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The effect of seasonal variation on indoor and outdoor carbon monoxide concentrations in Eastern Mediterranean climate

Maher Elbayoumi [1], **Nor Azam Ramli** [1], **Noor Faizah Fitri Md Yusof** [1], **Wesam Al Madhoun** [2]

[1] *Clean Air Research Group, School of Civil Engineering, Universiti Sains Malaysia, Penang, Malaysia*
[2] *Environment and Earth Science Department, The Islamic University at Gaza, Palestine*

ABSTRACT

Monitoring of carbon monoxide (CO) concentration in school microenvironments is extremely important due to its impact on children's health. CO concentration levels were monitored inside and outside 36 natural ventilated classrooms of 12 schools located in Gaza Strip, Palestine. Measurements were carried out by using electrochemical analyzer during fall, winter, and spring from October 2011 to May 2012. The average concentration of indoor and outdoor CO was 0.79±0.75 and 0.96±0.91 ppm, respectively. The reported concentration levels showed that the indoor CO concentration was lower than the outdoor CO concentration. The mean daily indoor–outdoor ratio ranged between 0.30 and 1.90 in the three seasons. The measured indoor and outdoor CO concentrations showed seasonal variation. During winter, the mean indoor CO was 3.0 and 1.50 times higher than that during fall and spring, respectively. Meanwhile, the outdoor CO concentration in winter was 2.80 and 1.4 times higher than in fall and spring, respectively. Although these levels were below World Health Organization guidelines, these concentrations pose a risk to students' health and affect their academic performance.

Keywords: *Natural ventilation, indoor air quality, Gaza, seasonal variation, indoor–outdoor (I/O) ratio*

Corresponding Author:
Noor Faizah Fitri Md Yusof
☎ : +(60)-4-5996269
🖷 : +(60)-4-5941009
✉ : *noorfaizah@eng.usm.my*

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1. Introduction

The quality of indoor air is recently threatened with various contaminants from indoor and outdoor sources. According to World Health Organization (WHO), nearly 2 million people a year die prematurely from illnesses attributable to indoor air pollution. Among these deaths, 44% are due to pneumonia, 54% from chronic obstructive pulmonary disease (COPD), and 2% from lung cancer (WHO, 2011a). Therefore, this risk factor is the second largest environmental contributor to ill health, behind unsafe water and sanitation.

Children worldwide spend one third of their time inside school buildings and approximately seven or more hours a day in school of their time indoors (Pegas et al., 2010; Almeida et al., 2011). Indoor environmental quality in school is a key element as it can affect students and teachers in several ways, such as health productivity, performance, and comfort (Kwok and Chun, 2003). A growing body of evidence has demonstrated that serious inadequate operation and maintenance of facilities inside school buildings are seen as a result of chronic funding shortage (Mendell and Heath, 2005). Moreover, indoor air quality (IAQ) problems in schools may be even more serious than in other categories of buildings because of higher occupant density and insufficient ventilation rate (BVR) in schools compared with other buildings (Pegas et al., 2010). The results of exposure to pollutants are more acute for the sensitive groups of the population, such as children. Children's tissues and organs are actively growing (Mendell and Heath, 2005). In addition, children are more active than adults are; thus, the former intake more air compared with the latter (Salvi, 2007).

CO, which is colorless and odorless, exhibits toxicity characteristics and is one of the most characteristic air pollutants from traffic. This pollutant arises from both natural and anthropogenic sources and is produced as a primary pollutant during the incomplete combustion of fossil fuels and biomass in fumes, produced by portable generators, stoves, and gas ranges (U.S. EPA, 2013). CO has high affinity for hemoglobin, forming carboxyhemoglobin, which reduces the delivery of oxygen to the body's tissues. The affinity of hemoglobin for CO is 200 times to 250 times that for oxygen (WHO, 2000). Inhalation of air with a volumetric concentration of 0.3% CO can result in death within 30 min (Chaloulakou and Mavroidis, 2002).

Several population–based studies have established a strong correlation between exposures to CO ranging from 0.5 ppm to 10 ppm and increasing adverse cardiovascular outcomes, asthma symptoms, asthma severity, hospital admission rates, and heart rate among children. These values correspond to approximate steady–state blood COHb levels of <2% for the mean and <10% for the maximum (Slaughter et al., 2003; Liao et al., 2004; Cakmak et al., 2006; ATSDR, 2012). A large body of epidemiologic studies has provided evidence that exposure to low concentrations of CO for a long period may affect learning, manual dexterity, driving performance, and attention level (Raub and Benignus, 2002; Goniewicz et al., 2009; HPA, 2009). In addition to common syndromes that children may experience due to exposure to low concentrations of CO for a long period, such as headaches, dizziness, nausea (feeling sick) and tiredness, CO may affect the students' ability to concentrate and think clearly (HPA, 2009; U.S. EPA, 2013).

Seasonal variation is considered one of the main reasons that may increase CO concentrations and consequently increase the burden of disease. Different factors, such as outdoor air concentration, meteorological factors, and human activity, may influence seasonal variation of indoor CO concentration. The annual average outdoor CO concentrations worldwide are roughly 0.12 ppm in the Northern Hemisphere and about 0.04 ppm in the Southern Hemisphere. However, the outdoor CO concentration varies from season to season, with seasonal maximum levels occurring during late winter in both hemispheres and minimum levels being observed during late summer (ATSDR, 2012). The fluctuation of meteorological factors, such as temperature, humidity, pressure, and wind speed, through the course of year affect CO dispersion and destruction processes by photochemical reactions over a period of months (HPA, 2009).

The major source of CO in Gaza Strip, which has the sixth highest population density in the world, is the exhaust of about 60 901 motor vehicles, most of which are more than 15 years old and are out–dated (PCBS, 2012). Exhaust contains large quantities of CO, CO_2, $PM_{2.5}$, and hydrocarbons. In addition, during the frequent power outages, many people and institutions use portable electrical generators. Most of the generators involved were placed outside but were very close to the buildings to allow the generators to connect to the central electric panel. CO from these sources can build up in enclosed or partially enclosed spaces.

