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Field Measurement and Assessment of Some Air Pollutants within a Number of Alimentary Schools in the Al–Karkh Region in Baghdad City, Iraq

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Abstract

To determine the main pollutants influencing classroom environments and examine their relationships with ventilation effectiveness, student density, and school location characteristics, this study was carried out to assess the IAQ in primary schools in Baghdad's Al-Karkh district. To reflect a range of building ages, structural designs, and levels of exposure to nearby traffic, twelve elementary schools were chosen at random. Calibrated portable instruments were used to measure the concentrations of carbon dioxide (CO_2), carbon monoxide (CO), fine particulate matter ($PM_{2.5}$), inhalable particulate matter (PM_{10}), total volatile organic compounds (TVOCs), temperature, and relative humidity within the classrooms during the wet season of 2025 (the first academic semester). The findings revealed that numerous schools had pollution levels beyond the international recommended standards. $PM_{2.5}$ varied from 24 to 95 µg/m³, PM_{10} varied from up to 191 µg/m³, TVOCs varied from 442 to 521 µg/m³, and CO_2 concentrations varied from 1,000 to 1,525 ppm. On the other hand, in rooms with inadequate ventilation, the CO concentrations were near the threshold levels but remained within tolerable bounds (1.5–6 ppm). During the cooler months, the mean inside temperature was approximately 19 °C, which was marginally warmer than the outdoor readings. The relative humidity averaged 67%, which indicated limited air exchange and the buildup of pollutants. These results offer compelling evidence that inadequate ventilation exacerbates indoor air deterioration in classrooms, especially when paired with outside traffic pollutants and poor thermal-humidity conditions. To safeguard children's respiratory health and to create safer and healthier learning environments in Baghdad's schools, this study concludes that improved ventilation techniques, regular IAQ monitoring programs, and the application of sustainable preventive measures are crucial.

Keywords:
Indoor air quality, alimentary school, air pollutants, particulate matter; field measurement.

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Introduction

Air pollution is a major global issue that impacts ecosystems, the economy, and public health. When harmful things are in the air, it is called air pollution. It can come from both the inside and the outside. People do things at home that pollute the air, such as by cooking and heating. Things such as factories

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and cars and natural disasters such as wildfires pollute the air outside (Smith, 2021). The World Health Organization (WHO) says that Iraq's air pollution levels are higher than what they recommend. This means that people are more likely to develop cancer and die early from toxins in the environment (IQAir, 2022). According to the 2022 Iraq Air Quality Index, the air quality in Iraq was the second worst in the world. On May 19, 2022, the PM2.5 concentration in Iraq was 162, indicating that the air quality was poor (Abbas, 2021). You need to know what makes these two types of pollutants different in order to develop good ways to cut them down. Air pollution is a major global issue that impacts ecosystems, the economy, and public health. When harmful things are in the air, it is called air pollution. It can come from both the inside and the outside. People do things at home that pollute the air, such as by cooking and heating. Things such as factories and cars and natural disasters such as wildfires pollute the air outside (Smith, 2021). The World Health Organization (WHO) says that Iraq's air pollution levels are higher than what they recommend. This means that people are more likely to develop cancer and die early from toxins in the environment (IQAir, 2022). According to the 2022 Iraq Air Quality Index, the air quality in Iraq was the second worst in the world. On May 19, 2022, the PM2.5 concentration in Iraq was 162, indicating that the air quality was poor (Abbas, 2021). You need to know what makes these two types of pollutants different in order to develop good ways to cut them down. The air quality in Baghdad, Iraq's capital, is poor because the population is growing, the city is becoming more urban, and the infrastructure is old. Baghdad University and other schools in the city have been leading the way in research on these issues, showing how pollution affects people's health and quality of life in cities. Even with these efforts, the city still has to address a growing population and falling apart infrastructure, which makes pollution worse and raises public health concerns (Al-Obaidi & Al-Azzawi, 2023). Air quality is very important for life on Earth because it affects the health of living things and the economy (Bai, 2018). by a large increase in the amount of pollution. Accelerated industrialization, increased usage of private vehicles, and ongoing fossil fuel consumption are intimately related to this environmental problem (Singh, 2016). Numerous dangerous pollutants, including CO_2, CO, SO_2, NO_2, CH_4, O_3, and particulate matter such as PM2.5 and PM10, are currently present in the atmosphere and present serious risks to ecological stability and living things (Bai, 2018). Indoor and outdoor pollution are the two main categories into which air pollution is typically divided (Van Aardenne, 2018). Numerous household and environmental factors, such as the use of scented items, poor ventilation, pet dander, culinary emissions, freshly painted interiors, high occupancy density, smoking, and the infiltration of contaminated outdoor air, can contribute to indoor pollutants and radiation. Power plants, industry, transportation, road dust from construction, open garbage burning, biomass burning, brick kilns, and emissions are the main sources of outdoor air pollution (Carne, 1964). Approximately 4 million deaths were ascribed to this problem in 2019 alone, with Central Europe and East Asia having the greatest death rates (Leung, 2015). In addition, a number of studies have shown a strong correlation between air pollution and a high risk of developing cancer. According to related research, almost 250,000 individuals worldwide claim air pollution-related stomach and lung cancers (European Environment Agency, 2022). In addition to pollutants, microclimatic factors such as the indoor temperature and relative humidity significantly influence IAQ dynamics, affecting ventilation efficiency and pollutant persistence (World Health Organization, 2021). The European Environment Agency (EEA) performed a study and reported that 10% of cancer cases in Europe are caused by air pollution. Approximately 3 million new cases of cancer and 1.3 million cancer-related deaths occur each year. Freas (1995) states that these cases cost the economy 178 million euros. With an emphasis on measuring air pollution levels in multiple Baghdadi schools and comparing them to worldwide trends, this study attempts to evaluate the effects of certain air pollutants and environmental factors on students' health. The goal is to draw attention to how crucial it is to keep an eye on school air quality and put suitable measures in place to lower any health concerns.

Materials and Methods

Study Area Description and Data Collection

The urban agglomeration of Baghdad (Figure 1) is predicted to have 8,141,120 residents as of mid-2025. In accordance with the most recent United Nations assessment of World Urbanization Prospects, this figure represents the metropolitan region, which encompasses both the city of Baghdad and its surrounding suburbs. The Karkh side (western bank of the Tigris) of Baghdad is home to 1,374 elementary schools, according to a geospatial education analysis (Figure 1). This figure corresponds to approximately 46% of all schools in the Baghdad governorate; approximately 1,608 schools (54%) are located on the Rusafa (eastern) side (Korchenko, 2019). During the academic year 2024–2025, a cross-sectional survey was carried out in 12 elementary schools in the Al-Karkh neighborhood of Bagdad city.

For this investigation, a purposeful (nonprobability) collection was employed (Figure 2).

Figure 1. The map shows the distribution of the current study of 12 (private and public) primary schools (Karkh).

