantly closed led to heat buildup in some classrooms and a corresponding increase in relative humidity. An inverse relationship was sometimes observed between temperature values considered suitable for thermal comfort and CO_2 accumulation. Indoor air exchange is provided entirely through natural ventilation, i.e., by opening windows. This situation reduces the frequency of ventilation, especially in cold weather conditions, and carries the risk of increasing CO_2 accumulation indoors.

Discussion and Conclusion

The primary purpose of CO_2 measurements is to identify areas with inadequate air circulation and encourage the adoption of daily practices that increase clean air exchange. This enables the development of effective improvement programs and the implementation of behavioral controls from a comprehensive perspective. Measures aimed at improving air quality in schools are important not only in helping prevent the onset of illnesses among students but also in raising awareness.

Measurements taken in classrooms revealed that the average CO_2 concentration in classrooms was above 1000 ppm. Concentration changes measured on different days of the week showed that indoor CO_2 concentrations were generally lower than the corresponding outdoor levels and that indoor concentrations increased in the afternoon compared to the morning hours. Furthermore, the measured indoor concentration levels showed seasonal variation.

According to the results of the study, the geographical location of schools plays an important role in indoor and outdoor air quality. When assessing indoor air quality risks, outdoor areas in the immediate vicinity of schools should be taken into consideration. This study found that a large proportion of the schools selected as samples were located in areas with moderate to high exposure to traffic-related pollutants. This situation may be due to the absence of such environmental risks at the time some schools were built or to urbanization accelerating after school construction, thereby increasing traffic density. The findings indicate that urban development around schools is a significant determinant of indoor and outdoor air quality.

The use of natural ventilation provides acceptable indoor air quality levels and reduces energy consumption due to the associated decrease in the use of mechanical ventilation. In schools without mechanical ventilation, it is important to maintain CO_2 levels at a level that protects students' physical and mental health through natural ventilation. Inappropriate natural ventilation practices can compromise indoor air quality. Therefore, it is essential to develop mitigation strategies to improve indoor air quality and prevent the spread of infectious diseases in naturally ventilated classrooms. When planning natural ventilation strategies in schools, outdoor pollution must be taken into account. Therefore, local strategies for different school locations, such as proximity to transportation routes and industrial areas, should be developed to suit the characteristics of schools in different regions.

Recommendations for improving air quality in school environments:

Increasing green spaces through landscaping; In schools, the primary source of CO_2 is outdoor air, such as traffic and industrial emissions. Infiltration from outdoor air, especially at short distances from roads or high-density industrial or traffic areas, strongly affects indoor levels. The geographical location of the school plays an important role in determining indoor and direct outdoor air quality. Therefore, it is important to improve the environmental characteristics of schools. Increasing green areas through landscaping in school gardens and improving classroom air quality by using the right plants in classrooms is necessary. When selecting landscaping plants for gardens, they should be enriched with plant species that are compatible with local climate conditions, require little maintenance, and are durable. Care should be taken to ensure that these plants are colorful, fragrant, and varied in type to attract children's interest.

Establishing regular and natural ventilation systems; An effective ventilation system is necessary to ensure acceptable indoor air quality in classrooms.

Monitoring CO_2 and particulate matter levels in enclosed spaces using CO_2 sensors; CO_2 sensors are mandatory in classrooms where the required amount of fresh air is provided through natural ventilation. If the required amount of fresh air is provided through mechanical ventilation, a system must be installed to monitor that the amount of fresh air complies with the TS EN 16798-1 standard, and the system must be designed to sound an alarm if the amount of fresh air deviates by -10% from this standard value.

Optimizing ventilation intervals according to class schedules; Students should be encouraged to adopt behaviors that increase air exchange frequency and improve ventilation with clean outdoor air for indoor air quality.

Providing air quality awareness training to students and staff; Schools should focus on educating staff and students about the potential environmental impacts of air quality. Scientific activities and seminars should be organized to improve students' knowledge and awareness of the importance of indoor air quality.

The existing hard surfaces in school gardens should be replaced with natural materials and permeable surfaces. Teachers and parents should be encouraged to participate in the process of improving gardens and ensuring their sustainability. Their involvement in this process will support the long-term maintenance of the gardens and contribute to the development of students' environmental awareness.

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