Indoor CO concentrations are a function of outdoor CO concentrations, indoor sources, infiltration, ventilation, and air mixing between and within rooms. Differences in temperature, humidity, pressure, atmospheric stability, and wind conditions between outdoor and indoor environments can alter the penetration rate of outdoor air into the built environment. Most studies focused on the spatial variations or on the indoor–outdoor (I/O) relationship of CO, and few studies were devoted specifically to seasonal variations. Thus, this study aims to contribute on the literature regarding the effect of seasonal variations on indoor air quality because this area is not properly addressed. This work measures and compares the indoor concentration levels of CO to determine the seasonal variations across schools in Gaza Strip.

2. Materials and Methods

2.1. Description of study area

Gaza Strip (365 km^2, 40 km long and between 6 to 12 km wide) is located on the eastern coast of the Mediterranean Sea as shown in Figure 1. Due to the geographical location, Gaza Strip forms a transitional zone between three zones the sub–humid coastal zone of Israel in the north, the semiarid plains of the northern Negev Desert in the east and the arid Sinai Desert of Egypt in the south (PMD, 2012).

Gaza Strip climate, Mediterranean climate, is characterized by four seasons. Winter season (December–March) dominated by rainfall, mild and humid. The summer months (June–September) are characterized by high humidity and the lack of wet precipitation. The remaining two transition seasons spring (March–June) and fall (September–December) are characterized by unsettled winter type weather and abrupt summer type weather (Kocak et al., 2010; PMD, 2012).

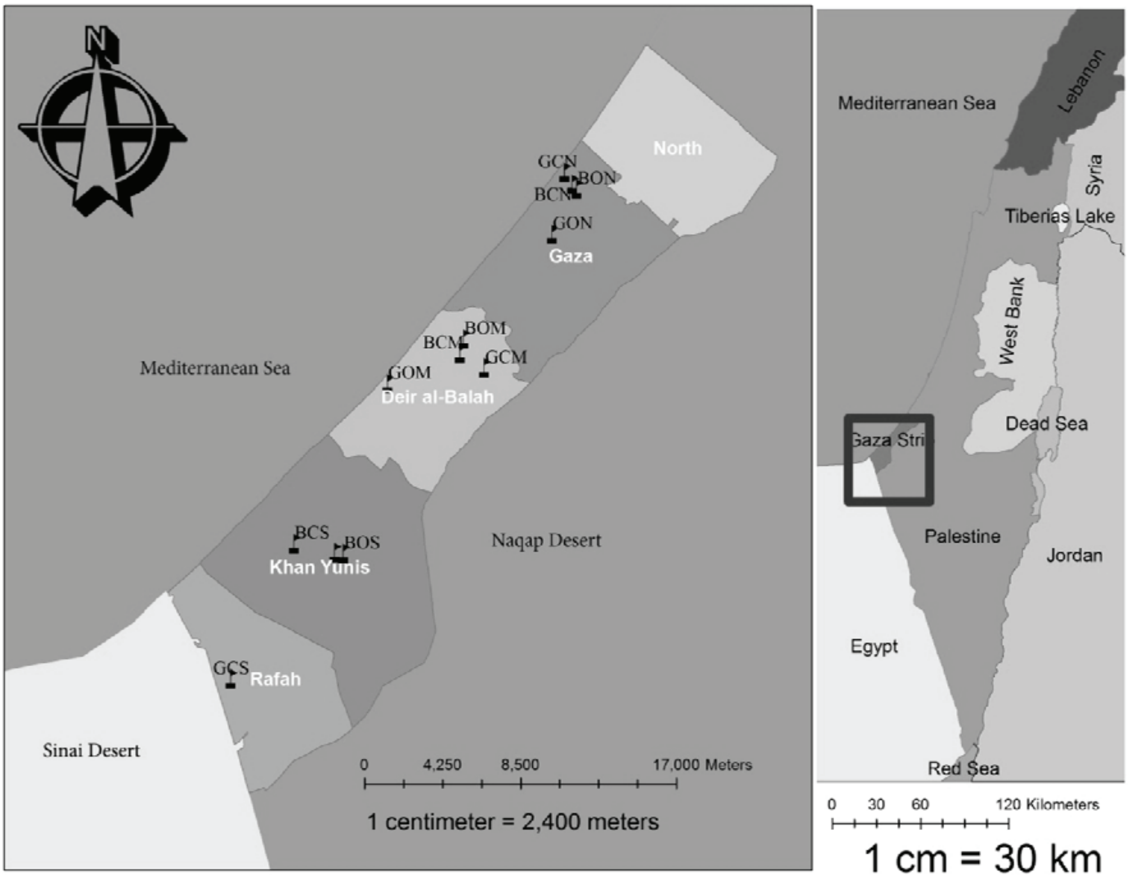

Figure1. *Spatial distribution of the 12 schools in Gaza Strip studied in this work.*

2.2. Sampling locations

Sampling was performed in 12 naturally ventilated school buildings with no provision for thermal conditioning (e.g., space heating for the winter). A preliminary study by Elbayoumi et al. (2013) in the same monitoring schools revealed that these schools had high indoor and outdoor levels of PM_{10} and $PM_{2.5}$. The selection of schools was based on the geographical distribution of the students, building type, and male or female students in the schools. Table 1 and Figure 1 present the details of each school. All schools in Gaza strip are naturally ventilated schools with three storey buildings and a total height of 10 meters. There are two common design models for schools buildings. The first model is L–shape model which is naturally cross ventilated with single banked. Meanwhile, the second model is parallel shape model which is cross ventilated with double banked and consist of two symmetric rows of classrooms embracing in corridors. Furthermore, the floor material and ceiling material in all monitored schools are made of concrete slab and concrete tiles with broken gravel, respectively. Due to large number of student most of the schools work in double sessions.

In each selected school, three representative classrooms were selected for three sampling days. The initial inspection of wind direction was made in every school to identify the windward side of the building and one classroom was selected from each floor.

