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Indoor air quality in primary school classrooms in Sweden, Slovakia, and the United Arab Emirates

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ABSTRACT

The indoor environment was investigated in 75 primary school classrooms in three countries with different climate zones, building types and cultural and social aspects. Temperature, relative humidity and concentrations of CO_2, formaldehyde, TVOC, NO_2, ozone and particulate matter (PM) were measured over a one-week period in 45 schools in Sweden (winter), 15 schools in the United Arab Emirates (UAE; mild winter & hot summer) and in 15 schools in Slovakia (winter). The schools in the UAE were newer (average age 13 years vs. 70 in Sweden, 93 in Slovakia) and smaller (average volume 149 m^3 vs. 174 m^3 and 213 m^3, respectively) with similar or higher occupancy. Schools in Sweden, mostly ventilated with mechanical ventilation operating with outdoor air, demonstrated the highest ventilation rates (median 3.2 h^{-1} vs. 0.47 h^{-1} in Slovakia and 0.57 h^{-1} in UAE in winter) and lowest concentrations of most pollutants. Natural ventilation in Slovakia and mechanical ventilation with air recirculation in the UAE resulted in elevated concentrations of some of the pollutants. Median levels of CO_2 (1550 ppm in Slovakia, 1550 in UAE in winter), TVOC (434, 485 μg/m^3, respectively) and NO_2 (12.2, 34.2 μg/m^3, respectively) exceeded recommended guideline values. Lower median air change rates, ozone and NO_2 concentrations and higher CO_2, formaldehyde and TVOC concentrations were measured in the UAE in the summer than in the winter. Indoor environmental control strategies should take into account local environmental and building conditions and cultural factors in order to promote children's health, comfort, and learning.

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1. Introduction

Exposure to poor indoor air quality (IAQ) can result in decreased academic and cognitive performance and increased absenteeism of school children [1]. The societal consequences of poor indoor air quality in schools also extend beyond the schools themselves. These include lower quality of education, loss of quality of life and economic losses due to loss of productivity and costs associated with sickness and refurbishment of problematic school buildings [2,3]. Studies around the world have shown that many schools do not provide adequate IAQ since indoor air often has elevated levels of volatile organic compounds (VOCs), particulate matter (PM), and other pollutants generated indoors or outdoors [4–6]. In an extensive review, Salthammer et al. [7] conclude that current studies on school environment report similar problems, including too small classrooms for high number of pupils, poor ventilation, considerable outdoor air pollution, strong indoor sources of air pollution, and the absence of legally binding limit values for the majority of indoor air pollutants.

Ventilation is an important factor for indoor environmental quality. The type of ventilation in the classroom can affect the indoor environment. Most educational buildings in the world use natural ventilation [6]. When this is not the case, various hybrid and mechanical ventilation systems and strategies are applied. These include split unit ventilation, variable refrigerant unit ventilation, and balanced mechanical ventilation with constant or variable air volume. These can operate with various ratios between outdoor air intake and recirculation air, continuously or intermittently [8]. Therefore, mechanical ventilation systems do not necessarily ensure adequate indoor air quality. They are often controlled with respect to the concentration of CO_2. However, even at CO_2 concentrations below 1000 ppm, which is the widely accepted guideline value, health protective guideline values for some other chemicals such as formaldehyde or benzene can be exceeded in large fractions of classrooms [9–11].

Many studies have investigated the thermal comfort and indoor air quality in schools. The studies differ in methodology, sample size, geographical coverage, and approach [12–15]. Some studies include objective measurements, others focus on subjective evaluations using questionnaires [15–18]. Other studies focus on the effects of building characteristics on indoor environmental quality (IEQ) or the effects of IEQ on children's health, well-being, and performance [5,17,19,20]. Studies combining children's perceptions of the indoor environmental quality and indoor environmental measurements are limited [21,22]. Moreover, most studies are limited to a single geographic area.

We could identify only two studies in the peer-reviewed literature that investigated schools in multiple countries simultaneously. First, the InAirQ study investigated the indoor air quality in 64 primary school buildings in five Central European countries (Czech Republic, Hungary, Italy, Poland, and Slovenia) [14]. Significant differences in the concentrations of volatile organic compounds, aldehydes, $PM_{2.5}$, carbon dioxide, radon, as well as physical parameters were observed across the countries. Average CO_2 concentrations varied between 1205 ppm in Czech Republic and 1475 ppm in Italy. Average air change rates varied between 1.1 h^{-1} Slovenia and 3.0 h^{-1} in Hungary. About 80 % of the schools did not comply with the recommended concentration of carbon dioxide of 1000 ppm. Different health risk assessments indicated that the highest concern was $PM_{2.5}$, radon, formaldehyde, and carbon dioxide in the investigated classrooms.

Second, the SINPHONIE study collected data on several indoor air pollutants, physical and thermal parameters and their association with eye, skin, upper and lower respiratory and systemic disorder symptoms from 114 schools in 23 European countries using a harmonized and standardized protocol [18,23]. Northern Europe and Western Europe showed the highest percentage of classrooms with CO_2 levels <1000 ppm, whereas Central and Eastern Europe and Southern Europe had higher percentages of classrooms with CO_2 levels higher than 1500 ppm. The majority of schools had ventilation rates lower than the then desirable value of 4 L/s/child. Median formaldehyde concentrations across the countries varied between approximately 5 and 35 $\mu g/m^3$, NO_2 between 5 and 20 $\mu g/m^3$, and ozone between 0 and 30 $\mu g/m^3$. None of these studies included countries outside Europe and they did not compare the schools using an indoor environmental index combining temperature, relative humidity and air pollutant levels. Studies on school environment across countries with very different geographic locations, climates, building characteristics, and cultures using standardized methodologies are thus limited.

Our previous study performed in Sweden investigated the impact of three ventilation strategies in primary school classrooms on thermal environment, indoor air quality, and perception by school children, and the relationship between subjective perceptions and environmental measurements [24,25]. The study also developed an index describing the indoor environmental quality of classrooms based on a few simple questions related to the children's perception [25]. The current study expands this dataset to cover a range of building types, climate zones, and cultural and social aspects of school environments. The methodology developed for 45 classrooms in Sweden was applied in 15 schools in the United Arab Emirates (UAE) (both winter and summer seasons) and in 15 schools in Slovakia (winter season).

The objectives of the study are to assess and compare the indoor environmental parameters, children's perceptions, and building characteristics including ventilation, and to look for associations between these across the three countries with their distinct climates, buildings, cultures, and societies. This paper presents the results of the thermal environment and indoor air quality measurements, as well as the indoor environmental indexes reflecting these measured conditions, in the 75 classrooms across the three countries. Results of the questionnaire survey regarding children's perception will be published in a separate paper.

2. Methodology

We collected environmental data from 15 classrooms in 15 separate primary schools located in Slovakia, and in 15 classrooms in 15 schools in the United Arab Emirates (UAE). Data were collected following identical experimental protocol as that used in 45 classrooms in 23 schools in our earlier study in Sweden [24]. All schools in Slovakia were naturally ventilated, while all schools in the UAE were equipped with split units. Two schools had variable refrigerant unit ventilation. These systems work with a large fraction of air recirculation. Only one school had supplementary fresh air units. In Sweden, 14 classrooms (7 schools) had natural ventilation and the remaining 31 classrooms (16 schools) had balanced mechanical ventilation with 100 % conditioned and filtered outdoor air (8 with constant air volume, 8 with variable air volume). All schools in Slovakia and Sweden were public and free, while schools in the UAE were private schools with mid-to high tuition fees compared to the range of fees in Ajman and Sharjah Emirates. Measurements in the UAE and Slovakia were performed between January and March 2023. Additionally, measurements were repeated in the same classrooms in the UAE in the hot months of the school year (here referred to as summer season) from September to October 2023 as the country experiences much higher temperature levels during this period. The data in Sweden were collected in the heating season from February to early April 2019 and from October to March 2020. The majority of the classrooms were with children 11–12 years of age to be able to compare the results of a questionnaire survey conducted among the pupils across the three countries.