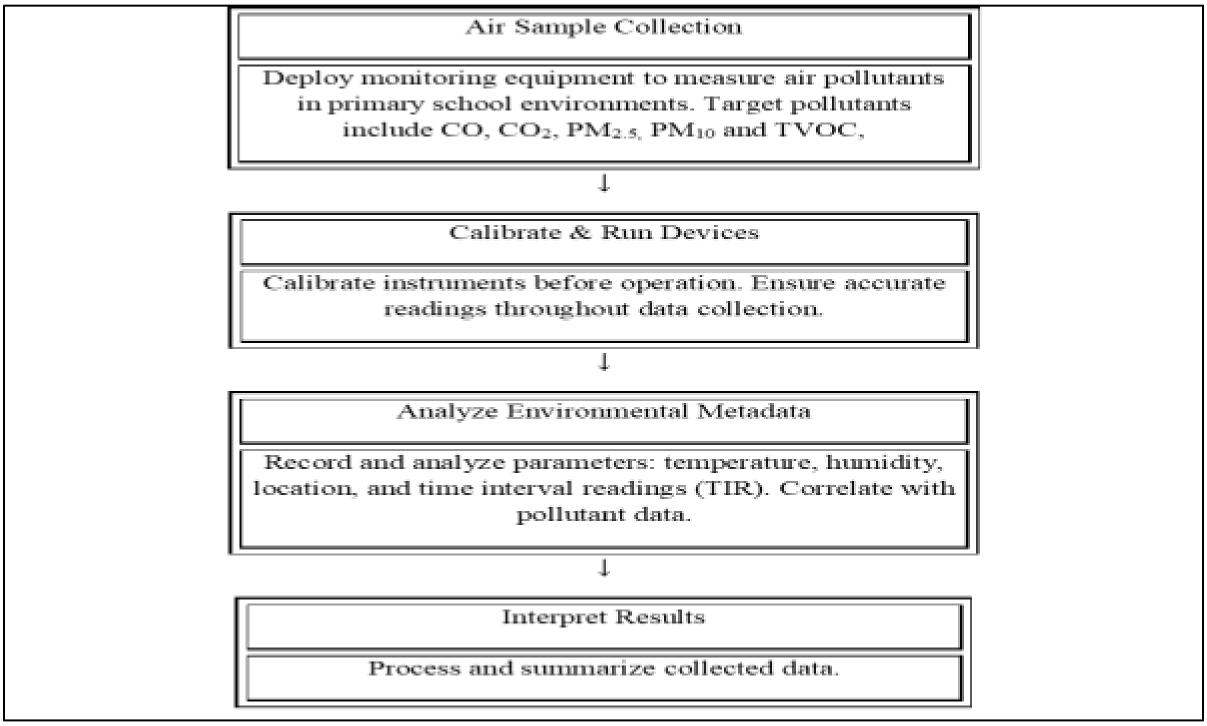

Figure 2. Air Quality Collection – Analysis in Primary School

Data collection and statistical analysis

To guarantee accuracy and scientific rigor, all the gathered data were subjected to systematic validation, organization, and analysis. An IAQ-CALC Model 7545 (TSI Inc., USA) was used to monitor the amounts of carbon dioxide (CO_2) and carbon monoxide (CO). AEROCET 531 (Met One Instruments Inc., USA) was used to measure the levels of fine and coarse particulate matter ($PM_{2.5}$ and PM_{10}, respectively). Testo 435 (Testo SE & Co. KGaA, Germany) was used to measure the total volatile organic compounds (TVOCs). An EXTECH HD500 (Extech Instruments, USA) was used to measure microclimatic data, such as air temperature and relative humidity. They all use portable instruments that are calibrated and are often used in Iraqi environmental monitoring labs. It is a good place to study. We selected twelve primary schools from the Al-Karkh district of Baghdad—six public, six private, and two reference schools—which were used as controls. The selection process was performed randomly to account for differences in the structure, ventilation systems, and environment around the buildings.

Data were collected during the wet season of 2025. A number of classroom-specific or structural factors, such as building age, construction materials, classroom area, ventilation type, and the presence of auxiliary facilities such as windows, corridors, and green spaces, were analysed to determine the statistical relationships between the measured indoor pollutants (CO_2, CO, $PM_{2.5}$, PM_{10}, and TVOCs). To assess the impact of these functional and physical attributes on pollutant buildup and variability across schools, correlation and comparison statistical tests were used.

Statistical Analysis

The frequency distribution was used to examine the variability and distribution patterns of the indoor air pollution concentrations in the classrooms. The concentration data were normally distributed, and GraphPad Prism software, version 8.0.1 (GraphPad Software, Inc., USA), was used to compute the mean and standard deviation using one-way ANOVA to test for group differences. To examine the degree of correlation between the ambient and microclimatic factors under study, Pearson's product–moment correlation coefficient (r) was calculated. A probability level of $p < 0.05$ was deemed significant, whereas a $p > 0.05$ level was regarded as nonsignificant. The studies were conducted in accordance with Montgomery's (2020) conventional environmental biostatistical methodology.

Results and Discussion

Temperature

According to the temperature data shown in Figure (3), the classroom temperatures in every region that was investigated fell between 16 and 19.5 degrees Celsius, with only slight variations between public and private schools. International guidelines indicate a thermal comfort range of 20 to 24 degrees Celsius for educational settings; however, these indoor temperature values fall short (ASHRAE 55:2021; WHO, 2021). Poor ventilation effectiveness, infrequent use of air conditioners, and the impact of exterior weather conditions during Baghdad's winter season could all be responsible for the lower temperatures. Al-Jihad and Al-Saydiya had the lowest average temperatures, both of which were less than 17 °C, whereas Hay Al-Jamiah and Al-Kadhimiya public schools had the highest temperatures (≈ 19 °C). These spatial differences reveal how wall insulation, building design, and student occupancy density affect heat retention. While older buildings with thin walls and damaged windows lose heat more quickly to the outdoors, classrooms with higher occupancy are likely to experience a small temperature increase because of metabolic heat generation (Ali et al., 2023). Additionally, the findings indicate that there is no statistically significant difference ($p > 0.05$) between public and private schools, suggesting that both have comparable operational and architectural constraints with respect to heat control. However, the slightly higher average in private schools can be due to smaller class sizes and greater upkeep, which increase ventilation and lessen heat dissipation (Al-Rikabi et al., 2022). According to Jantunen et al. (2011), students' respiratory health, comfort, and attention span may all suffer from suboptimal classroom temperatures (below 20 °C), especially in the early morning when outside temperatures are lower. To reduce heat stress and guarantee suitable learning settings, the World Health Organization stresses that classroom temperatures should be maintained between 20 and 24 °C (WHO, 2021). (Mendell & Heath, 2005; Wargocki & Wyon, 2013).