2.3. Selection of monitoring instruments

The concentrations of CO and CO_2 have been monitored using Kanomax IAQ Monitor model 2211. The monitor performs measurements by using electrochemical analyzer**.** Zero and span were checked at regular intervals using zero air and a standard CO concentration. The same sampler was used for temperature and relative humidity measurements. Meanwhile, Smart Sensor electronic anemometer was used for wind speed measurements.

2.4. Sampling method

The monitoring program started from October 2011 to May 2012 at the twelve monitoring schools in order to cover fall, winter and spring seasons. However, during July and August months schools are closed on account of summer holidays. As a result, sampling was not carried out in those months. The measurements were taken place in each site during school hours for three consecutive days from 7:00 am to 12:00 pm in winter and spring seasons and from 12:00 pm to 5:00 pm in fall season. Sampling was conducted both inside and outside the selected classrooms during the studying activities. The samplers were placed inside the classroom opposite the blackboard at least 1 m from the wall and at least 1.5 m height from the floor (Blondeau et al., 2005; WHO, 2011b). For outdoor sampling the samplers were placed at the front side of the building, usually near the playground area. Due to the lack of multiple samplers, indoor and outdoor measurements were taken alternately after each 15 minute. In every selected classroom, 15 minute grab sampling technique with 10 second sampling interval were used during the class time and followed by a 15 minute period of outdoor concentration measurements (Habil and Taneja, 2011). Therefore, the individual 540 indoor and outdoor measurements at each school were equally distributed over the monitoring duration (three days) in order to cover meteorological conditions and pollutant concentrations as much as possible. The surface wind speed, ambient temperature and relative humidity in each site were simultaneously measured at the same time with particulate matter measurements.

For qualitative control of the measurements, a 5 minute interval for the device stability was maintained after each 15 minute measurement period. In addition, a protocol of information had to be filled out every day. The protocol included the time in which each measurement was taken, current weather conditions such as rain, wind, fog and dust storm and other relevant observations.

2.5. Building ventilation rate (BVR)

Building ventilation rate was calculated by using of indoor concentration of carbon dioxide as a surrogate of the ventilation levels per occupant (Kulshreshtha and Khare, 2011; WHO, 2011b). The generation of CO_2 and consumption of oxygen depends primarily on level of physical activity and occupant size (ASHRAE, 1999). Therefore, CO_2 concentrations have been used to calculate ventilation rate of classrooms using the following equation.

$$Q_O = \frac{1.8 \times 10^6 \times G}{C_{in} - C_{out}} \tag{1}$$

where, Q_o is the outdoor airflow rate into the space (L/s), G is the estimated CO_2 generation rate in the space (L/s), C_{in} is the measured indoor CO_2 concentration in the space (mg/m^3), and C_{out} is the measured outdoor CO_2 concentration (mg/m^3). The CO_2 generation rate of an individual student (G) is calculated using the following equation:

$$G = V_{O2}RQ \tag{2}$$

Table 1. *Characteristics of monitored schools*

School name	Code	Number of Students	Distance From Main Road (m)	Width of Main Road (m)	Electric Generators	Orientation of the Building	Location Area
Nusirate Prep Boys A	MCB	733	43	10	Yes	West	Over populated camp
Nusirate Prep Boys D	MOB	712	65	10	Yes	West	Over populated camp
Elburaj Prep Girls B	MCG	903	50	20	Yes	East	Over populated camp
Dier Elbalah Prep Girls	MOG	1 024	50	16	Yes	West	Small town
Bany Suhiela Prep Boys	SOG	1 132	40	20	Yes	West	Urban area
Bany Suhiela Prep Girls B	SOB	1 448	55	30	Yes	North	Urban area
Ahmad Abed Elaziz Prep Boys B	SCB	729	50	10	Yes	North	Urban area
Rafah Prep Girls B	SCG	578	55	12	Yes	North	Over populated camp
Elzaytoon Prep Girls B	NOG	883	58	20	Yes	West	Urban area
New Gaza Prep Boys A	NCB	1 066	30	20	Yes	East	Urban area
Beach Prep Girls B	NCG	1 183	50	10	Yes	West	Over populated camp
Salah Eldien Prep Boys	NOB	623	43	10	Yes	South	Urban area

where, V_{O2} is the rate of oxygen consumption in L/s, and *RQ* is the respiratory quotient, i.e., the relative volumetric rates of CO_2 produced to O_2 consumed. The value of *RQ* depends on diet, the level of physical activity, and the physical condition of the person (Emmerich and Persily, 2001). Rate of oxygen consumption V_{O2} can be calculated using the following equation:

$$V_{O2} = \frac{0.00278\,AD \times M}{20.23RQ + 0.77} \tag{3}$$

where, *M* is the level of physical activity, or the metabolic rate per unit of surface area, in Mets, *RQ* is the respiratory quotient, *AD* is the DuBois surface area in m^2 that can be calculated using the following equation:

$$AD = 0.203H^{0.725}W^{0.425} \tag{4}$$

where, *H* is the body height (m), and *W* is the body mass (kg). The height and weight averages were obtained from students health records and from Abudayya et al. (2007).

2.6. Statistical analysis

All data were normalized before the model development. Normalized data were calculated according to the following equation:

$$NI_{i;j} = \frac{\mathrm{I(i,j) - min(j)}}{\mathrm{max(j) - min(j)}} \tag{5}$$

where, *I* is the input value, *NI* is the normalized value, *i* is the number of measurements, *j* is the measured value of the variable, min and max are the global minimum and maximum, respectively, of the entire data set (Ozbay et al., 2011).

Two softwares were used for data analysis, the statistical software SPSS version 20 and MATLAB version 10. The data was classified randomly into two sets using MATLAB software. Set 1, which consisted of 70% of the original data, was used for model formulation. Data set 2 (30%) was used for model validation.