2.1. Selection of the study population and classrooms

In Slovakia, the 15 selected schools were located in the urban areas of the capital city Bratislava. The schools in the UAE were located in the city centers of the emirates of Ajman and Sharjah and their locations were surrounded by residential areas with proximity to main roads. The schools in Sweden were mostly located in city center or residential areas of Gothenburg. Classrooms in all three countries were on the ground floor or first floor and they were typically occupied for 6.5–7.5 h daily, from 08:00 to 14:30 or 15:30. Schools in the emirate of Sharjah were occupied for 7.5 h from Monday to Thursday, as these schools operate four days a week, with weekends spanning from Friday to Sunday. Table 1 lists the basic characteristics of the selected schools.

2.2. Environmental measurements

The measured parameters included indoor air temperature, relative humidity (RH), concentrations of carbon dioxide (CO_2), nitrogen dioxide (NO_2), ozone (O_3), total volatile organic compounds (TVOC), formaldehyde, and particulate matter (PM_{10} and $PM_{2.5}$). The measurements were initiated on Monday morning following the installation of the equipment prior to the children's arrival in the school, and concluded on Friday afternoon (Thursday in Sharjah) after the children left the classroom. In Slovakia and the UAE, the indoor air temperature, RH and CO_2 were measured using newly calibrated Vaisala GMW 90R monitors (Vaisala, Finland) connected to HOBO UX120-006M 4-channel analog data loggers (Onset Computer Corp., USA). The accuracy of the instrument is ± 0.6 °C for temperature, ± 2.5 % between 0 % and 60 %, ± 3.0 % between 60 % and 80 %, and ± 4.0 % between 80 % and 95 % for relative humidity, and ± 35 ppm + 2 % of reading for CO_2 within the temperature range of +10 °C to +40 °C with a temporal resolution of 10 min. PM_{10} and $PM_{2.5}$ were measured by Flow 2 (PlumeLabs, France), with an accuracy of $\pm$15–20 %. The Flow sensor detects particles in the range of 0 μg/m^3 to 200 μg/m^3. The time resolution of these measurements was 1 min. In Sweden, indoor air temperature, relative humidity, and CO_2 levels were measured using a factory calibrated Wöhler CDL210 device (Wöhler Technik GmbH, Germany) with a time resolution of 2 min. The TSI DustTrak DRX model 8533 optical particle counter (TSI Inc., Shoreview, Minnesota, USA) was used to monitor particles (PM_{10} and $PM_{2.5}$) with a temporal resolution of 10 min, with an accuracy of ± 0.1 % of reading or 0.001 mg/m^3, whichever is greater. Further details about the measurements in Sweden can be found in Cabovska et al. [24].

Air change rates (ACR) in the classrooms were calculated by analyzing the exponential, first-order decay curves of CO_2 concentration over time, specifically when the children exited the classrooms for breaks or at the end of the school day. The method uses the procedure to calculate air change rate using a tracer gas decay technique, assuming that the classroom functions as a single zone with a uniform CO_2 content. In cases when a period of clear concentration decay could not be identified, we used the concentration build-up method or the steady state concentration method [26], using an assumed per child CO_2 emission rate of 13.9 L/h, measured room volume and outdoor CO_2 concentration of 400 ppm, which represents the average global background concentration in 2021 [27]. In the UAE and Sweden, the classroom doors are closed and locked between and after classes. Hence, the impact of possible interzonal air transfer on the calculated air change rates is likely minimal. In Slovakia, much lower air change rates were obtained from night-time decay of residual CO_2 than from concentration decay at the end of the school day, indicating that doors may have stayed open after class for cleaning purposes. Moreover, all classrooms were naturally ventilated, with windows operated during teaching hours when it was determined that the air quality required it. Thus, the data were noisy and the behavior in the classroom was not well documented. Here we rely on air change rates calculated from shorter periods of concentration build-up, decay and steady state deemed reliable during the teaching period. The reported air change rate for each classroom in each country is the average of the air change rates obtained for all selected time periods during the monitoring week. The ventilation rate in each classroom (L/s/person) was determined from the air change rate, the room volume and the number of children in each classroom.

NO_2 and ozone were sampled using passive/diffusive samplers described by Ferm and Rodhe [28]. The concentrations of the target compounds were determined by wet chemical procedures utilizing a spectrophotometric approach for NO_2 and ion chromatography for O_3. DSD-DNPH Aldehyde Diffusive Sampling Devices (Supelco, Bellefonte, PA) were employed to sample formaldehyde. The samples were subsequently analyzed using high-performance liquid chromatography/UV detection following solvent extraction. Volatile organic compounds (VOCs) were passively sampled on Tenax TA adsorbent tubes (PerkinElmer). These tubes were thermally desorbed into a gas chromatograph and subsequently identified and quantified by a mass selective detector. The total VOC (TVOC) has been measured as the aggregate of all individual compounds that eluted between n-hexane and hexadecane (C_6 to C_{16}) and was quantified as toluene equivalent concentrations. Limits of detection (LOD) were 1 μg/m^3 for NO_2, 7 μg/m^3 for ozone in Slovakia and UAE, 9 μg/m^3 for ozone in Sweden, 10 μg/m^3 for the TVOCs and 0.1 μg/m^3 for formaldehyde. The LODs were based on 3 times the signal-to-noise ratio. Further details on the analytical procedures can be found in Cabovska et al. [24]. The passive sampling provided

Table 1

Characteristics of the selected classrooms. The values are average ± standard deviation.

Country	No. of School Buildings	No. of Classrooms	Age of the school building (years)	Classroom floor area (m^2)	Classroom volume (m^3)	Number of children per classroom	Floor area per child[a] (m^2)	Classroom volume per child[a] (m^3)
Sweden (Winter)	23	45	70 ± 42	56 ± 8	174 ± 30	21 ± 3	2.8 ± 0.61	8.6 ± 2.0
Slovakia (Winter)	15	15	93 ± 58	60 ± 8	213 ± 32	19 ± 4	3.3 ± 0.72	11.6 ± 3.1
UAE (Winter)	15	15	13 ± 10	42 ± 11	149 ± 42	20 ± 7	2.4 ± 1.1	8.5 ± 4.3
UAE (Summer)	15	15	13 ± 10	42 ± 11	149 ± 42	24 ± 5	1.9 ± 0.58	6.7 ± 2.4

[a] Based on individual data, not the average values for floor area, volume and number of children in this table.

concentrations of NO_2, ozone, formaldehyde, and TVOC integrated across the whole sampling period, resulting in what we call "weekly average". Time-resolved temperature, relative humidity, CO_2, and particle readings are reported both as "weekly averages" (all obtained data) and "occupied time averages" (hours when the classrooms were occupied).

Outdoor data were obtained from the nearest municipal ambient monitoring stations in Sweden (Gothenburg) and Slovakia (Bratislava). These included hourly readings of air temperature, relative humidity, and concentrations of NO_2, ozone, PM_{10}, and $PM_{2.5}$. Not all ambient air quality monitoring stations measured all parameters. In the UAE, temperature and relative humidity data were obtained from the open database "Weather Underground". No other outdoor data could be obtained from relevant monitoring stations.

The Indoor Environmental Index (IEI) developed by Sofuoglu and Moschandreas [29] was used to combine all measured parameters in a classroom into one parameter. We used weekly averages to ensure consistency across the input datasets. The IEI is calculated as the average of the Indoor Discomfort Index (IDI) and the Indoor Air Pollution Index (IAPI). IAPI relates the measured levels of air pollutants to the range of values that have been recorded and to a demarcation value, which is the recommended guideline value for indoor air quality. IDI relates the observed temperature and relative humidity to the optimal values and to upper and lower comfort limit levels. The indexes range from 0 (best) to 10 (worst). The optimal values, comfort levels and demarcation values are listed in Table S1.