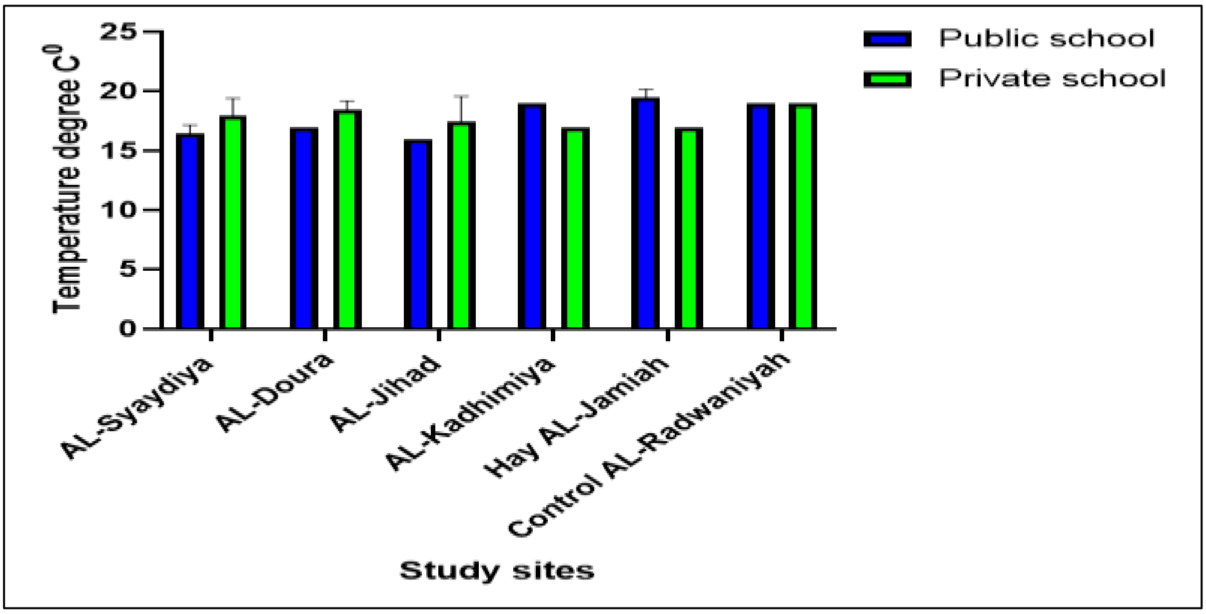

Figure 3. Variation in indoor temperature (°C) among public and private primary schools in the current study.

The findings, which are summarized in Table (1), show that the classroom temperatures in the Baghdad Al. Karkh region under investigation ranged from 16 °C to 19.5 °C, with a normal range of 20 to 24 °C for schools to be comfortable (ASHRAE 2021; WHO, 2021). The statistical analysis revealed no significant differences (P > 0.05) in temperature between public and private schools across all regions, suggesting a consistent thermal pattern throughout the study area. These results clearly show that most of the classrooms were either too hot or too cold. Those in the Al-Syaydiya, Al-Doura, and Al-Jihad public schools were the worst. The average temperature at Al-Jihad Public School was 16 ± 0 °C, and the average temperature at Hay Al-Jamiah Public School was 19.5 ± 0.71 °C. This difference is probably because the buildings are set up differently, the walls are insulated differently, and it is easier to reach the air conditioners or heaters (Al-Rikabi et al., 2022). Compared with private schools, public schools often lose heat because they are in older buildings with poor insulation and crowded classrooms. The private schools, on the other hand, had slightly higher means (up to 18.5 ± 0.71 °C in Al-Doura). This could mean that they were better maintained, had smaller class sizes, and used the HVAC system less often. Interestingly, the Al-Kadhimiya site showed the opposite trend: public schools (19 ± 0 °C) were warmer than private schools were (17 ± 0 °C). These findings indicate that being outside different microclimatic conditions, such as wind corridors, solar orientation, shade, and local infrastructure, can help even out differences between different types of schools (Ali et al., 2023). Although there were differences between regions, there was no statistically significant difference (p > 0.05) between public and private schools. This means that both types of schools have similar problems in terms of maintaining the best indoor conditions. This consistency shows that the cold winters in Baghdad, along with the city's high population density and lack of mechanical ventilation, make it difficult for people to control the temperature inside. From a physiological and educational perspective, schoolchildren, particularly those with allergies or asthma, may experience increased pain, respiratory distress, and difficulties in concentration. when exposed to temperatures below 20 °C (Jantunen et al., 2011). Therefore, maintaining classroom temperatures between 20 and 24 °C is crucial for supporting both health and cognitive function (WHO, 2021).

Table 1. Table (1) Statistical Analysis of Indoor Temperatures (Mean ± SD, °C) for Public and Private primary schools in the current study.

Regions	**Type school (mean ±SD)**	
	Public	**Private**
AL-Saydiya	16.5±0.71Aa	18±1.4Aa
AL-Doura	17±0.0Aa	18.5±0.71Aa
AL-Jihad	16±0.0Aa	17.5±2.1Aa
AL-Kadhimiya	19±0.0Aa	17±0.0Aa
Hay AL-Jamiah	19.5±0.71 Aa	17±0.0Aa
Control AL-Radwaniyah	19±0.0Aa	19±0.0Aa
Normal range Temperature 20-24^{o} C		

Differences in capital letters in columns and small letters in rows indicate significant differences (P value <0.05).
Similar capital letters in columns and small letters in rows indicate nonsignificant differences (P value >0.05).

Humidity

The relative humidity (RH) levels in the classrooms that were assessed ranged from 58% to 75.5%, as shown in Figure 4 and Table 2. These findings indicate that institutional and spatial differences were present across the Baghdad regions that were examined.

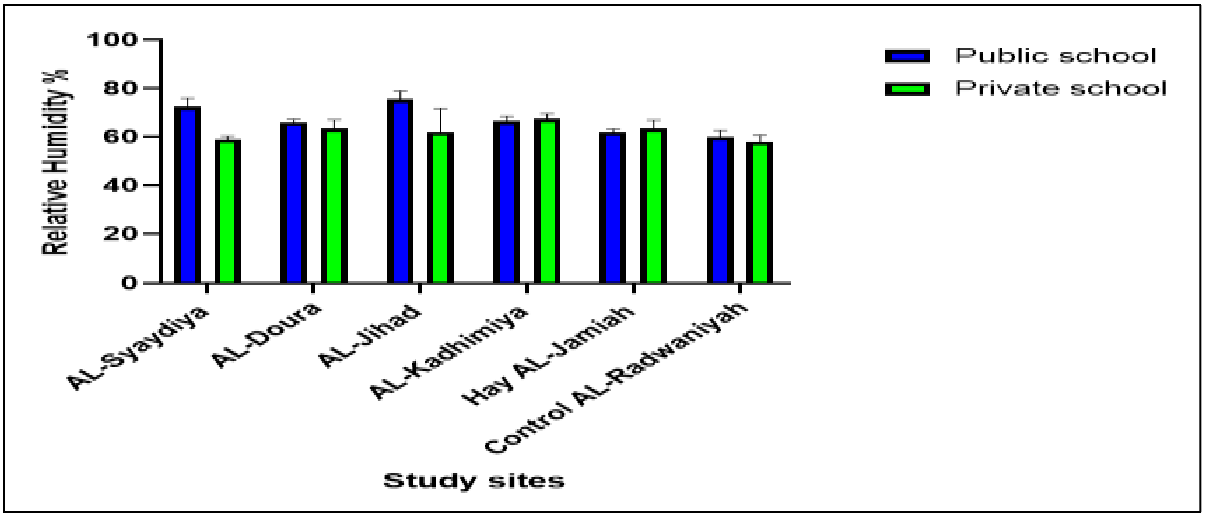

Figure 4. Variation in Indoor Relative Humidity (RH, %) between Public and Private primary schools in the current study.

