AMERICAN UNIVERSITY OF BEIRUT

TOWARDS A HEALTHY INDOOR AIR QUALITY IN A SCHOOL ENVIRONMENT

by
KAREN ZAHY GEBRAEL

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KAREN ZAHY GEBRAEL

Approved by:

Dr. Mutasem El-Fadel, Professor — Advisor
Department of Civil and Environmental Engineering

Dr. Ibrahim Alameddine, Assistant Professor — Co-Advisor
Department of Civil and Environmental Engineering

Dr. May Massoud, Associate Professor — Co-Advisor
Department of Environmental Health

Date of thesis defense: February 8, 2016

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AN ABSTRACT OF THE THESIS OF

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Title: Towards a healthy indoor air quality in a school environment

This study targeted the assessment of indoor air quality in a school environment. For this purpose, $PM_{2.5}$ and CO were monitored in classrooms of forty public and private schools located in urban and rural areas. The field experimental results were coupled with mathematical modeling to estimate the air exchange rate (AER), $PM_{2.5}$ and CO equivalent emission rates (ER), and $PM_{2.5}$ deposition and re-suspension rates ($DR_{PM2.5}$ and $RR_{PM2.5}$).

The field monitoring results showed that elevated $PM_{2.5}$ levels were prevalent indoors, ranging between 20 and 180 ug/m^3 with a mean of 62 ug/m^3. Concurrently, outdoor $PM_{2.5}$ ranged between 20 and 170 ug/m^3, with a mean of 50 ug/m^3. On the other hand, indoor and outdoor CO concentrations were below threshold values with indoor CO ranging from 1.05 to 6.03 ppm at a mean of 1.62 ppm and outdoor CO ranging from 0.7 to 6.43 ppm at a mean of 1.4 ppm. The corresponding AER ranged between 0.01 and 23.35 h^{-1} with a mean of 2h^{-1}. In certain schools, higher AERs were associated with high indoor $PM_{2.5}$ and CO levels due to greater outdoor concentrations. Indoor ERs ranged from 0 to 39.04 mg/h, with a mean of 2.81 mg/h for $PM_{2.5}$, and from 0 to 157.23 mg/h, with a mean of 7.89 mg/h, for CO. This confirmed the presence of indoor sources such as the usage of chalks and re-suspension of settled particles for $PM_{2.5}$, and smoking inside schools for CO. Note that $PM_{2.5}$ DRs varied between 0 and 0.5 h^{-1} with a mean of 0.1h^{-1} and were less than the AERs in most classrooms, indicating that the effect of deposition rates on particle removal was negligible compared to the impact of AERs. The study concludes with defining measures towards controlling IAQ in schools.

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This thesis is dedicated to my family.

INTRODUCTION

The assessment of indoor air quality (IAQ) is essential and requires similar attention as the outdoor air, since people spend most of their time indoor. Indoor air exposure can reach higher levels than the outdoor and can be the cause of morbidity and premature mortality (Lee and Chang, 1999). In this context, children are more vulnerable than adults to air pollution because they have immature organs and need to breathe more quantity of air. Therefore, it is important to assess air quality in places where children spend long stretches of time, such as schools where with 6 to 8 hours of daily exposure inside classrooms (Chithra and Nagendra Shiva, 2012), health problems may occur and contribute to increased absenteeism due to various indoor sources including cleaning products, smoking, combustion by-products, etc. or by migration of outdoor air pollutants to the indoor from emissions associated with industries, construction sites, and traffic amongst others (Lee and Chang, 1999). Opened windows or doors and cracks in walls facilitate the entrance of outdoor pollutants to the indoor (Meng et al., 2005) with $PM_{2.5}$ and CO as major pollutants commonly encountered in the indoor air.

$PM_{2.5}$ is linked to health problems because of its small aerodynamic diameter (less than 2.5 um) that enables those particles to enter the lungs and reach the alveoli. $PM_{2.5}$ is also able to deposit in the nasal passages and upper airways causing throat and nose irritation, sneezing and coughing (Majumdar and William, 2009). Inside classrooms, the major source of $PM_{2.5}$ is the usage of chalks that is still used in many schools especially in developing countries with teachers getting the most exposure given their proximity to chalkboards and engagement in continuous talks (Majumdar and William, 2009). $PM_{2.5}$ is also emitted by indoor activities, such as smoking, combustion or re-suspension of deposited particles due to people movement or by air flow from the outside (Diapouli et al., 2008). $PM_{2.5}$ generated outside schools (by industries, construction activities, power plants, combustion, vehicle exhausts, grinding and crushing activities…etc.) are sources of indoor particles as well (Meng et al., 2005).

Similarly, CO is also considered hazardous since it blocks the action of hemoglobin by forming Carboxy-hemoglobin and consequently decreases the passage of oxygen to organs and tissues. It is generated mainly by incomplete combustion. Smoking, inefficient heating systems, generators, fuel powered engines, traffic, industrial facilities, power plants…etc. are considered sources of CO (WHO, 2000).