2.3. Statistical analysis

Statistical analyses were done using IBM SPSS Statistics 29.0. The normality of data distribution was tested with the Shapiro-Wilk test. Consequently, non-parametric tests were used. The Kruskal-Wallis test was used to look for statistically significant differences in the measured parameters between the three countries. Wilcoxon matched pairs signed-rank test was used to compare the measured winter and summer data in the UAE. Spearman rank correlations were used to analyze the relationship between the measured variables (weekly averages), indexes, and building characteristics. Statistical significance was considered when $p < 0.05$ (2-tailed).

3. Results

Tables 2–4 show a summary of measurement results across the classrooms in the three countries. Box plots in Figs. 1–7 display the mean (marked with X), median (marked with a horizontal line) and interquartile range (IQR). The whiskers denote the 10th and the 90th percentile and the dots the outliers.

3.1. Temperature, RH, CO_2 and ACR

The results for Sweden (SE) are presented in Cabovska et al. [24]. Briefly, median weekly (20.8 °C) and occupied time (21.0 °C) temperatures were within the range of 20–24 °C required by EN 16798–1:2019 for category II buildings, although minimum temperatures were lower. Weekly and occupied time median RH were 34 % and 36 %, both in line with recommended values. Median CO_2 level during occupancy (687 ppm) was below the recommended 1000 ppm (Table 2). In Slovakia (SVK), median classroom temperature for all week (22.9 °C) and occupied time (23.8 °C) were within the recommended range, although the maximum value was higher. Median RH was also within the recommended range, with both weekly and occupied time medians being 36 % and 35 %. The median CO_2 level during occupied time (1551 ppm) exceeded the recommended limit (Table 3).

During winter in the UAE, the median weekly temperature was 23.6 °C, while the occupied time median temperature was 23.0 °C. During the summer, the median weekly temperature was 27.0 °C, and the median temperature during occupied time was 25.0 °C (Table 4). The local guidelines for indoor environment provided in Dubai Government's Green Building Regulations and Specifications

Table 2
Summary of the measurements in classrooms in Sweden (winter; based on Cabovska et al. [24]; n = 45).

Parameter	Median	Interquartile range	Min	Max	Recommended guideline values	Reference
Temperature, °C, All week	20.8	1.4	18.7	23.4	20–24	[30]; cat. II
Temperature, °C, Occupied time	21.0	1.2	19.4	24.0	20–24	[30]; cat. II
RH, %, All week	34	9	22	54	25–60	[30]
RH, %, Occupied time	36	8.5	20	57	25–60	[30]
CO_2, ppm, All week	518	165	445	957	1000	[30]
CO_2, ppm, Occupied time	687	188	538	1628	1000	[30]
Air change rate (ACR), h^{-1}	3.2	1.7	0.31	5.1	[a]	[30]
NO_2, µg/m^3	9.7	5.6	2.9	32	10	[31]; annual mean
Ozone, µg/m^3	10.5	13.7	4.5[b]	55.6	100	[31]; 8-h average
TVOC, µg/m^3	118	72	35	590	300	[33]
Formaldehyde, µg/m^3	9.4	6.5	1.7	26.9	100	[32]
PM_{10}, µg/m^3, All week	10	7.0	2.0	28	15	[31]; annual mean
PM_{10}, µg/m^3, Occupied time	21	11	8.0	51	45	[31]; 24-h mean
$PM_{2.5}$, µg/m^3, All week	7.0	5.0	1.0	18	5	[31]; annual mean
$PM_{2.5}$, µg/m^3, Occupied time	13	8.0	5.0	29	15	[31]; 24-h mean

[a] Standards specify ventilation rates per floor area and number of occupants. Air change rate is a result of ventilation rate and size of a room.
[b] ½ LOD.

Table 3
Summary of the measurements in classrooms in Slovakia (winter; n = 15).

Parameter	Median	Interquartile range	Min	Max	Recommended guideline values	Reference
Temperature, °C, All week	22.9	1.9	20.1	25.8	20–24	[30]; cat. II
Temperature, °C, Occupied time	23.8	1.6	21.4	25.8	20–24	[30]; cat. II
RH, %, All week	36	8.5	25	51	25–60	[30]
RH, %, Occupied time	35	6.4	25	49	25–60	[30]
CO_2, ppm, All week	1235	391	895	1904	1000	[30]
CO_2, ppm, Occupied time	1551	432	1391	2566	1000	[30]
Air change rate (ACR), h^{-1}	0.47	0.15	0.12	1.1	[a]	[30]
NO_2, μg/m^3	12.2	3.8	7.6	26	10	[31]; annual mean
Ozone, μg/m^3	3.5	0	3.5[b]	10.7	100	[31]; 8-h mean
TVOC, μg/m^3	434	263	264	1943	300	[33]
Formaldehyde, μg/m^3	16.2	4.8	8.2	32.6	100	[32]
PM_{10}, μg/m^3, All week	39	15	20	57	15	[31]; annual mean
PM_{10}, μg/m^3, Occupied time	43	18	24	85	45	[31]; 24-h mean
$PM_{2.5}$, μg/m^3, All week	4.9	2.4	3.4	16	5	[31]; annual mean
$PM_{2.5}$, μg/m^3, Occupied time	5.3	1.6	3.7	22	15	[31]; 24-h mean

[a] Standards specify ventilation rates per floor area and number of occupants. Air change rate is a result of ventilation rate and size of a room.
[b] ½ LOD.

document and in their Technical Guidelines for Indoor Air Quality for Healthy Life recommend a temperature range of 22.5–25.5 °C all year round [34,35]. The occupied time average temperature was outside this range in 6 schools in the winter (5 below, 1 above the range) and in 8 schools in the summer (1 below, 7 above the range). The median RH in the winter was 51 % for all week and 47 % during occupied time. In the summer it was 49 % and 44 %, respectively. Both seasons met the local requirements of 30–60 % as well as the EN 16798–1:2019 requirements of 25–60 %. Median CO_2 levels during occupied hours exceeded the 1000 ppm guideline value in both seasons. In the summer it was 2641 ppm, in the winter it was 1549 ppm. The higher CO_2 concentrations during summer reflect the hot local climate. In contrast to Slovakia and Sweden, both with cold winters and more moderate summers, summer is the season in the UAE when air conditioning is most used and building tightness is most required for energy efficiency.

Fig. 1 shows the average CO_2 concentrations measured in the individual classrooms during occupied time. Significant differences were found between the three countries and the two seasons in the UAE. The examined schools in Sweden had the lowest median CO_2 concentration of 687 ppm. On the other hand, the median CO_2 level across all classrooms in Slovakia was 1551 ppm, which was similar to that in the schools in UAE in the winter (1549 ppm). The highest CO_2 concentrations were measured in the UAE during summer with a median value of 2641 ppm. The differences illustrate varied degrees of ventilation effectiveness, with schools in Sweden constantly maintaining higher air quality, whilst the UAE's summer season highlights the need for improved ventilation systems during peak occupancy. Most of the differences between the countries were statistically significant (Table S2). It should be noted that naturally ventilated schools in Sweden had significantly higher CO_2 concentrations than mechanically ventilated ones. These concentrations were still lower than those measured in Slovakia (natural ventilation) or the UAE (mechanical ventilation).

Calculated air change rates (ACR) and per person ventilation rates reflect the trends in CO_2 concentrations (Fig. 2). The schools in Sweden had the highest median ACR of 3.2 h^{-1} during winter with 3.6 h^{-1} in mechanically ventilated classrooms and 1.3 h^{-1} in naturally ventilated classrooms. Schools in Slovakia had the lowest median ACR of 0.47 h^{-1} during winter, lower than that of the naturally ventilated buildings in Sweden. In the UAE, the median ACR was 0.46 h^{-1} in summer and 0.57 h^{-1} in winter. Per person ventilation rates were lowest in the UAE in the summer. The seasonal difference in the UAE was statistically not significant. The low ACR in the UAE despite the presence of mechanical ventilation may be explained by the relatively young buildings stock and hot climate resulting in tight buildings and by the mechanical ventilation systems mostly operating with recirculated air. It should be noted that the highest floor area and classroom volume per child was recorded in Slovakia, the lowest in the UAE (Table 1).