"Significant differences ($P < 0.05$) were observed in relative humidity between public and private schools in Al-Saydiya and Al-Jihad, indicating that ventilation quality and building structure had a measurable effect on indoor moisture levels. For interior comfort, the normal suggested relative humidity range is 40–65% (WHO, 2021). The highest humidity levels were reported at public schools, especially those in Al-Jihad (75.5 ± 3.5%) and Al-Saydiya (72.5 ± 3.5%), which were clearly above the top comfort limit. Conversely, the RH levels in private schools were often lower, ranging from 59 ± 1.4% in Al-Saydiya to 62 ± 9.8% in Al-Jihad. These variations can be ascribed to operational and structural factors. Public schools frequently have older buildings with inadequate window insulation, little ventilation, and a high student population, all of which contribute to the development of indoor moisture (Ali et al., 2023). In line with the thermodynamic predictions, the results also revealed a negative correlation between temperature and humidity: cooler classrooms tended to maintain greater RH values. In Al-Syaydiya and Al-Jihad, where the lowest temperatures (16–17 °C) correlated with the highest humidity measurements, this link was very noticeable. Similar results were reported by Hussein (2019) at the University of Baghdad, who reported that pupils in Baghdad's schools experienced discomfort and excessive humidity because of crowded classrooms and inadequate ventilation. Al-Kadhimiya, Hay Al-Jamiah, and Al-Radwaniyah were among the schools whose humidity levels were within the permissible range of 60–67%, but the average RH for public schools was still greater than that for private schools. While low humidity (<40%) might result in mucosal dryness and irritation, excessive indoor humidity (>65%) is known to promote microbial and fungal development, lower air quality, and impair cognitive function (Arundel et al., 1986; Wolkoff, 2018). Thus, to promote thermal comfort, respiratory health, and ideal indoor air quality, the RH must be maintained between 40 and 60%. Seasonal measurements revealed that, as a result of decreased ventilation, external relative humidity (63–72%) increased indoor moisture buildup during November–December 2024. The findings demonstrate that both public and private schools must use integrated humidity–temperature management measures, such as routine HVAC maintenance, a regulated ventilation schedule, and enhanced insulation.

Table 2. Means ± SDs of relative humidity (%) within public and private primary schools in the current study.

Regions	**Type school (mean ±SD)**	
	Public	**Private**
AL-Syaydiya	72.5±3.5Ba	59±1.4Ab
AL-Doura	66±1.4Aa	63.5±3.5Aa
AL-Jihad	75.5±3.5Ba	62±9.8Ab
AL-Kadhimiya	66.5±2.1Aa	67.5±2.1Aa
Hay AL-Jamiah	62±1.4Aa	63.5±3.5Aa
Control AL-Radwaniyah	60±2.8Aa	58±2.8Aa
Normal range Humidity 40-65%		

Differences in capital letters in columns and small letters in rows indicate significant differences (P value <0.05). Similar capital letters in columns and small letters in rows indicate nonsignificant differences (P value >0.05).

CO_2

Indoor CO_2 concentrations in the classrooms that were examined throughout the monitoring period ranged significantly between 533 ppm and 1485 ppm, as indicated in Figure (5) and Table (3), demonstrating significant variations among school types and areas.

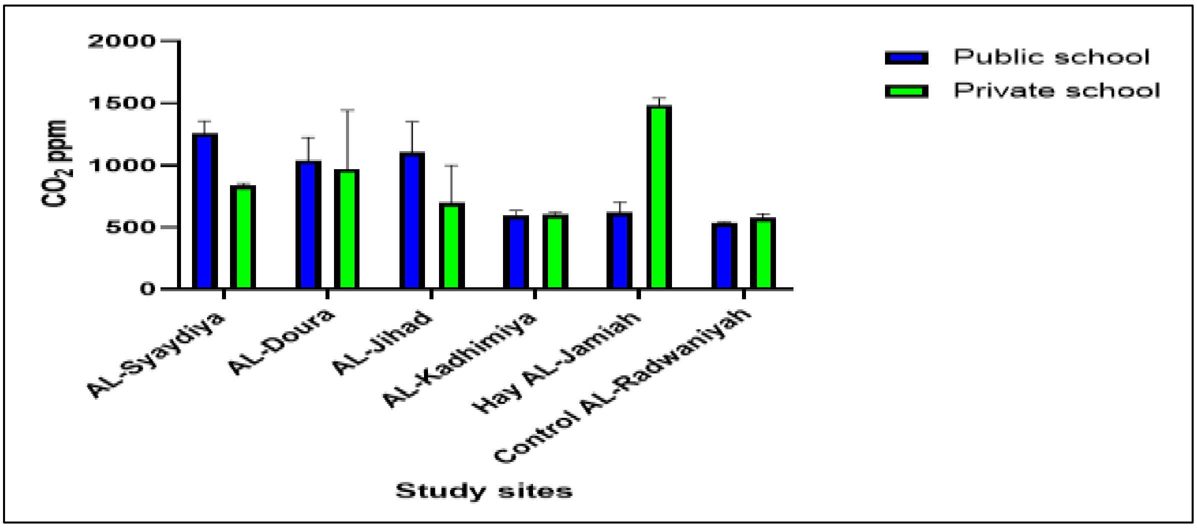

Figure 5. The indoor values of CO2 within public and private primary schools in the current study.

400–1000 parts per million is the suggested tolerable range for indoor CO_2 levels (ASHRAE, 1992; WHO, 2021). Statistical analysis revealed significant differences ($P < 0.05$) in CO_2 levels between different types of schools in Al-Syaydiya and Hay Al-Jamiah. This means that public and private schools had very different levels of ventilation effectiveness. Al-Syaydiya public schools (1256 ± 97.58 ppm) and Hay Al-Jamiah private schools (1485 ± 56.57 ppm) had the highest mean values, both of which were above the maximum comfort level. On the other hand, Al-Radwaniyah (533–574 ppm) and Al-Kadhimiya (594–602 ppm) had the lowest concentrations, both of which are within permissible limits. Variations in classroom ventilation, building design, and occupant density are the causes of this spatial variation. Owing to restricted air exchange and the metabolic output of crowded student groups, classrooms lacking air conditioning or sufficient mechanical ventilation, especially those in Al-Syaydiya, Al-Doura, and Al-Jihad, tended to collect greater concentrations of CO_2 (Ali et al., 2023). Students may experience decreased cognitive performance, weariness, and focus loss as a result of the high CO_2 levels seen in these areas, which suggest inadequate indoor air renewal (Wolkoff, 2018). On the other hand, better ventilation and perhaps fewer students per classroom are the reasons for the lower CO_2 concentrations in the control and Al-Kadhimiya schools. With the exception of Hay Al-Jamiah, where ventilation systems were either nonfunctional or not operational during measurement periods, statistical comparisons revealed that public schools generally had higher CO_2 averages than private schools did. The primary indoor source of CO_2 is human respiration, especially in crowded and enclosed environments. Minor contributions may arise from combustion-based heating or laboratory activities; however, the dominant factor remains exhalation (Hussein, 2019). According to ASHRAE Standard 62 (1992), concentrations exceeding 1000 ppm indicate insufficient ventilation relative to occupant load, a condition that aligns with results from Al-Syaydiya and Al-Jihad public schools. Maintaining indoor CO_2 levels below 1000 ppm is critical for preserving acceptable air quality and student comfort. The current findings reinforce the need to improve ventilation infrastructure, regularly inspect HVAC systems, and enforce classroom occupancy limits to align with international indoor air quality standards.