Bivariate correlation matrix, Pearson, of all data was obtained to determine the measure of pair–wise association among the all variables. Stepwise multiple linear regressions (MLR) were conducted for CO. MLR can be expressed according to the following equation:

$$\mathrm{y = b_0 + b_1x_{1i} + b_2x_{2i} + \cdots + b_kx_{ki} + \varepsilon} \tag{6}$$

where, *b* stands for the regression coefficients, *x* represents the explanatory variables, *i*=1,2,......*k*, and *ε* is stochastic error associated with the regression (Agirre–Basurko et al., 2006).

Spatial variability of the monitored CO across all the sampling schools was assessed by using coefficients of divergence (COD). COD values provide indication of the differences between the absolute concentrations of pollutants at sampled monitoring sites (Pinto et al., 2004; Krudysz et al., 2008). The COD provides degree of uniformity between simultaneously sampled sites, *j* and *k* by:

$$COD_{I,k} = \sqrt{\frac{\sum_{\mathrm{i-1}}^{\mathrm{p}}\left(\frac{\mathrm{x_{i,j} - x_{i,k}}}{\mathrm{x_{i,j} + x_{i,k}}}\right)^2}{\mathrm{p}}} \tag{7}$$

where, $x_{i,j,k}$ is the concentration measured at two different sites *j* and k over the sampling period, and *p* is the number of observations. A small COD (*r*<0.2) indicates similar pollutant concentrations between two sites, whereas a value approaching unity indicates significant difference in the absolute concentrations and subsequent spatial non–uniformity between the sites.

3. Results and Discussions

3.1. Meteorological measurements

Table 2 presents the mean values of temperature, relative humidity, and wind speed during the three monitored seasons, namely, fall, winter, and spring.

3.2. Carbon monoxide concentration

All measurements were conducted for seven months in Gaza Strip. The six–hour average daily indoor and outdoor CO concentrations for all the schools during the study period were 0.79±0.75 and 0.96±0.91 ppm, respectively. Figure 2 illustrates the average CO indoor and outdoor concentrations at urban sites and overpopulated sites. During the study period, the average indoor CO concentrations were less than the average outdoor CO concentrations. The average indoor CO concentrations for urban sites ranged from 0.10 ppm to 2.30 ppm with a mean of 0.69 ppm and for overpopulated sites ranged from 0.10 ppm to 2.30 ppm with a mean of 0.90 ppm. By contrast, the outdoor CO concentration varied from 0.10 ppm to 2.46 ppm with a mean of 0.88 ppm for urban sites and varied from 0.10 ppm to 2.71 ppm with a mean of 1.02 ppm for overpopulated sites. Furthermore, by comparing the error bars in Figure 2, it seems that there is a statistically significant difference between the indoor CO between urban and camps measurements during sampling period except November where their confidence intervals overlap. Although these levels were below WHO guidelines, epidemiological studies have associated mean CO levels of 2.73 ppm (range: 0.65 ppm to 6.23 ppm) with a 3.8% increase in absenteeism by school children and several health effects (Currie et al., 2009; ATSDR, 2012).

Table 2. *Detailed statistics of temperature, relative humidity, ventilation rate and* CO_2

Parameters	Fall		Winter		Spring	
	Min–Max	Mean±S.Dev	Min–Max	Mean±S.Dev	Min–Max	Mean±S.Dev
$PM_{10\ indoor}$ (μg/m^3)	135–845	360±134	17–1 545	493±209	69.0–813.0	196±101
$PM_{2.5\ indoor}$ (μg/m^3)	20–162	55±24	72–570	198±85	21.0–172.0	59±25
Ventilation rate (L/s/person)	5.0–29.0	10.0±5.0	2.0–18.0	7.0±3.0	3.0–19.0	8.0±3.0
$CO_{2\ indoor}$ (ppm)	457–1 881	787±225	486–2 370	1 156±322	667–1 538	957±167
$CO_{2\ outdoor}$ (ppm)	390.0–485.0	398.54±16.6	400.0–754.7	602.3±64.8	390.0–583.0	487.7±38.6
RH_{indoor} (%)	42.0–96.0	62.0±9.0	37.0–100.0	66.0±12.0	19.0–100.0	79.0±17.0
$RH_{outdoor}$ (%)	30.0–95.0	60.0±8.0	28.0–94.0	64.0±14.0	15.0–100.0	73.0±18
WS (m/s)	0.1–7.0	3.5±1.5	0.1–13.0	3.0±2.5	0.1–9.0	3.0±2.0
$Temp_{indoor}$ (°C)	24.5–30.6	27.0±1.5	10.0–21.0	14.7±1.7	11.0–33.0	19.0±3.0
$Temp_{outdoor}$ (°C)	24.8–31.6	27.4±1.8	8.3–21.3	14.1±2.4	9.0 –34.0	18.0±4.0