3.2. Air pollutants

3.2.1. NO_2 and ozone

The primary contributor to indoor NO_2 and ozone is outdoor air, as internal sources are limited in schools. Combustion- and traffic-related, and industrial emissions are the major outdoor sources of NO_2, and higher concentrations are observed during winter due to lower mixing in the boundary layer [36,37]. Ozone is produced photochemically through a complex set of gas phase reactions involving organic compounds and nitrogen oxides and requiring UV radiation from sunlight. Elevated outdoor ozone levels at moderate latitudes are frequently observed in polluted areas with much sunshine during spring and early summer. With negligible indoor sources, outdoor to indoor transport is the major source of indoor NO_2 and ozone. The WHO's recommended maximum annual mean concentration of NO_2 is 10 μg/m^3 [31]. Dubai government recommends a maximum annual average of 40 μg/m^3 in existing buildings [35]. The median indoor NO_2 concentration in the schools in Sweden was 9.7 μg/m^3; as with air change rate, it was slightly higher in mechanically ventilated schools (10.4 μg/m^3) than in naturally ventilated ones (9.0 μg/m^3), although the difference was not statistically significant (Mann-Whitney *U* test, p-value = 0.14). The NO_2 levels exceeded the WHO limit in 47 % of classrooms. In the schools in Slovakia, the median NO_2 concentration was 12.2 μg/m^3, with 87 % of classrooms exceeding the WHO limit. The median outdoor

Table 4
Summary of the measurements in classrooms in UAE (winter and summer; n = 15).

	UAE Winter				UAE Summer				Recommended guideline values	Reference
Parameter	Median	Interquartile range	Min	Max	Median	Interquartile range	Min	Max		
Temperature, °C, All week	23.6	1.6	22.1	26.5	27.0	2.1	24.0	30.0	22.5–25.5	[34,35]
Temperature, °C, Occupied time	23.0	2	20.6	26.0	25.0	2.4	22.0	29.0	22.5–25.5	[34,35]
RH, %, All week	51	3.5	47	56	49	6.5	39	66	30–60	[34]
RH, %, Occupied time	47	6.6	43	59	44	13	33	54	30–60	[34]
CO_2, ppm, All week	873	330	508	1481	1186	723	466	2190	1000	[30]
CO_2, ppm, Occupied time	1549	676	712	4095	2641	1523	677	3972	1000	[30]
Air change rate (ACR), h^{-1}	0.57	0.46	0.15	1.4	0.46	0.46	0.15	1.7	[a]	[30]
NO_2, μg/m^3	34.2	18.1	11.9	57.4	20.6	11.8	10.5	41.4	10	[31]; annual mean
Ozone, μg/m^3	12	6.3	3.5[b]	21.1	3.5[b]	6.9	2.9	32.4	100	[31]; 8-h mean
TVOC, μg/m^3	485	394	223	6943	925	531	436	3154	300	[33]
Formaldehyde, μg/m^3	13.3	10.2	8.8	36.8	24.4	16.9	6.4	60.5	100	[32]
PM_{10}, μg/m^3, All week	16	33	3.0	79	25	38	4.8	88	15	[31]; annual mean
PM_{10}, μg/m^3, Occupied time	12	44	3.0	67	21	22	3.5	93	45	[31]; 24-h mean
$PM_{2.5}$, μg/m^3, All week	4.1	3.9	2.0	12	8.0	7.8	2.5	27	5	[31]; annual mean
$PM_{2.5}$, μg/m^3, Occupied time	3.1	2.9	2.0	11	5.0	4.1	2.1	10	15	[31]; 24-h mean

[a][a] Standards specify ventilation rates per floor area and number of occupants. Air change rate is a result of ventilation rate and size of a room.Structured.
[b] ½ LOD.

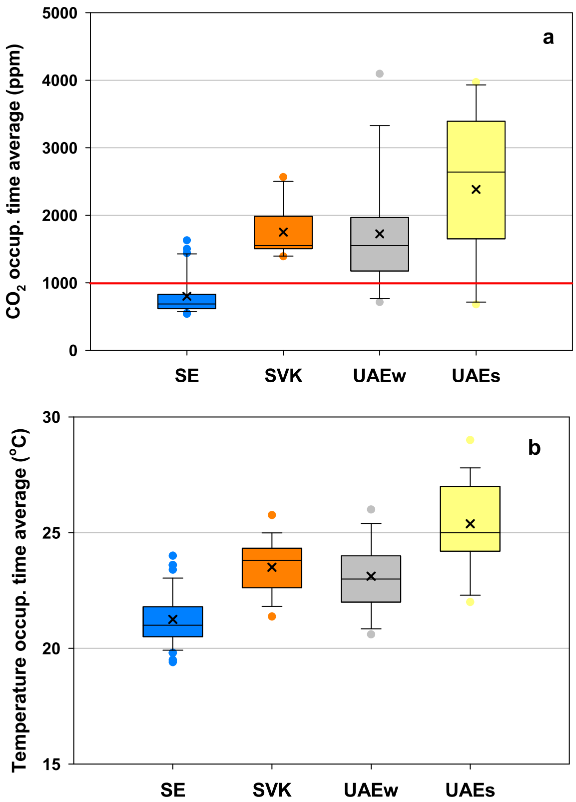

Fig. 1. Box plots of the a) CO_2 concentrations and b) temperature measured in individual classrooms (average during occupied time). SE-Sweden, SVK-Slovakia, UAEw-United Arab Emirates winter measurements, UAEs-United Arab Emirates summer measurements. The red line indicates the recommended limit value of 1000 ppm.

NO_2 level was 40.7 μg/m^3 (compared to 16.1 μg/m^3 in Sweden). Since all indoor-to-outdoor (I/O) concentration ratios were below 1 in Slovakia, the high outdoor levels were responsible for the high rate of schools with NO_2 exceeding the limit. The highest NO_2 concentrations were measured in the UAE classrooms (median 34.2 μg/m^3 in winter and 20.6 μg/m^3 in summer). All schools in both seasons exceeded the WHO limit. Outdoor data were unavailable in the UAE, but generally, the outdoor air is the main source of indoor NO_2. The lower concentrations in the summer may reflect seasonal differences [36,37]. Additionally, the extreme heat may result in a decrease in outdoor activities including transportation, the main source of ambient air NO_2, during the summer months.

The median ozone concentration in the Swedish schools was 10.5 μg/m^3, well below the WHO 8-h average guideline value of 100 μg/m^3. It was lower in naturally ventilated schools (4.5 μg/m^3) than in mechanically ventilated schools (11.2 μg/m^3). The levels in almost all classrooms in Slovakia were below the detection limit. Corresponding median outdoor ozone levels were similar, 44 μg/m^3 and 49 μg/m^3 in Sweden and Slovakia, respectively (I/O ratio thus lower in Slovakia). In the UAE, median winter concentration was 12 μg/m^3, while half of the classrooms had an ozone level below the detection limit in the summer. Outdoor data were not available. The local 8-h average guideline value is 60 μg/m^3 [35]. Lower ventilation rates in Slovakia and the UAE, combined with possibly higher outdoor levels in the UAE some periods of the year may explain the observed trends. Outdoor ozone concentrations during the sampling periods in the UAE schools, January–March and September–October, tend to be quite similar over the Arabian peninsula [38]. Lower ACRs are associated with lower I/O ozone ratios, leading to lower indoor concentrations at given outdoor air concentrations [39,40]. The lower indoor ozone concentrations in summer compared to winter in the UAE could be attributed to lower ACR in summer, as also indicated by higher CO_2. However, none of the schools in any of the countries exceeded the WHO limit for 8-h average ozone.