Differences in capital letters in columns and small letters in rows indicate significant differences (P value <0.05).
Similar capital letters in columns and small letters in rows indicate nonsignificant differences (P value > 0.05).

Table (3): Statistical Analysis of Indoor Carbon Dioxide (CO_2) Concentrations (Mean ± SD, ppm) within Public and Private primary schools in the current study.

Regions	Type school (mean ±SD)	
	Public	Private
AL-Saydiya	1256±97.58Aa	837.5±17.68Bb
AL-Doura	1040±186Aa	973±468.8Ba
AL-Jihad	1106±245Aa	699.5±301Bb
AL-Kadhimiya	594±41.01Ba	602±21.21Ba
Hay AL-Jamiah	618±84.85Ba	1485±56.57Ab
Control AL-Radwaniyah	533±9Ba	574±35Ba
Normal range CO_2 400-1000		

CO

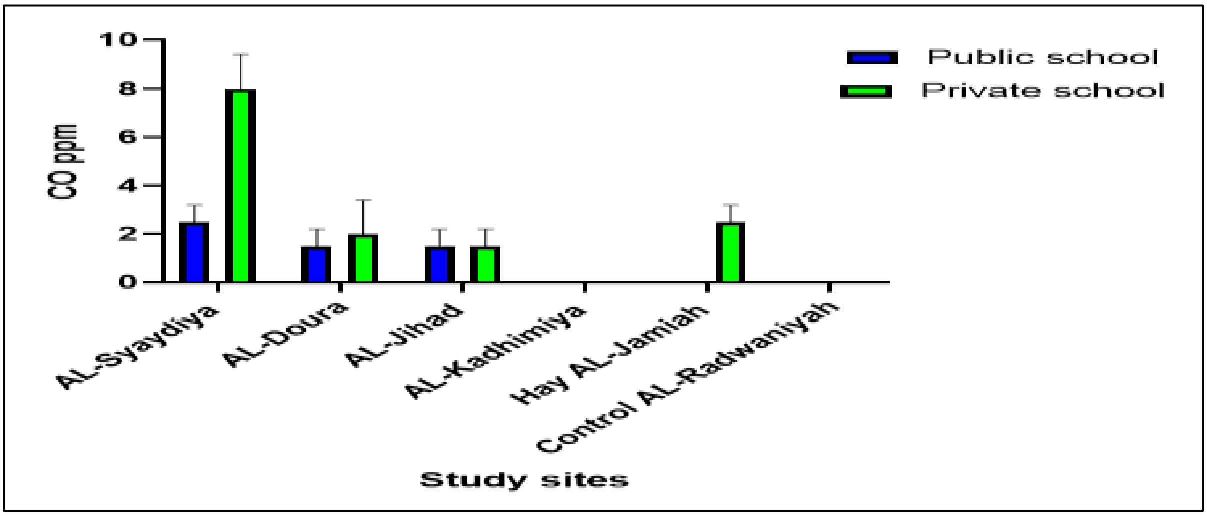

Figure 6. Indoor CO levels (ppm) within public and private primary schools in the current study.

The data in Figure 6 and Table 4 of this study indicate that the concentrations of carbon monoxide in the schools examined were within the normal range, between 0 ppm and 8 ppm, as defined by the World Health Organization (2021). The concentration at Al-Saydiya Private School was excessively high, reaching approximately 8 ± 1.4 ppm. Al-Kadhimiyah Public Schools showed measurable levels of carbon monoxide, while the control site showed no detectable presence. The Al-Dawra, Al-Jihad, and Al-Jami'a neighborhoods were three such sites with minimal exposure, ranging from 1.5 to 2.5 ppm. A significant difference ($P < 0.05$) was observed between public and private institutions in Al-Saydiya. The elevated carbon monoxide levels were not accidental; rather, they resulted from deliberate improvements to the school's ventilation infrastructure and increased duration of outdoor student activity. In contrast, the Al-Kadhimiyah site and the control site did not significantly differ ($P > 0.05$). It appears that carbon monoxide levels were low and remained so in these less polluted areas.

All origins can be ascribed to geographic fluctuations in carbon monoxide concentrations. Schools such as Al-Saydiya and Al-Dora, owing to their proximity to major thoroughfares and minor industrial establishments, have likely exacerbated carbon monoxide emissions. Recent research conducted in Iraq has established that elevated external traffic density and proximate industrial workshops significantly contribute to increased indoor carbon monoxide levels in educational and office settings in Baghdad (Al-Dughair and Hassan, 2022; Karim and Al-Khafaji, 2023). Insufficiently sealed doors, windows, and openings permit the ingress of pollutants into classrooms, particularly in the absence of mechanical systems and where natural ventilation is predominant (Al-Bayati et al., 2022). Moreover, statistical research revealed a strong correlation between the number of classes and habitable floor space and carbon monoxide concentrations, aligning with the notion that larger room dimensions facilitate more efficient pollutant dispersion through turbulent diffusion and mass air movement. This finding corresponds with recent studies from Iraq indicating that tiny, densely populated indoor environments exhibit swift carbon dioxide buildup during active hours (Hussein and Abdul-Razzaq, 2021). Conversely, contaminants can swiftly collect in smaller, more congested classrooms, especially during school hours when air exchange is restricted. The elevated carbon dioxide concentrations in Al-Saydiya and the University District, where private schools are near major thoroughfares and corporate parking facilities, may be attributed to localized outdoor exposure. Recent measurements in Baghdad (Fadel and Al-Saadi, 2023) corroborate the environmental theory that dispersion and dilution mechanisms result in a reduction in pollutant concentrations as the distance from emission sources increases. Prolonged exposure to levels exceeding 4 parts per million in educational environments is concerning, despite the reported values being significantly lower than industrial benchmarks. This is because even minor CO accumulation might affect oxygen transport, lower cognitive function, and cause headaches or exhaustion in children (WHO, 2021). The present findings emphasize the necessity of installing CO detectors, improving classroom ventilation, and minimizing student exposure to external exhaust emissions through proper building siting and traffic management (Hussein, 2019).

Table 4. Means ± SDs of Indoor Carbon Monoxide (CO) Concentrations (ppm) in Indoor CO Levels (ppm) within Public and Private primary schools in the current study

Regions	**Type school (mean ±SD)**	
	Public	**Private**
AL-Saydiya	2.5±0.7Aa	8±1.4Ab
AL-Doura	1.5±0.7Aa	2±1.4Ba
AL-Jihad	1.5±0.7Aa	1.5±0.7Ba
AL-Kadhimiya	0 ±0.0Ba	0±0.0Ca
Hay AL-Jamiah	0±0.0 Ba	2.5±0.7Bb
Control AL-Radwaniyah	0 ±0.0Ba	0±0.0Ca
Normal range CO 0-4		

Differences in capital letters in columns and small letters in rows indicate significant differences (P value <0.05).
Similar capital letters in columns and small letters in rows indicate nonsignificant differences (P value >0.05).