Furthermore, weather conditions such as wind, temperature and rain affect indoor and outdoor pollutant levels. For instance, high wind speed causes dispersion of outdoor $PM_{2.5}$, resulting in low outdoor $PM_{2.5}$ levels. It causes also re-suspension of settled indoor $PM_{2.5}$ by air currents that enter classrooms and consequently increases indoor levels (Chan, 2002). Moreover, outdoor temperatures higher than indoor temperatures, result in replacement of indoor air by outdoor warmer air, causing migration of pollutants from outdoor to indoor, resulting in high indoor pollutants levels in the absence of proper filtration. In contrast, indoor temperature higher than outdoor temperature causes migration of pollutants from inside to outside resulting in lower indoor levels (Elbayoumi et al., 2013).

This study focuses on comparing indoor and outdoor air pollution levels ($PM_{2.5}$ and CO) with national and international standards, identifying the difference in air quality between rural and urban areas, and investigating outdoor and indoor sources of air pollution in schools.

MATERIALS AND METHODS

1. Study area

Indoor and outdoor air quality were assessed at 40 public and private schools located in the Greater Beirut area (GBA) and surrounding rural areas (Figure 1). They encompass 10 rural-public, 10 rural-private, 10 urban-public and 10 urban-private schools. The schools were chosen randomly based on the acceptance of the administration of private schools and the approval of the Ministry of Education for public schools. Schools were contacted through phone calls or e-mails describing the project. The chosen schools are located in different geographic areas and have different environments and social fabric around them. The location of sampled schools with corresponding characteristics are summarized in Annex A (Table A1).

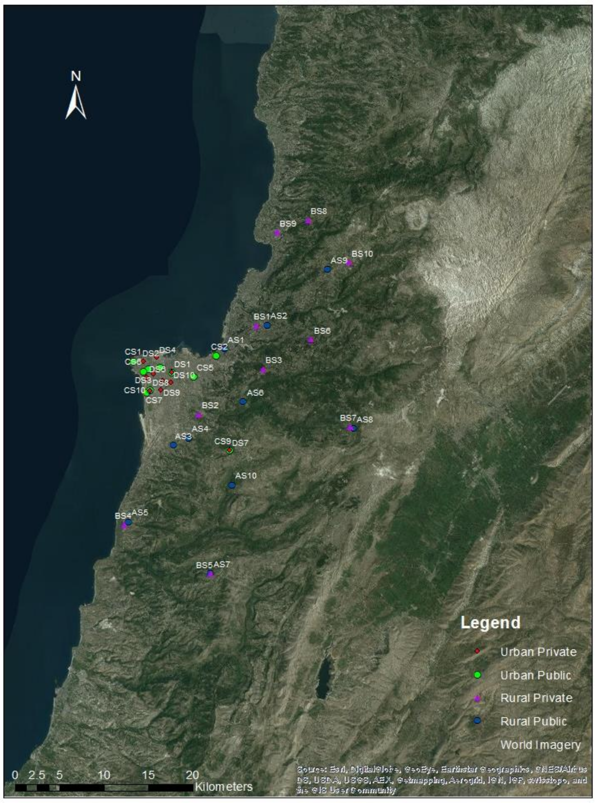

Figure 1. Location of sampled schools

2. Field monitoring

At each school, one classroom located in the first floor was selected to conduct air quality monitoring during one hour. The classrooms were chosen in the first floor since they are nearest to the outdoor with expected greater exposure. Indoor and outdoor characteristics of sampled classrooms are presented in Annex A (Table A1).

$PM_{2.5}$ and CO were monitored using a TSIDustTrakTM II Aerosol Monitor and a Langan L76n meter, respectively while temperature, wind and rainfall were noted qualitatively. Sampled classrooms had a similar rectangular shape but different sizes. At each classroom, the monitoring of air quality indicators was conducted over a period of one hour. The sampling equipment were located at the opposite end of the writing board to avoid direct exposure to emissions from chalks used for writing. Sampled locations were away from opened windows and doors to avoid disturbance from air current (Rivas et al., 2014). Only one window in a sampled classroom was kept open. The sampling equipment was set at ~1.2 to 1.5 meters above ground, near the nose level where students inhale. Concurrently, outdoor air quality monitoring was conducted at an outdoor location near the experimental classroom. Outdoor and indoor characteristics were noted including school surroundings and conditions, area/volume of sampled classrooms, number of students in classrooms, ventilation, weather conditions, and potential disruptive factors such as the presence of students near equipment that may affect IAQ (Fromme et al., 2007).

Sampling equipment

Indoor and outdoor CO concentrations were monitored concomitantly using two portable Langan CO analyzers (model L76n) with a log interval of 1 minute. The analyzers have a resolution of 0.1 ppm, a response time of 40 seconds and a measurement range of 1-200 ppm. Their accuracy was tested against a non-dispersive infrared spectrometry process and it's found to be between 0 and 3 ppm (Abi-Esber et al, 2013; Langan products Inc., 2006).