3.2.2. Formaldehyde and TVOC

There were significant differences in the median values (Table S2) of formaldehyde ($p = 0.001$) and TVOC ($p = 0.001$) between the three countries (Figs. 3 and 4). The median formaldehyde concentration in the classrooms in Sweden was 9.4 μg/m^3. It was higher in naturally ventilated buildings (12.2 μg/m^3) with lower air change rate than in mechanically ventilated ones (8.6 μg/m^3) [24]. The median concentration was 16.2 μg/m^3 in the schools in Slovakia. In the UAE it was 13.3 μg/m^3 in winter and 24.4 μg/m^3 during the summer, with larger variability in the summer. The measured concentrations in all classrooms were below the World Health Organization's recommended value of 100 μg/m^3 for 30-min average [32]. However, 47 %, 93 %, 80 % and 93 % of the classrooms in Sweden, Slovakia, and the UAE in winter and summer, respectively, exceeded the long-term (one year) indoor guideline value of 10

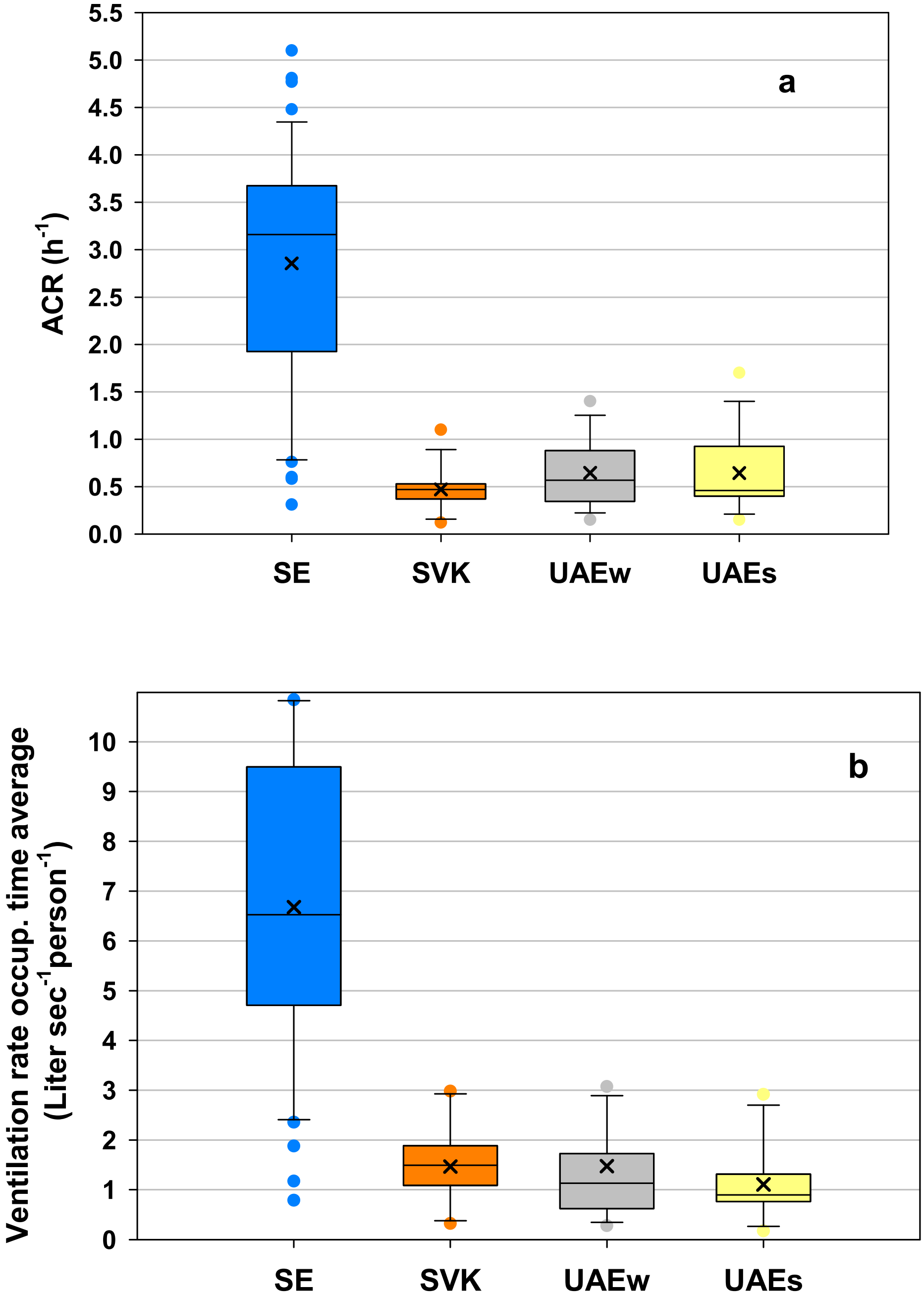

Fig. 2. Box plots of a) the measured ACR and b) ventilation rates per person across the three countries. SE-Sweden, SVK-Slovakia, UAEw-United Arab Emirates winter measurements, UAEs-United Arab Emirates summer measurements.

μg/m^3 suggested by Public Health England [41].

In Sweden, the median TVOC level was 118 μg/m^3, higher in naturally ventilated schools (155 μg/m^3) than in mechanically ventilated schools (103 μg/m^3) [24]. This is below the recommended long-term guideline value of 300 μg/m^3 [33]. The median concentration was 434 μg/m^3 in Slovakia, 485 μg/m^3 in the UAE in winter and 925 μg/m^3 in the UAE in the summer, all exceeding the recommended guideline value. 4.4 %, 87 %, 93 % and 100 % of the classrooms in Sweden, Slovakia, and the UAE in winter and summer, respectively, exceeded the guideline value. However, Dubai Municipality's recommendation for maximum 8-h average TVOC concentration in existing buildings is 600 μg/m^3 [35].

3.2.3. Particulate matter PM_{10} and $PM_{2.5}$

PM_{10} and $PM_{2.5}$ concentrations are difficult to compare between Sweden and the other two countries, because they were measured

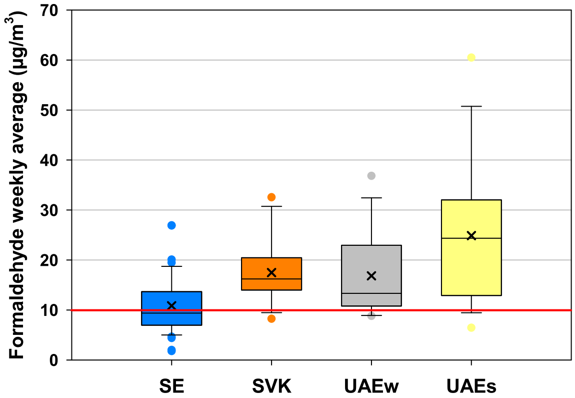

Fig. 3. Box plots of the formaldehyde concentrations across the three countries. SE-Sweden, SVK-Slovakia, UAEw-United Arab Emirates winter measurements, UAEs-United Arab Emirates summer measurements. The recommended limit value for 30-min average is 100 µg/m^3 (WHO). Public Health England recommends a one-year indoor guideline value of 10 µg/m^3 (red line).

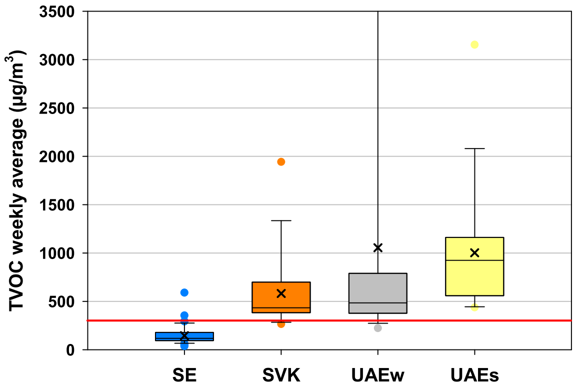

Fig. 4. Box plots of the TVOC concentrations across the three countries. Note that the highest value in UAE winter was 6943 µg/m^3, outside the range indicated in the figure. SE-Sweden, SVK-Slovakia, UAEw-United Arab Emirates winter measurements, UAEs-United Arab Emirates summer measurements. The red line indicates the recommended limit value of 300 µg/m^3.