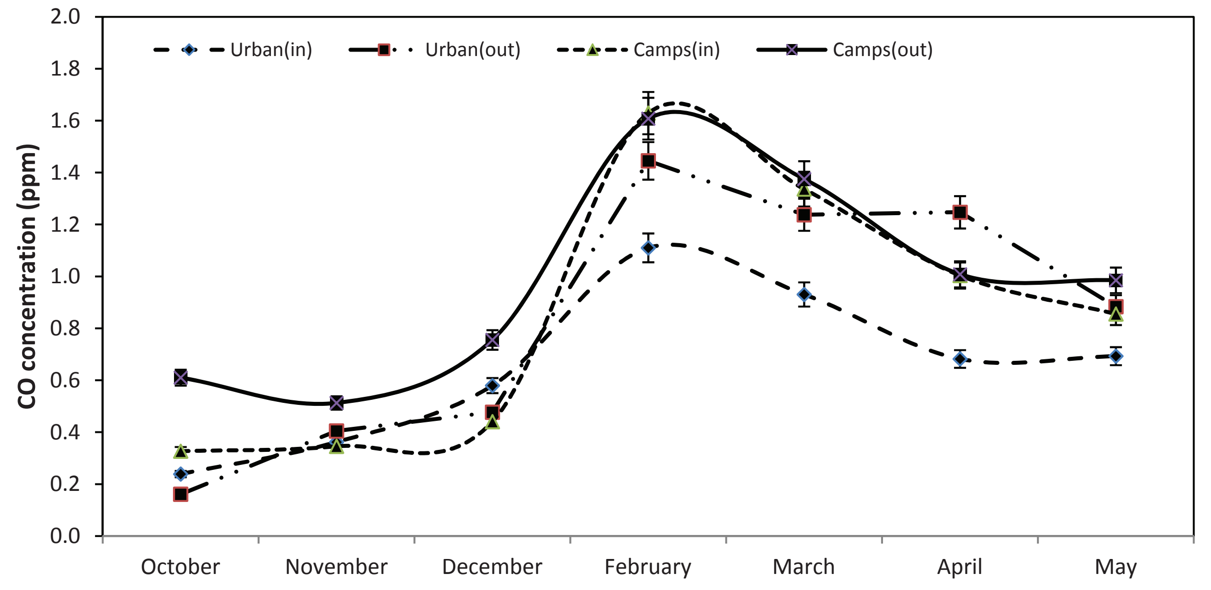

Figure 2. *Average monthly concentrations of CO in urban and overpopulated camps schools. The error bars indicate 5% value.*

3.3. Indoor and outdoor ratios (I/O)

The I/O ratio is an indicator of the strength of indoor sources and the infiltration from outdoor sources. The average daily I/O ratio ranged from 0.2 to 6.0 with a mean of 0.94 (SD±0.6) as demonstrated in Figure 3. Furthermore, the mean I/O ratios for the CO concentrations in schools located in the urban areas and camps have different trends. The highest I/O ratios were found during fall in schools located in the urban area (NOB=1.23, SCB=1.7 and NOG=1.96). However, in the winter and spring season, the I/O ratios at schools located in overcrowded camps (MOB=1.55, MCG=1.05) are higher compared with those in the urban area. The high I/O ratios found in fall could be attributed to the higher BVR in this season than that in winter and spring ($p<0.01$), which ranged from 5 L/s/person to 29 L/s/person. As mentioned, the fall season is characterized by high temperature and high relative humidity. Thus, classroom windows and doors are kept open. Given this natural ventilation, polluted air from outdoors flows indoors, leading to indoor–accumulated CO in classrooms. Several studies reported that indoor concentrations have been shown to be greatly and quickly influenced by the opening and closing of windows (Sowa, 1998; Dimitroulopoulou, 2005). The location of schools may be another factor that influences indoor CO concentrations. CO is considered an urban scale pollutant that is generated by road traffic and tends to be present at high concentrations throughout the city and at significantly reduced concentrations in adjacent rural areas (WHO, 2005).

High I/O ratios were observed in winter and spring for schools located in overcrowded camps. During winter and spring, windows and doors were kept closed to prevent cold from the outside to achieve thermal comfort. Thus, the high ratio in these schools was probably caused by infiltration through cracks and leaks in the building envelope from outdoor sources. In the last two years and as a result of the deficiency of electricity in Gaza Strip, power generators were installed to supply schools with electricity. The generators in most of the monitored schools were placed outside the building but around 2 m near an indoor environment for security purposes. This setup results in harmful CO exposure. The US Centers for Disease Control and Prevention reported that up to half of non–fatal CO poisoning incidents during the hurricane seasons in 2004 and 2005 involved generators operated outdoors but within 2 m of the houses (CDC, 2006). Muscatiello et al. (2010) reported increasing rates of emergency room and other hospital visits caused by CO poisoning in association with power outages.

The I/O ratio varies seasonally, where in winter, 42% of the monitored schools had I/O ratios equal to or greater than 1.00. Similar results were obtained by Chaloulakou et al. (2003), who revealed that air pollutants, such as CO, that are non–reactive and cannot be absorbed strongly on walls have an I/O ratio close to 1.0 in the absence of indoor sources. Thus, the building envelope provides little protection from outdoor CO pollution, and peaks in indoor concentrations reached the extremes of outdoor concentrations regardless of the airtightness of these buildings. By comparing the I/O ratio of the present study with other studies conducted internationally, we observed that the I/O in the present work is 1.3 times to 1.8 times higher than that of the other studies (Chaloulakou et al., 2003; Yang et al., 2009; Chithra and Nagendra, 2012).

3.4. Temporal variation

Figure S1 (see the Supporting Material, SM) shows the full–day variation of CO during the three seasons for two monitored schools in urban and overpopulated camp locations. In fall, the outdoor concentration of both locations was higher than that of the indoor concentration because of high BVR and because of the absence of any internal source. Furthermore, in schools located in camps, the outdoor concentration showed a peak at 1:00 p.m., during which activities such as cooking take place from the neighboring residential buildings. During winter, the indoor and outdoor CO concentrations in camps showed an increasing trend from morning until afternoon and reached their maximum values in the afternoon. The urban school showed a different trend, that is, the indoor and outdoor CO concentrations are high in the morning and decreased slowly with small peaks at 8:00 a.m. and 10:00 a.m. until reaching their minimum values. The trend in spring was similar to that in winter for both buildings. This increasing indoor CO rate may be attributed to the build–up process, in which infiltration from outdoors was the main source. The outdoor CO concentration was the main contributor for indoor CO concentration. This result is in agreement with the results of other studies on natural ventilated schools located in different climates and environments (Chaloulakou and Mavroidis, 2002; Chithra and Nagendra, 2012).