PM2.5
The PM2.5 concentrations in the schools that were assessed ranged from 16 µg/m³ to 67 µg/m³, which is above the recommended guideline value of 0–35 µg/m³ by the World Health Organization (WHO, 2021) in most areas, as indicated in Figure (7) and Table (5). The mean concentrations were greatest in the public schools Al-Kadhimiya (67 ± 39.6 µg/m³) and Al-Jihad (66 ± 21.21 µg/m³), whereas the control samples from Al-Radwaniyah had the lowest values (16 ± 1.4 µg/m³).

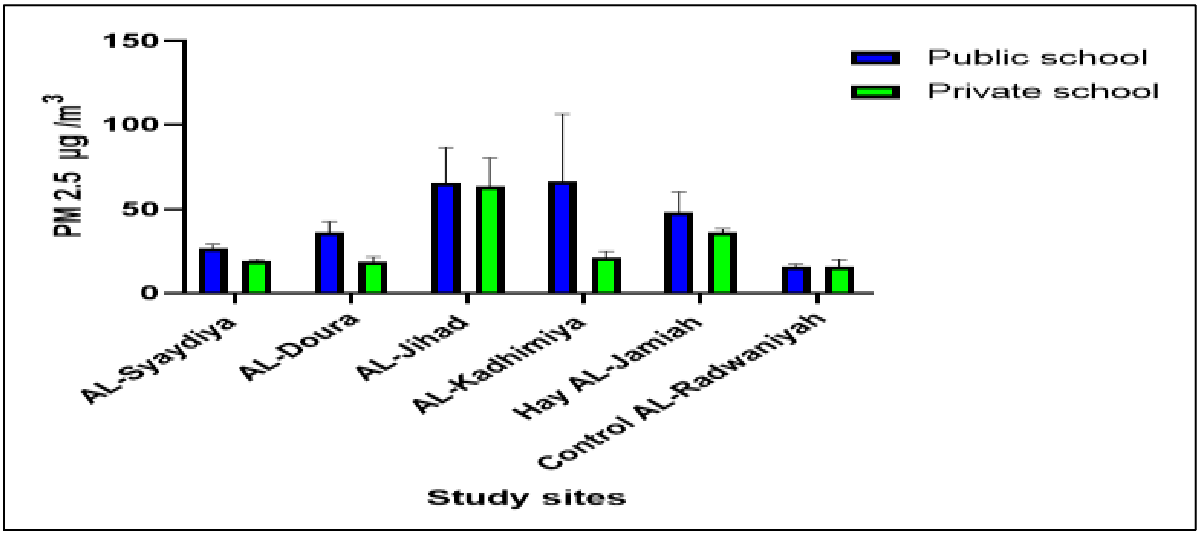

Figure 7. The indoor distribution of PM2.5 within public and private primary schools in the current study. µg/m3.

Increased exposure to fine airborne particulates from adjacent traffic corridors, dust resuspension, and inadequate air filtration are indicated by the increased values at Al-Kadhimiya and Al-Jihad. Statistical analysis revealed that these localized microenvironmental effects differ considerably ($P < 0.05$) from those obtained in Al-Saydiya, Al-Doura, and the control schools. In Al-Kadhimiya and Al-Doura, notable differences were detected between private and public schools ($P < 0.05$). Private classrooms had significantly lower $PM_{2.5}$ levels, most likely as a result of better building maintenance, smaller class sizes, and the use of air conditioners that improve filtration efficiency.

Table 5. Statistical Analysis of Indoor Fine Particulate Matter ($PM_{2.5}$) Concentrations (Mean ± SD, µg/m³) within Public and Private primary schools in the current study.

Regions	**Type school (mean ±SD)**	
	Public	**Private**
AL-Saydiya	27±2.3Aa	19.5±0.7Aa
AL-Doura	36.5±6.3Aa	19±2.8Ab
AL-Jihad	66±21.21Ba	64±16.97 Ba
AL-Kadhimiya	67 ±39.6Ba	21.5±3.5ACb
Hay AL-Jamiah	48.5±12.02 Aa	36.5±2.1Ca
Control AL-Radwaniyah	16±1.4Aa	16±4.2Aa
Normal range PM2.5 0-25		

According to earlier studies, the resuspension of deposited dust during normal cleaning and student movement causes indoor $PM_{2.5}$ concentrations to frequently surpass outdoor concentrations (Freas, 1995; Emmerich, 2003). Children may be at risk for health problems because of the presence of lead, pesticide residues, and other harmful chemicals in these particles. Particles smaller than 2.5 µm can enter the pulmonary system more deeply, evading the body's natural defenses and exacerbating illnesses such as bronchitis and asthma. In line with earlier environmental studies in urban Iraqi schools, the difference across schools is a result of the building design, ventilation rate, and closeness to outside emission sources (Hussein, 2019). Additionally, new data from around the world show that one of the key factors determining indoor exposure to $PM_{2.5}$ is still penetration from outside emissions, particularly traffic and dust from unpaved roads (de Melo et al., 2025). Taken together, our findings reveal that the particle concentrations in most of the classrooms under study surpass global safety standards, indicating insufficient filtration and ventilation. To lessen PM_2 exposure in Baghdad's elementary schools, wet cleaning techniques should be used on a regular basis, HVAC filters should be upgraded, and surrounding traffic emissions should be reduced.

PM_{10}

The indoor PM_{10} concentrations in the classrooms surveyed in this study varied significantly, ranging from 24.5 µg/m³ to 188.5 µg/m³, exceeding the World Health Organization's (WHO, 2021) recommended limit of ≤50 µg/m³ at almost all the sites except the control school, as shown in Figure (8) and Table (6). Al-Saydiya had the lowest mean concentration, while Hay Al-Jamiah Private School had the highest concentrations (188.5 ± 4.9 µg/m³) and Al-Jihad Private School (171 ± 28.28 µg/m³).