using different, albeit factory calibrated, instruments (Figs. 5 and 6). Nevertheless, it is informative that weekly and occupied time average PM_{10} concentrations were lowest in the classrooms in Sweden, highest in the ones in Slovakia. In the UAE, where the variability was much larger, they were slightly higher in summer than in winter, while in Sweden they were higher in naturally ventilated schools with lower air change rates than in mechanically ventilated schools with particle filtration. Occupied time concentrations were higher than weekly concentrations in Sweden, but the two were similar in Slovakia and the UAE. The median PM_{10} level exceeded the respective WHO limit values in the Slovak schools (weekly average) and the UAE schools (weekly average both winter and summer) (Tables 3 and 4). The weekly average PM_{10} in 22 %, 100 %, 50 % and 67 % of the classrooms in Sweden, Slovakia, and the UAE in winter and summer, respectively, exceeded the WHO guideline value for annual mean of 15 µg/m^3 [31]. The occupied time average PM_{10} in 9 %, 43 %, 29 % and 13 % of the classrooms in Sweden, Slovakia, and the UAE (winter and summer), respectively, exceeded the WHO guideline value for 24-h mean of 45 µg/m^3 [31]. It's worth to note that the Dubai Government's Technical Guidelines for Indoor Air Quality for Healthy Life recommends the 24-h PM_{10} levels in existing buildings to be below 150 µg/m^3 [35].

Weekly average $PM_{2.5}$ concentrations were relatively low and comparable among the three countries, occupied time average $PM_{2.5}$ was slightly higher in the Swedish schools. In the UAE schools they were slightly higher in summer than in winter, while in Sweden they were higher in naturally ventilated schools with lower air change rates than in mechanically ventilated schools. Occupied time concentrations were higher than weekly concentrations in Sweden and Slovakia, but not in the UAE. The median $PM_{2.5}$ level exceeded the respective WHO limit values in Sweden (weekly average) and the UAE (weekly average in summer) (Tables 2–4). The weekly average $PM_{2.5}$ in 73 %, 46 %, 36 % and 73 % of the classrooms in Sweden, Slovakia, and the UAE in winter and summer, respectively, exceeded the WHO guideline value for annual mean of 5 µg/m^3 [31]. The occupied time average $PM_{2.5}$ in 31 % and 8 % of the classrooms in Sweden and Slovakia, respectively, exceeded the WHO guideline value for 24-h mean of 15 µg/m^3 [31]. None of the measured schools in the UAE exceeded this limit value during the occupied time. Moreover, the Dubai Government's Technical Guidelines for Indoor Air Quality for Healthy Life recommends the 24-h $PM_{2.5}$ levels in existing buildings to be below 35 µg/m^3 [35].

Cabovska et al. [24] concluded that the higher PM levels in naturally ventilated classrooms in Sweden may be explained by the lower ventilation rates and thus less removal of PM generated indoors and the lack of particle filtration of outdoor air. Higher occupied

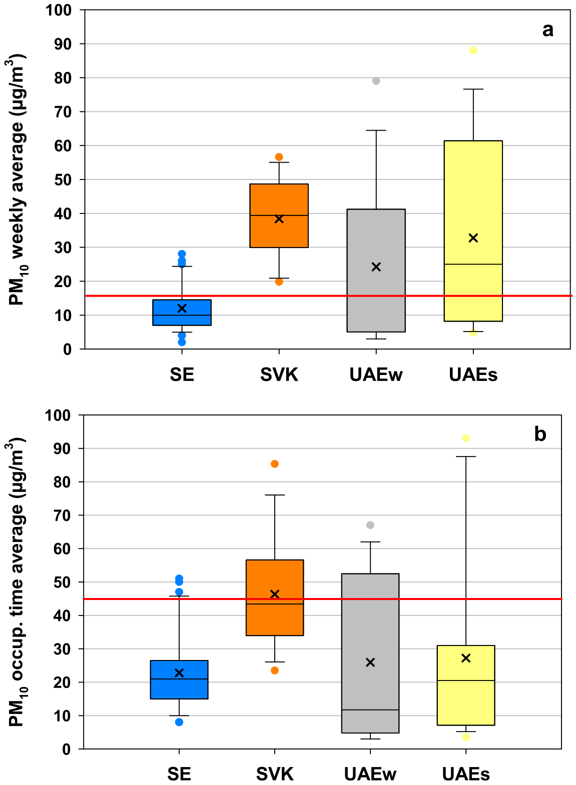

Fig. 5. Box plots of the PM_{10} concentration: a) weekly average; b) occupied time average. SE-Sweden, SVK-Slovakia, UAEw-United Arab Emirates winter measurements, UAEs-United Arab Emirates summer measurements. The red lines indicate the recommended limit value of 15 μg/m^3 (annual mean; used for weekly average) and 45 μg/m^3 (24-h mean; used for occupied time average).

time levels compared to weekly averages and I/O PM ratios around and above 1 indicated the presence of indoor sources such as resuspension and particles brought in and generated inside by the occupants. The highest PM_{10} concentrations observed in the naturally ventilated Slovak schools (low ACR) and the slightly higher occupied time levels than weekly averages may also indicate the presence of indoor sources in Slovakia. The I/O PM_{10} ratios for Sweden and Slovakia (median 0.9 and 1.4 for weekly data and 1.6 and 1.5 for occupied time data, respectively) also imply the presence of indoor sources of PM_{10}. However, airing occurs during occupancy and the effect of outdoor sources during occupied periods should be considered. The lower PM_{10} levels in the UAE schools compared to Slovakia may reflect the combination of similarly low air change rates and the presence of filtration in the mechanical ventilation systems operating mostly with recirculated air.

$PM_{2.5}$ results show a different trend. The highest weekly concentrations were measured in the classrooms in Sweden (especially in naturally ventilated schools with low ACR) and in the UAE in summer. During occupied period, schools in Sweden had the highest $PM_{2.5}$ concentrations (and greatest variability), in the UAE in the winter the lowest. Measurements in Slovakia and the UAE were made with identical instruments and schools in both countries had similarly low air change rates. The lower concentrations in the UAE may be the result of mechanical ventilation with filtration. Additionally, while the I/O $PM_{2.5}$ ratios were above 1 in Sweden indicating the presence of indoor sources (median 1.37 for weekly data, 2.21 for occupied time data), they were around 0.3 in Slovakia both for weekly data and occupied time data. The results thus indicate that outdoor sources may have been more dominating in Slovakia and the UAE than in Sweden. It should however be emphasized that PM comparisons should be made with caution. The indoor concentrations in Sweden, those in Slovakia and the UAE, and the available outdoor concentrations have all been measured using different instruments. Moreover, the available outdoor values were obtained from monitoring stations, not from measurements outside of the investigated schools.

3.3. Indoor environmental indexes

There were significant differences in the three indexes between the three countries (Fig. 7). The Indoor Discomfort Index (IDI) was significantly higher in the UAE schools in summer than in the other countries or in UAE in the winter, and the variability of the data was large, due to the elevated indoor temperatures in some of the schools. The Indoor Air Pollution Index (IAPI) was significantly lower in Swedish schools than elsewhere. Similar to the concentrations of CO_2 and other pollutants, it was highest in the UAE in summer. The Indoor Environmental Index (IEI) followed the trends observed for IDI, with UAE in the summer being significantly higher, and no significant differences between the other sets of measurements (Table S2). In Sweden, IAPI was significantly higher in classrooms with