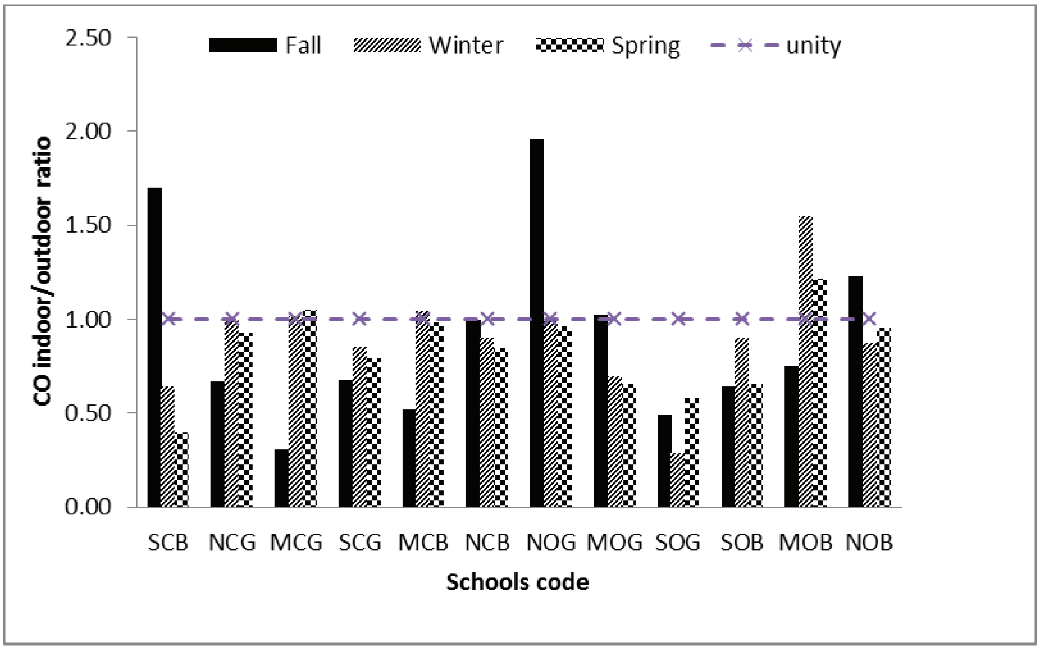

Figure 3. *I/O ratios of CO concentrations in fall, winter and spring seasons.*

3.5. Spatial variability

Table S1 (see the SM) shows the COD values calculated for all monitored schools during three seasons. COD values larger than 0.2 indicate spatial heterogeneity and are highlighted with one asterisk (lowest) and three asterisks (highest). Most of the sites displayed moderate to high spatial heterogeneity. The school locations displayed in Table 1 are very close to street intersections, and most of the schools located in overpopulated areas are characterized by congested traffic. Thus, frequent traffic jams resulting from poorly maintained roads, high traffic density, and very low wind speed are considered the main factors that contribute to high emissions, accumulation, and low dilution of generated CO. These factors may also strengthen the spatial heterogeneity between these sites.

Relatively high divergence was observed in winter than in the other two seasons. In winter, 73% of the COD values were greater than 0.50, whereas 23% of the COD values were smaller than 0.20. In fall, 59% of the COD values were greater than 0.50, whereas 0.03% of the COD values were smaller than 0.20. In spring, 32% of the COD values were greater than 0.50, whereas 1% of the COD values were smaller than 0.20. The CO production in overcrowded residential areas increases when cars move slowly near schools. Moreover, during winter and most of spring, the catalytic converters of vehicles take time to reach the operating temperature when the engine is cold, thereby resulting in increased CO emissions (Markovic et al., 2008). These values are indicative of similar conclusions of spatial divergence and seasonal variation among monitored sites.

3.6. Seasonal variability

A significant difference in CO concentration was noted in fall, winter, and spring, as shown in Figure 4. Although, indoor and outdoor CO concentrations were small in most of the monitoring schools, the schools were a significantly different from each other during fall, spring and winter seasons. In fall, the maximum daily averages (15 min average concentration during the 3 monitoring days) for indoor and outdoor CO concentrations were 1.60 and 3.50 ppm, respectively. Meanwhile, in winter, the maximum daily average indoor and outdoor CO concentrations were 6.10 and 5.00 ppm, respectively. In spring, the maximum daily average indoor and outdoor CO concentrations were 2.70 and 9.00 ppm, respectively. To investigate the effect of seasonality on CO concentrations, the winter to fall, spring to winter, and spring to fall average ratios were calculated, and the results are shown in Table 3. A significant difference exists among the three seasons, and a general pattern of increasing levels from fall to winter was observed. The indoor and outdoor CO concentrations increased six times in winter than in fall. Meanwhile, the indoor and outdoor CO concentration decreased from winter to spring. The average concentration of CO was the highest during winter, reflecting the high emission sources (vehicular emission exhaust) around these sites in this period. Studies showed that the average of different pollutant concentrations tend to be higher in winter, which is the season with the lowest ventilation capability (Arkouli et al., 2010). This finding can be supported by the fact that the outdoor concentration increases with lower temperatures, high relative humidity, organics emitted from vehicles, and decreased atmospheric mixing height (Somuri, 2011).

Several studies confirmed that the IAQ is dependent on outdoor concentrations and local conditions, such as weather changes and seasonal variations (Roberts, 2004; Kam et al., 2011). Therefore, to identify the factors that may influence the seasonal indoor CO concentrations, bivariate correlation was used. The value of the correlation coefficient (*r*) between the indoor and outdoor data can be used as an indicator of the degree to which CO measured indoors is attributed to the infiltration from outdoors. A strong relationship exists between indoor and outdoor CO concentrations in fall and winter and a very strong relationship during spring (*r*=0.66, 0.75, and 0.81 for fall, winter, and spring, respectively). Morawska et al. (2001) and Chaloulakou et al. (2003) showed that the indoor peak concentrations of CO are slightly dampened and lag behind outdoor peaks, thus suggesting that indoor CO concentrations are not immediately affected by outdoor concentration changes due to changes in BVR. In another study, Kirchner et al. (2002) showed that the correlation between indoor and outdoor levels was higher when time lag was applied. The air quality varies at any place from season to season because the atmospheric dynamics and the meteorological conditions play an important role in governing the fate of air pollutants. Thus, the inter–correlation between the average CO concentration, temperature, relative humidity, and wind speed was explored as shown in Table 4. The indoor CO concentration was found to be negatively correlated with indoor relative humidity in winter and spring. This finding is in agreement with the findings of Chaloulakou et al. (2001), who suggested that relative humidity is a good predictor of indoor CO concentrations. In naturally ventilated buildings, high building BVR promptly brings indoor humidity to the same level encountered outside. Thus, a negative correlation between humidity and CO infiltration and/or build–up inside the building is expected. Furthermore, a negative correlation exists between indoor and outdoor CO concentration and wind speed in spring because low wind speeds favor the accumulation of pollutants (low wind speeds are also related to stable atmospheric conditions). The number of students (girls schools and boys schools) which is related directly to the ventilation rate show a negative correlation in fall season.