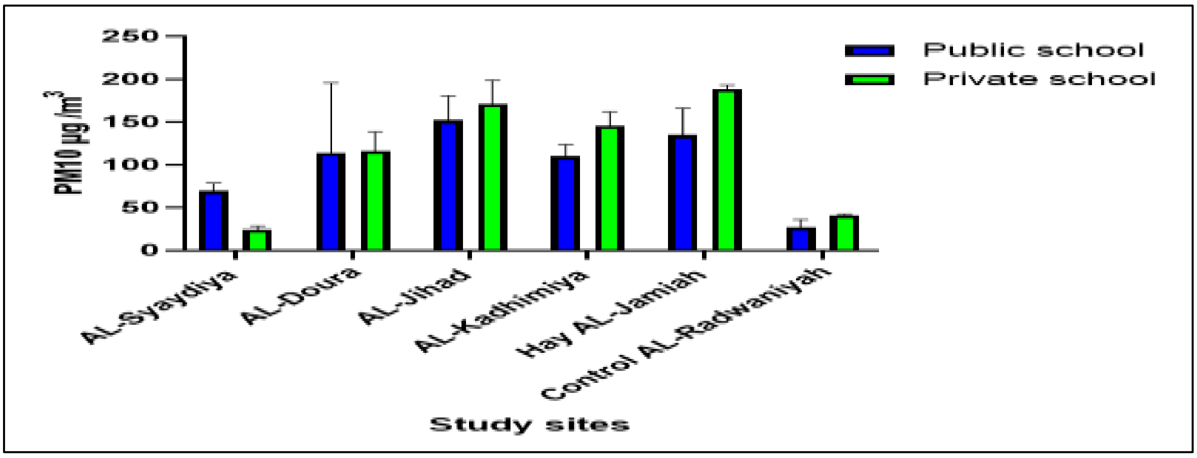

Figure 8. The indoor distribution of PM10 within public and private primary schools in the current study. Mg/m3.

3.5 µg/m³ at a private school (24.5 ±). Significant differences ($P < 0.05$) between public and private schools were found in a number of regions, including Al-Saydiya, Hay Al-Jamiah, and the control site (Al-Radwaniyah). These findings suggest that building design, ventilation efficiency, and proximity to outdoor sources all have quantifiable effects on PM_{10} levels. On the other hand, Al-Doura, Al-Jihad, and Al-Kadhimiya did not significantly differ ($P > 0.05$), indicating comparable exposure patterns for both school types in these districts. The concentrations of PM_{10} were highest in the classrooms of primary schools 3, 5, 6, 7, 8, 9, and 11, which are situated close to busy intersections and older buildings. These results imply that interior PM_{10} levels are affected by indoor resuspension processes, such as student mobility and classroom activities that disturb settled dust particles, in addition to outdoor penetration from vehicle emissions and road dust. Similar trends have been documented elsewhere. In German schools, Fromme et al. (2008) reported that indoor particulate matter levels were higher than outdoor air levels, and Stranger, Potgieter-Vermaak, and Van Grieken (2008) reported the same results in Belgian primary schools. Similarly, Oeder et al. (2012) reported that indoor PM_{10} concentrations in Munich schools might be up to five times higher than outdoor concentrations, highlighting the importance of occupant activity, cleaning practices, and inadequate ventilation as major factors in particulate buildup. The results of this study are consistent with those of de Melo et al. (2025), who reported that schools located close to busy roads or industrial areas are more vulnerable to the penetration of coarse particles. Furthermore, it was observed that a significant contributing element to the brief increase in the PM_{10} concentration was the "personal cloud effect," which is caused by children's physical activity. Taken together, the statistics show that the PM_{10} levels in Baghdad's schools greatly surpass international health requirements because of inefficient ventilation and the combined effects of indoor and outdoor sources. To lower student exposure and improve indoor air quality, it is imperative to implement effective air filtration systems, maintain better buildings, and limit traffic emissions close to schools.

Table (6): Statistical Analysis of Indoor Particulate Matter (PM_{10}) Concentrations (Mean ± SD, µg/m³) within Public and Private primary schools in the current study.

Regions	Type school (mean ±SD)	
	Public	Private
AL-Saydiya	69.5±9.2Ba	24.5±3.5Fb
AL-Doura	114±82.2Ba	116±21.9Ea
AL-Jihad	152±29.7Ba	171±28.28 Da
AL-Kadhimiya	110 ±14.14Ba	145.5±16.26Ca
Hay AL-Jamiah	134.5±31.82 Ba	188.5±4.9Bb
Control AL-Radwaniyah	27.5±9.2Aa	41±1.4Ab
Normal range PM10 0-45		

Differences in capital letters in columns and small letters in rows indicate significant differences (P value <0.05).
Similar capital letters in columns and small letters in rows indicate nonsignificant differences (P value >0.05).

TVOC

The results revealed that the total volatile organic compound (TVOC) concentrations in the schools that were surveyed ranged from 22 µg/m³ to 306 µg/m³, as shown in Figure (9) and Table (7). The highest mean values were found at Hay Al-Jamiah Private School (306 ± 30.4 µg/m³) and Al-Doura Private School (266.5 ± 24.8 µg/m³). The concentration at Al-Syaydiya Public School was the lowest, at 22 ± 1.4 µg/m³.

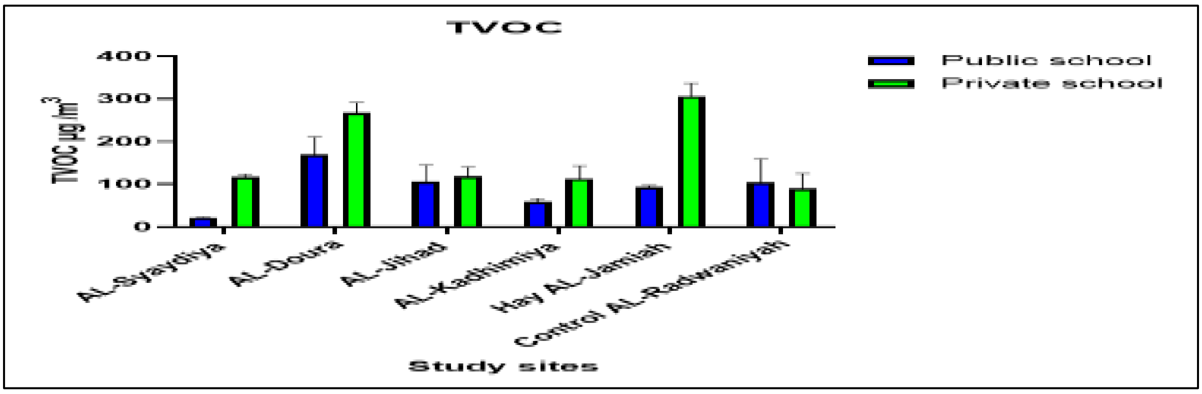

Figure 10. The indoor concentration of TVOCs within public and private primary schools in the current study. µg/m3.

To reduce the risk of sensory irritation and discomfort, the World Health Organization (WHO, 2000) advised that indoor TVOC levels should not surpass 300 µg/m³. In a number of localities, including Al-Syaydiya, Al-Doura, and Hay Al-Jamiah, statistical analysis revealed substantial differences ($P < 0.05$) between public and private schools, with private schools showing significantly greater concentrations. This fluctuation reflects variations in classroom activity, ventilation efficiency, building age, and material type. On the other hand, Al-Jihad, Al-Kadhimiya, and Al-Radwaniyah did not significantly differ ($P > 0.05$), indicating comparable emission sources and similar exposure patterns. A number of possible indoor emission sources, such as air fresheners, paints used for student artwork, pen inks, and classroom furnishings, were identified. However, the high scores reported in some schools cannot be entirely explained by these factors alone. These findings are consistent with previous research that highlights that TVOCs are not direct indications of toxicity but rather composite indicators of overall chemical emissions and ventilation adequacy (European Collaborative Action, 1997; Andersson et al., 1997). Both the

The WHO's recommended limit (300 µg/m³) and the 666 µg/m³ threshold linked to irritation of the eyes, nose, and throat are exceeded by the measured mean concentration across all classes (≈815 µg/m³) (Brasche et al., 2004). Individual classroom readings varied from 200 to 3000 µg/m³, indicating that certain situations, especially those with inadequate air circulation, may cause mild to moderate sensory irritation and discomfort. More serious side effects, such as headache, exhaustion, and irritation of the mucosa, have been linked to concentrations higher than 3000 µg/m³ (Molhave & Nielsen, 1992).