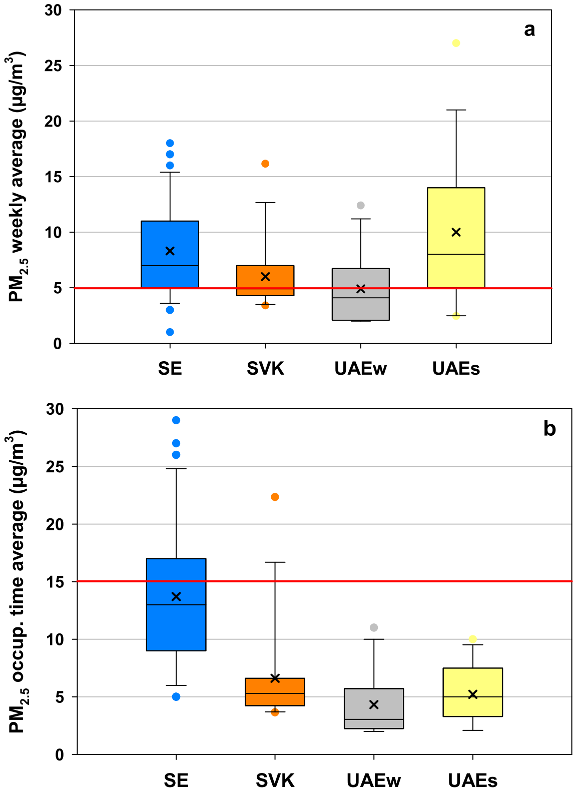

Fig. 6. Box plots of the $PM_{2.5}$ concentration: a) weekly average; b) occupied time average. SE-Sweden, SVK-Slovakia, UAEw-United Arab Emirates winter measurements, UAEs-United Arab Emirates summer measurements. The red lines indicate the recommended limit value of 5 µg/m^3 (annual mean; used for weekly average) and 15 µg/m^3 (24-h mean; used for occupied time average).

natural ventilation [24]. The IEI was highest in these classrooms.

3.4. Correlations of measured variables and building characteristics

Spearman rank correlation tests were performed on the measured variables and selected building characteristics (Tables S3–S12). As in Sweden [24], ACR was moderately correlated with ozone, TVOC, CO_2, formaldehyde, PM_{10}, and $PM_{2.5}$ in schools in Slovakia and the UAE in winter. These correlations were weaker in the UAE in the summer than in the winter. However, ACR was strongly correlated with NO_2 and ozone in the summer, but not in winter. Due to elevated temperatures, temperature in the UAE schools in summer was strongly correlated with CO_2, RH, and the indexes IDI, IEI, and moderately with ACR. Similar results were obtained in the schools in Slovakia using data for occupied time. Ozone was strongly negatively correlated with TVOC in the UAE and formaldehyde in Sweden. Formaldehyde was significantly correlated with relative humidity, except in UAE in winter. RH and temperature were correlated strongest during occupied time in Slovakia, likely due to natural ventilation, but also in UAE in summer. IAPI was mainly driven by concentrations of TVOC and PM in the Swedish schools, and formaldehyde and PM in the schools in UAE and Slovakia. In the UAE in summer and in Slovakia IEI was much more strongly correlated with IDI (especially temperature) than with IAPI. $PM_{2.5}$ and PM_{10} concentrations were strongly correlated in all datasets. They were, however, correlated with CO_2 (and thus occupancy; weekly data) strongly in Sweden and Slovakia, but not in the UAE. This further underlines the observation that occupant related indoor sources and airing contributed to PM in Sweden and Slovakia, while outdoor air was the constant main source of PM in the UAE.

Merging the data from all three counties (Tables S11–S12) shows a strong negative correlation between ACR and TVOC, formaldehyde, and PM_{10}, indicating that increased air change rates may help reduce the concentrations of these pollutants. However, it may increase ozone levels indoors, as suggested by the strong positive correlation between ACR and ozone. The influence of environmental factors on pollutant levels can be seen by the strong correlation between relative humidity as well as temperature and NO_2, TVOC, and formaldehyde. ACR was also strongly correlated with temperature and IAPI.

4. Discussion

Among the three countries, schools in Sweden had the highest air change rate with a median of 3.2 h^{-1}. This was the result of many of the schools having balanced mechanical ventilation operating with outside air. The high ventilation rate led to the lowest concentration of CO_2, TVOC, formaldehyde and PM_{10}. NO_2 concentrations were also the lowest, likely due to low outdoor concentrations.

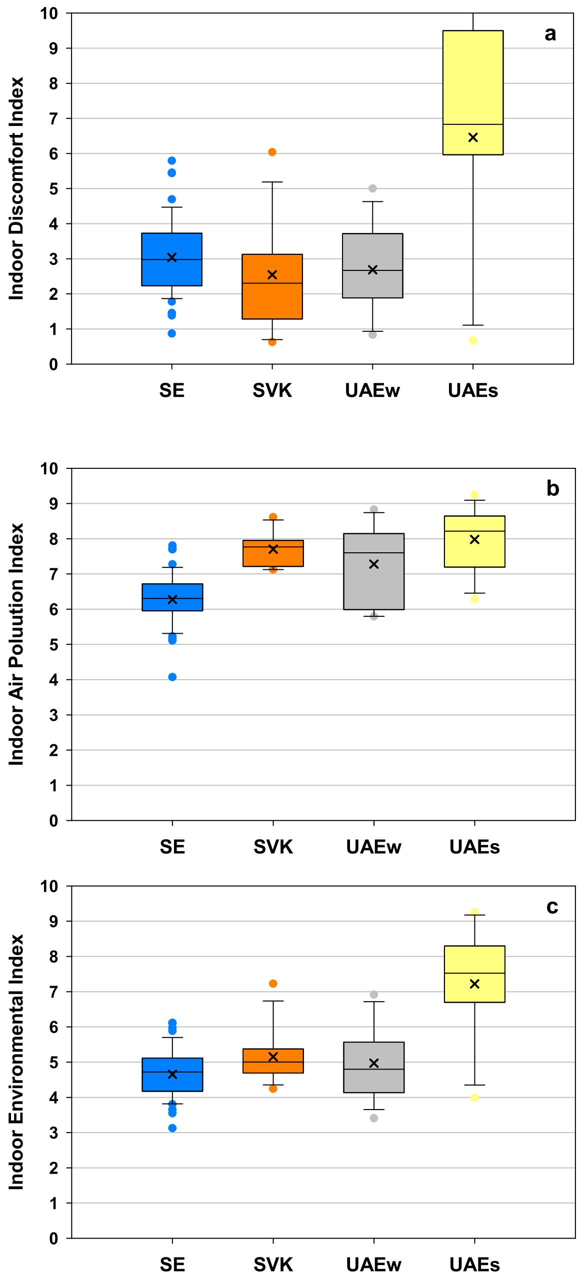

Fig. 7. Box plots of the a) IDI, b) IAPI and c) IEI in the classrooms in the three countries. SE-Sweden, SVK-Slovakia, UAEw-United Arab Emirates winter measurements, UAEs-United Arab Emirates summer measurements.

Elevated $PM_{2.5}$ concentrations reflect the presence of indoor sources. Relatively clean outdoor air combined with adequate ventilation resulted in indoor air quality better than in the other countries. Schools in Slovakia, all ventilated by opening windows, exhibited the lowest ACR in the winter, with a median of 0.47 h^{-1}, contributing to elevated CO_2, TVOC and formaldehyde levels. High PM_{10} concentrations reflect high outdoor levels and potentially the presence of indoor sources. However, ozone and $PM_{2.5}$ concentrations were low, indicating outdoor sources and low ventilation rates. The measured CO_2 and NO_2 concentrations, temperature and relative humidity were on average comparable with those reported for Slovakia in the SINPHONIE project. Our formaldehyde levels and ventilation rates were higher, $PM_{2.5}$ levels were much lower [23].

In the UAE schools, the ACR was similarly low as in Slovakia. However, school buildings in the UAE are newer, possibly tight, they have mechanical split or VRV ventilation operating with very low amount of outdoor air, and the arid desert climate is very different from Slovakia's and southern Sweden's continental climate. CO_2, TVOC, and formaldehyde concentrations were the highest, especially in the very hot summer, when contact with the outside is minimized. Moreover, VOC and especially formaldehyde emissions from materials are strongly temperature dependent [42,43]. Thus, the high temperature and RH levels in the UAE classrooms in the summer, combined with low ACR, may have exacerbated indoor air quality issues, leading to elevated concentrations of indoor pollutants. NO_2 levels were highest in the UAE, reflecting strong outdoor sources. The lower ozone and NO_2 levels in the summer may indicate lower ventilation rates in summer and seasonal variations in the ambient air concentrations. However, the limitations of determining air change rates from occupant generated CO_2 outlined by Bekö et al. [26] should be taken into account. The schools in the UAE had the lowest $PM_{2.5}$ concentrations in the winter, likely due to primarily outdoor sources, low ventilation rates and the differences and inaccuracies of the applied measurement techniques. On the other hand, summer $PM_{2.5}$ levels were higher in the UAE schools, which may also point at the presence of indoor sources and lower ACR in the summer.