3.7. The effect of building ventilation rate on the CO concentration

Given typical occupant density of 33 per 90 m^2 (2.7 m^2/student), the current ASHRAE standards recommends a minimum ventilation rate of 7.5 L/s/person (15 cfm/person) for classrooms (ASHRAE, 1999). The ventilation rate ranged from 2.0 to 29.0 L/s/person with a mean of 8.27±4.56 (Table 2). In winter, 83.3% of the schools were below the ASHRAE 62–2004 standard. This poor BVR is attributed to two main reasons. Firstly, several classrooms had windows that were closed by students during the cold season to maintain thermal comfort (the adaptation action). These windows may also be obstructed by posters and furniture to prevent sunrays from entering the classrooms during fall. Secondly, the BVR in naturally ventilated buildings depends on two forces, namely, wind–driven force and buoyancy–driven force. Wind is the main mechanism of wind–driven ventilation, whereas buoyancy–driven ventilation occurs as a result of the directional buoyancy force that results from temperature differences between indoor and outdoor environments. By using the data from all monitored classrooms, the relation between ventilation rate, ambient temperature and indoor–outdoor temperature difference was investigated. To analyze the data, contour plot technique was used to map the relation among the three parameters as illustrated in Figure S2 (see the SM). The main results of the entire analysis are as follows:

- When the ambient temperature ranged from 28 °C to 32 °C and when the ambient temperature is significantly higher than indoor temperatures, the students tend to keep a limited number of windows open and reduce the flow rate to protect themselves from ambient heat and sunrays.

- When the ambient temperature ranged between 18 °C and 28 °C and when the indoor temperature is significantly greater than the outdoor temperature, the students tend to open classroom windows and door (the adaptation actions), which results in increased flow rate.

- When the ambient temperature is less than 15 °C and when the indoor–outdoor differences are equal to or smaller than 0, the adaptation actions take place.

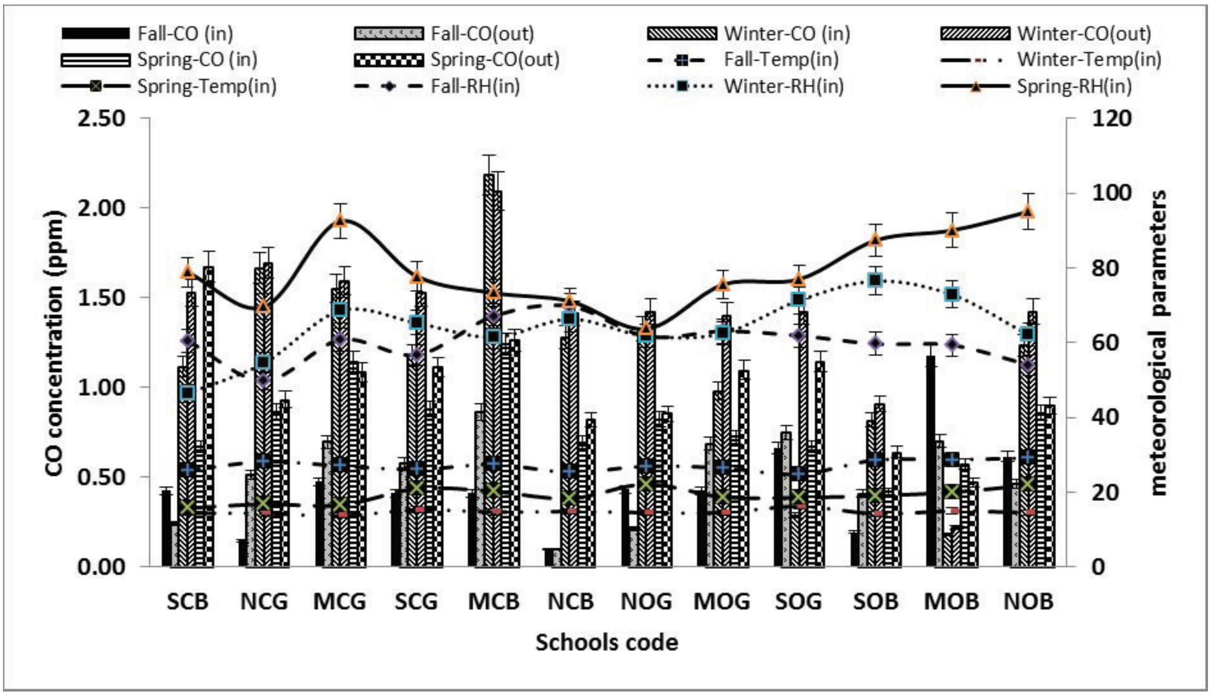

Figure 4. *Seasonal variations of CO concentration and meteorological parameters (temperature in °C, RH in %). The error bars indicate 5% value.*

Table 3. *Season to season ratios for CO*

	Minimum	Maximum	Mean±S.Dev	*t*- test
Indoor winter/fall	0.11	23.04	6.48±6.23	$p<0.001$
Outdoor winter/fall	0.10	24.57	6.10±6.68	$p<0.001$
Indoor spring/winter	0.37	3.78	0.95±0.77	$p=0.003$
Outdoor spring/winter	0.45	2.89	0.97±0.60	$p=0.018$
Indoor spring/fall	0.11	13.28	4.06±3.57	$p<0.001$
Outdoor spring/fall	0.10	22.00	4.53±4.82	$p<0.001$

Table 4. *Correlation coefficients between indoor and outdoor CO and meteorological parameters*