Table (7): Statistical Analysis of Indoor Total Volatile Organic Compounds (TVOCs) Concentrations (Mean ± SD, µg/m³) within Public and Private primary schools in the current study.

Regions	**Type school (mean ±SD)**	
	Public	**Private**
AL-Saydiya	22±1.4Da	117±5.6Bb
AL-Doura	169.5±41.72Ca	266.5±24.8Bb
AL-Jihad	106±39.6Aa	119.5±21.9 Ba
AL-Kadhimiya	59.5 ±7.78Ba	113±29.7Ba
Hay AL-Jamiah	93.5±3.5 Ba	306±30.4Bb
Control AL-Radwaniyah	104±55.15Aa	90±35.36Aa
Normal range TVOC 0-300		

Differences in capital letters in columns and small letters in rows indicate significant differences (P value <0.05).
Similar capital letters in columns and small letters in rows indicate nonsignificant differences (P value >0.05).
TVOCs are generally used as markers of material off-gassing and indoor air quality (WHO, 2000). Modern furniture coatings, new flooring materials, and frequent cleaning product use—all of which release volatile organic compounds that are built up in poorly ventilated spaces—are likely the causes of the high quantities in private schools. To lower long-term exposure hazards, the findings highlight the significance of airing out classrooms, enhancing ventilation, and choosing low-emissions materials during school restoration or furnishing. Different patterns of interaction between the observed indoor air quality measures in classrooms were identified by correlation analysis. As shown in Figure 11, a statistically significant positive correlation was detected between CO_2 and TVOCs ($r = 0.45$, $p < 0.05$), indicating that both pollutants have a common source related to human occupancy and indoor activities such as breathing, metabolic emissions, and the use of cleaning agents or classroom materials.

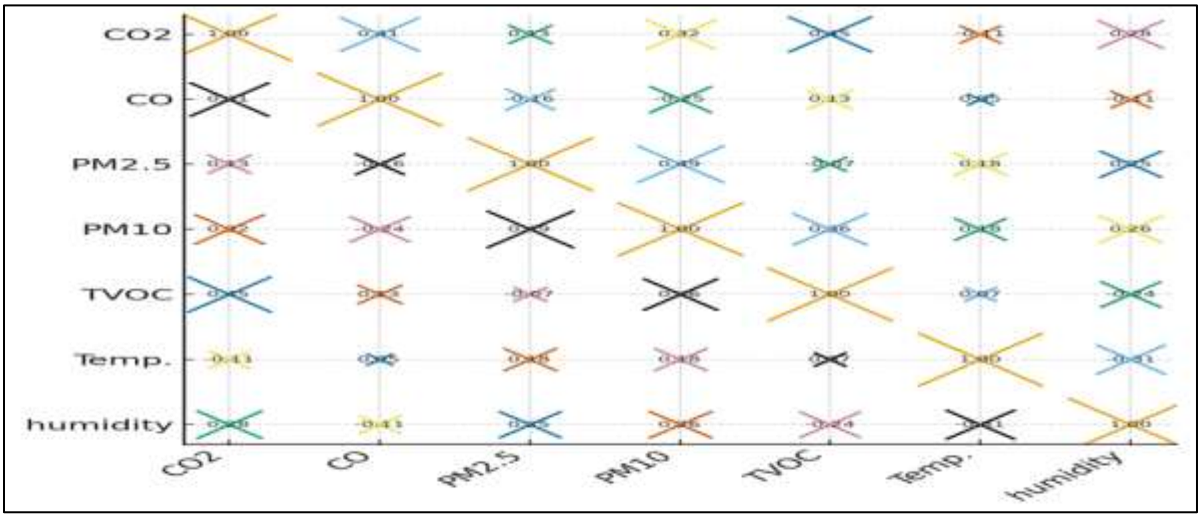

Figure 11 Correlation Matrix of Indoor Air Quality Parameters in Classrooms

Similarly, a noteworthy positive connection was discovered between CO_2 and CO ($r = 0.41$, $p < 0.05$), suggesting that inadequate ventilation not only encourages the build-up of CO_2 but also makes it easier for combustion-related pollutants to accumulate when they enter through heating systems or traffic. The fine and coarse $PM_{2.5}$ and PM_{10} particulate matter fractions were strongly positively correlated ($r = 0.49$, $p < 0.05$), reflecting similar aerodynamic behavior and common sources, such as outdoor particulate penetration, chalk use, and dust resuspension from student movement. Furthermore, there was a moderately significant connection ($r = 0.36$) between PM_{10} and TVOCs, suggesting that air stagnation and a lack of filtration permit the simultaneous accumulation of particles and volatile compounds in enclosed classrooms. There were weaker and statistically insignificant associations between pollutants and microclimatic variables. While humidity was slightly positively correlated with CO_2 ($r = 0.28$) but inversely correlated with TVOCs ($r = -0.24$), temperature was negatively correlated with both CO_2 ($r = -0.11$) and TVOCs ($r = -0.068$). These weak associations demonstrate that ventilation and occupancy, rather than heat conditions, were the main determinants of pollutant fluctuations in the classrooms under investigation. Overall, the correlation structure highlights the impact of insufficient air exchange in classroom settings, where ineffective ventilation encourages the simultaneous increase in suspended particles, traffic-related pollutants, and human-derived gases. To reduce children’s cumulative exposure, these findings highlight the need for better ventilation techniques and pollution control measures in schools.

Conclusion

The current study revealed that ventilation effectiveness, classroom occupancy, and proximity to outside emission sources—particularly traffic—are the main factors influencing IAQ in Baghdad's primary schools. Several classrooms, particularly those with limited air exchange and high student population, had elevated amounts of CO_2, $PM_{2.5}$, PM_{10}, and TVOCs. These findings highlight how vital it is to enhance mechanical and natural ventilation systems, establish routine IAQ monitoring programs, and put preventative measures in place to lessen children's exposure to airborne contaminants. Strong correlations between particulate matter fractions (PM_2, CO_2, and PM_{10}) and among CO_2, CO, and TVOCs were also found by correlation analysis, indicating that these substances share a similar source of human activity and emissions associated with combustion. On the other hand, temperature and relative humidity, two microclimatic characteristics, did not significantly affect pollutant variability, indicating that human activity rather than environmental variables is primarily responsible for the decline in classroom air quality. Overall, implementing sustainable environmental management techniques—such as better ventilation, well-designed classrooms, and air filtration—can significantly improve schoolchildren’s respiratory health, cognitive function, and comfort level while also creating a more comprehensive and effective learning environment.

Author Contributions

All the authors contributed equally.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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