The observed differences in indoor air quality between the three countries is due to different outdoor conditions, building characteristics, ventilation methods, and likely even occupant behavior and culture (e.g., wear of uniform, shoe changing policy, time spent outdoors during the day, etc.). Outdoor air quality has a significant impact on indoor air quality. The outdoor air in the UAE and Slovakia tends to be more polluted than in Sweden. Additionally, some schools in the UAE were in the vicinity of heavy traffic areas or industrial areas. Poor indoor air quality can have adverse effects on health, especially among children, who are more vulnerable to respiratory exposures [18,44,45]. Elevated levels of indoor pollutants in schools may contribute to increased rates of asthma, allergies, and other respiratory disorders [6,13,46]. Classrooms with elevated levels of CO_2 and air pollutants can have a negative impact on learning abilities, memory, and concentration [47]. Additionally, exposure to air pollutants can result in building related symptoms such as eye irritation, fatigue, headache, respiratory symptom which can further impede academic performance. It has been shown that increased outdoor air supply rate can lead to increased cognitive performance and learning [48].

The high indoor summer temperatures in the UAE indicate that cooling power of the ventilation systems may be incapable of maintaining acceptable thermal conditions in summertime if the outdoor air fraction had been further increased. Improving ventilation and air filtration, more effective cooling in the summer, and limiting exposure to outdoor air during high pollution periods such as during dust storms could improve indoor air quality in UAE schools. In the winter season, which resembles spring or summer in Slovakia and Sweden, opening windows should be considered. This is currently not the general practice, likely because of outdoor air pollution, noise nuisance, but also cultural and safety reasons. Indeed, many schools adhere to strict regulations that prohibit the opening of windows. Schools in Slovakia would benefit from installation of mechanical ventilation. Using windows for ventilation in the cold months is a nuisance and insufficient due to limited airing to avoid low temperatures and draught. Also, slow decrease in classroom IAQ during class hours does not trigger window opening due to habituation of the sense of smell. As the results from the Swedish schools indicate, balanced mechanical ventilation with heat recovery and demand-controlled ventilation, operating with 100 % outdoor air, a requirement for all newly constructed school buildings in Sweden, can ensure sufficient ventilation and low air pollutant concentrations indoors. Indeed, almost 90 % of the 7509 Swedish school buildings are equipped with supply and exhaust mechanical ventilation systems with heat recovery [49], while 86 % of the 114 school buildings across 23 European countries studied in the SINPHONIE project were naturally ventilated [23]. In places with more polluted outdoor air, however, appropriate filtration of outdoor ventilation air should be applied. The potential indoor sources of air pollution, especially particulate matter, should be minimized. Real-time data from continuous monitoring systems could help with decisions towards short-term interventions when needed, to ensure that the air quality parameters remain within acceptable thresholds during undesired ambient air quality events (e.g., dust storms, high ozone days, high outdoor pollution days, periods with elevated indoor CO_2). For example, visual indication of the adequacy of the CO_2 concentration in the classrooms could increase window opening. Additionally, stronger legislation and indoor air quality regulation and improved public knowledge about indoor air quality, as is the case in Sweden compared to the UAE and Slovakia, may be part of the solution towards healthier indoor air quality in schools. Educating administrators, school instructors, and students on the importance of indoor air quality could be a crucial step toward reducing health risks from indoor air exposures.

To our knowledge, this study is one of the very few that utilized the very same methodology to evaluate indoor air quality in schools across three very different countries and climates. The limitations include a relatively small number of classrooms monitored in Slovakia and the UAE, the inconsistency in PM measurements and the lack of outdoor data for some of the schools. The schools were located in or near major cities. Future studies should also focus on schools in rural areas, which may operate with poorer economic and building conditions and have different outdoor environmental conditions. Differences in IAQ between urban and rural schools have been shown in past studies. These are caused by both different outdoor conditions and different indoor conditions, routines, and activities. While concentrations of pollutants with primarily outdoor sources (especially traffic) tend to be higher in urban areas, other pollutants (including ozone) can have similar or even higher concentrations in rural areas [12,13,50,51]. According to a recent review, parameters in addition to building location that should be considered in future IEQ assessments in educational buildings also include building layout and construction materials, building systems for ventilation and air cleaning, building finishing materials and class equipment, occupant demographics, and occupancy and activities [52].

The measurements lasted only one week in each classroom. Short-term measurements do not capture conditions that may arise during occasional school activities (higher physical activity; working with certain materials like wood, glue, etc.), and they do not capture the effects of seasonal changes in the outdoor environment. Although seasonal differences were investigated in detail in the UAE schools, they should receive more attention in the other locations as well. We believe that our results reasonably represent the general conditions in the measured schools, but generalization of the results for an entire school year should be done with caution. Future studies would benefit from continuous monitoring of indoor air quality over extended periods and across various seasons. Studies should also focus on the feasibility, effectiveness and cost effectiveness of different adopted measures, interventions, and technical solutions to improve IAQ in schools, as well as on health effects of indoor exposures, while considering regional differences in climate, building characteristics, energy requirements, economy, and cultural practices.

5. Conclusion

This study measured and compared the indoor air quality in school classrooms in three countries with very different climates, buildings and cultures in Sweden, Slovakia and the United Arab Emirates using the very same methodological protocol. Notable differences in air change rates (winter median in Sweden 3.2, Slovakia 0.47, UAE 0.57 h^{-1}), temperature (21.0, 23.8, 23.0 °C; occupied time), and concentrations of CO_2 (687, 1550, 1550 ppm), NO_2 (9.7, 12.2, 34.2 μg/m^3), ozone (10.5, 3.5, 12 μg/m^3), TVOC (118, 434, 485 μg/m^3), formaldehyde (9.4, 16.2, 13.3 μg/m^3), and particulate matter (PM_{10}, $PM_{2.5}$) were observed between the countries. Classrooms in Sweden had substantially better indoor air quality due to two thirds of the classrooms having higher air change rates achieved by balanced mechanical ventilation systems operating with outdoor air and air filtration. Both naturally ventilated schools in Slovakia and schools in the UAE ventilated with split and VRV systems with very little outdoor air and limited filtration exhibited increased concentrations of the measured pollutants (apart from ozone originating outdoors). The schools in the UAE were investigated both in the mild winter season and in hot summer months of the school year. IAQ was worse in the hot summer than in the mild winter (e.g., occupied time median CO_2 2640 vs. 1550 ppm; TVOC 925 vs. 485 μg/m^3; formaldehyde 24.4 vs. 13.3 μg/m^3), probably due to lower air change rates (0.46 vs. 0.57 h^{-1}) and elevated temperature (25.0 vs. 23.0 °C). Improved ventilation (mechanical ventilation with sufficient amount of outdoor air) and better control of indoor air quality in these countries are recommended. Increased air change rate alone decreases TVOC and formaldehyde concentrations while it may increase ozone levels indoors, as suggested by the strong positive correlation between air change rate and ozone (Spearman rho 0.58). The solutions should address local environmental conditions, building design, and social and cultural aspects in order to maintain an indoor environmental quality that promotes the children's health, comfort, and learning.

CRediT authorship contribution statement

Taher S. Eldanaf: Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis. **Pavol Stefanic:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Rawya Dagher:** Writing – review & editing, Investigation, Formal analysis. **Omnia Altemnah:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Riad Saraiji:** Writing – review & editing, Resources, Project administration. **Sarka Langer:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Gabriel Bekö:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Sarka Langer reports financial support was provided by Swedish Research Council Formas. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2025.113151.

Data availability

Data will be made available on request.

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