	Fall		Winter		Spring	
	CO (indoor)	CO (outdoor)	CO (indoor)	CO (outdoor)	CO (indoor)	CO (outdoor)
CO (indoor)	1.00	0.66 [a]	1.00	0.75 [a]	1.00	0.81 [a]
CO_2 (indoor)	0.07	0.04	0.13	0.05	0.68 [a]	0.64 [a]
CO_2 (outdoor)	–0.10	–0.08	–0.06	–0.11	–0.07	–0.04
RH (indoor)	0.06	0.12	–0.13	–0.17 [b]	–0.19 [a]	–0.14 [b]
RH (outdoor)	0.04	0.06	–0.07	–0.11	–0.13	–0.07
Temp (indoor)	–0.02	–0.01	0.05	0.05	–0.08	–0.13
Temp (outdoor)	–0.01	–0.02	0.05	0.09	–0.06	–0.12
WS	–0.01	0.04	0.04	–0.07	–0.15 [b]	–0.15 [b]
Building direction	0.04	0.08	–0.01	–0.03	–0.16 [b]	–0.20 [a]
Level of classroom	–0.05	0.14	–0.14	–0.06	–0.14	–0.11 [b]
Number of students per m^3	–0.10 [b]	–0.19	0.09 [b]	0.10	–0.07	–0.11

[a] *Correlation is significant at the 0.01 level (2–tailed).*

[b] *Correlation is significant at the 0.05 level (2–tailed).*

It can be observed from Figure S3 (see the SM) that I/O ratios were less influenced with the changes in BVR during the three seasons. In fall season with higher BVR comparing with the other two seasons, the I/O ratios were below 1.0 in most of the schools regardless the ventilation rate. Meanwhile in winter and spring the two seasons with reduced BVR, the I/O in most of the schools were below 1.0 except MOB school where the I/O ratio were 1.55 and 1.22 and BVR were 10 and 11 L/s/person in winter and spring, respectively. Given that CO is not released indoors and is highly positively correlated with the outdoor source, increasing the BVR may increase the indoor CO concentration. CO is a non–reactive gas; thus, when no indoor pollutant removal is available, the indoor and outdoor concentration will become equal regardless of the BVR. However, a higher BVR can increase the peak indoor concentrations as noted in SCB and NOG during fall and in MOB during winter and spring.

3.8. Factors influencing the seasonal variation of indoor CO concentrations

The results from the previous sections indicated that a seasonal variation exists in the concentrations of each pollutant and showed that meteorological parameters affect indoor and outdoor CO concentrations. Thus, seasonal IAQ predictive models should be designed for controlling CO.

Model development. MLR modeling (stepwise method) of indoor CO concentrations was conducted to find a predictive equation by using outdoor pollutant variables, such as CO, CO_2, BVR, and meteorological factors, with regression assumptions approximately satisfied. The coefficient of determination, R^2, provides the proportion of variation in CO concentrations, as explained by the independent variables in the models. Table S2 (see the SM) shows that when the best variable is fitted to the fall CO data, the R^2 value is approximately 0.338. Thus, approximately 33.8% of the variation in CO concentrations can be explained by the independent variables. Meanwhile, for CO winter and spring data, the R^2 values are approximately 0.574 and 0.735, respectively. Therefore, approximately 57.4% of the variation in CO concentrations can be explained by the three independent variables for winter data and 73.5% of the variation in CO concentrations can be explained by the five independent variables for spring data. The common variables in seasonal models suggest that the indoor CO concentration is strongly dependent on the outdoor CO concentration and on different meteorological parameters, which varied by season.

For all models the coefficients of the regressions were all highly statistically significant ($p<0.01$). The residual distributions were approximately normal, with zero means and no detectable serial correlation, an indication of adequate model fit. Furthermore, the collinearity problems in MLR might be diagnosed using the variance inflation factor (VIF) and tolerance indicator. The VIF values for seasonal MLR models were ranged between 1–1.23, which indicates several associations between predictor variables. However, generally, these factors are insufficient to cause problems. In addition, the tolerance values for the variables in both MLR models are higher than 0.6. In accordance with the findings of Field et al. (2009), the tolerance value must be smaller than 0.1 to indicate a multicollinearity problem.

MLR models validation. Model validation means confirming the validity of or to substantiate or conforming the developed models utility and capability for various conditions and at different sites. The seasonal models therefore, have been validated by using different data sets. The relationship between seasonally measured and predicted CO concentrations is presented in Figure S4 (see the SM). R^2 for CO during the three seasons were 0.58, 0.52 and 0.81 for fall, winter and spring seasons, respectively.

4. Conclusion

Indoor and outdoor carbon monoxide (CO) concentrations were measured in 12 naturally ventilated schools in Gaza Strip. Generally, the assessed CO occurred at I/O ratios ranging from 0.2 to 6.0 in the three seasons and showing the important influence of schools location in very crowded areas, building ventilation rate and using the electricity generators on IAQ. Furthermore, indoor CO concentration was found within the range that caused adverse health effects among children. Seasonal variation was found to affect indoor and outdoor concentration levels of CO with a general pattern of increasing levels from fall to winter and decreasing from winter to spring.

Bivariate and multiple linear regression analysis were used to correlate indoor CO levels with outdoor CO concentrations and with meteorological parameters. Results demonstrated that indoor CO levels were affected by outdoor concentrations of CO, relative humidity, building ventilation rate and building orientation tended to contribute significantly to indoor CO concentrations. The over overcrowded classrooms combined with bad thermal comfort condition through the three seasons which affect the building ventilation rate, and the location of electrical generators within 2 m of the buildings should be the main intervention factors to improve IAQ in schools.

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Supporting Material Available

Results of Coefficient of Divergence (COD) analysis for CO (Table S1), Results of the seasonal MLR analysis for indoor CO (Table S2), Temporal variation of CO concentration in fall, spring and winter seasons (Figure S1), Mapping of the relation between the air flow rate (L/s/p), the ambient temperature and the indoor–outdoor temperature difference (Figure S2), Effect of building ventilation rate on the CO concentrations (Figure S3), MLR analysis of seasonally observed vs. predicted CO using validation data (Figure S4). This information is available free of charge via the Internet at http://www.atmospolres.com.

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