Similarly, indoor and outdoor $PM_{2.5}$ levels were monitored concomitantly using two portable TSI DustTrak II aerosol monitor (model 8532) with a log interval of 1 min. The machines have an accuracy of 0.1% of readings or 0.001 mg/m^3 and a measurement range of 0.001-150 mg/m^3. They are factory calibrated and were zeroed with a zero filter before each test. A size selective impactor (for $PM_{2.5}$) was connected to the analyzers inlet prior to each test and cleaned using little drops of oil at the end of a test to sustain the flow within 5% of factory's set point (TSI, 2011).

3. Data analysis

At each school, the average indoor $PM_{2.5}$ and CO levels were compared with the Illinois Department of Public Health guidelines (IPDH) for IAQ. Indoor CO levels were also compared with the American Society of Heating, Refrigerating and Air-Conditioning Engineers guidelines for IAQ (ASHRAE). As for outdoor pollution, the average outdoor $PM_{2.5}$ and CO levels were compared with the National Ambient Air quality Standards (NAAQS), the World Health Organization (WHO) standards and the Environmental Protection Agency (USEPA) standards. Moreover, Outdoor CO levels were compared with the Lebanese standards for outdoor air quality (Table 1).

Table 1. Indoor and outdoor air quality guidelines and standards
(EPA, 2011; Illinois Department of Public Health, 2011; Chabarekh, 2010; MOE, Decision 52/1-1996)

Parameter	**Indoor air quality standards**		**Outdoor air quality standards**			
	IPDH guidelines	ASHRAE guidelines	NAAQS	WHO	EPA	Lebanese standards
CO	9 ppm	9 ppm	9 ppm (8hrs)	26 ppm ($30\ mg/m^3$) (1hr) 9 ppm ($10\ mg/m^3$) (8hrs)	35 ppm ($40\ mg/m^3$) (1hr) 9ppm ($10\ mg/m^3$) (8hrs)	26 ppm ($30\ mg/m^3$) (1hr) 9ppm ($10\ mg/m^3$) (8hrs)
$PM_{2.5}$	$65\ ug/m^3$ (24 hrs)	-	$35\ ug/m^3$ (24hrs)	$10\ ug/m^3$ (annual) $25\ ug/m^3$ (24hrs)	$15\ ug/m^3$ (annual) $35\ ug/m^3$ (24hrs)	-

The normality of the collected data was checked through the Shapiro –Wilk test, using the R program (p value > 0.05 indicates having normal data). Non-normal data were transformed using log transformation. One way ANOVA was performed to test for variability in pollutants concentrations measured in urban versus rural schools. Note that the non-parametric test Kruskal Wallis was utilized instead of ANOVA when normality was not met following log transformation. A two ways ANOVA test was performed to check the variability in pollutants concentrations between rural-public, rural-private, urban-public and urban private schools; the interaction between sector and setting was also assessed. When the normality assumption was not met, the Friedman test was used instead of the 2 ways ANOVA. Additionally, the correlation between indoor and outdoor concentrations was assessed using the Pearson correlation when the relationship between data was linear and through the Spearman correlation when the relationship was not linear (Venables and Smith, 2002).

4. Assessment of control parameters

The collected field data were relied upon to define several control parameters including the Air Exchange Rate (AER), $PM_{2.5}$ deposition rate (DR) and $PM_{2.5}$ and CO indoor equivalent emission rate (ER) as outlined below.

The AER was estimated for each classroom using a mass balance approach as expressed in Equation 1 (He et al, 2005) where the CO measurements recorded at 1 minute intervals were used.

$$\frac{dC}{dt} = AER\, C_{Ov} + \frac{S}{V} - (AER + DR)C \qquad (1)$$

Where AER=Air Exchange Rate (h^{-1}), C = Indoor CO concentration at time t (mg/m^3), C_{Ov} = Outdoor CO concentration (mg/m^3) at time t, S=Source generation rate (mg/h), V=Volume of classroom (m^3), DR=Deposition rate (h^{-1}) (DR=0 for CO over a short period of time (WHO, 2000) and t= duration (h).

The $PM_{2.5}$ deposition rate (DR) was estimated using the same equation (1) with measurements recorded at 1 minute intervals and after calculating corresponding AERs. In Equation 1, C = Indoor $PM_{2.5}$ concentration (mg/m^3) at time t and C_{Ov} = Outdoor $PM_{2.5}$ concentration at time t (mg/m^3). The estimated AERs and $PM_{2.5}$ DRs were then used in Equation (1) to estimate equivalent emission rates (ERs) of CO and $PM_{2.5}$ that will provide the best fit between simulated and measured data using the 1-minute frequency for field measurements and the Root Mean Squared Error (RMSE).

5. Management Measures

Management mitigation measures were defined with the aim to control IAQ in schools towards providing children protection and ensuring minimal exposure. The measures were defined within the context of regulatory and institutional stakeholders and determinants pertaining to air quality monitoring and control.

RESULTS AND DISCUSSION

1. Average $PM_{2.5}$ and CO exposure

The average $PM_{2.5}$ levels across schools are presented in Figure 2. IPDH guidelines for IAQ were exceeded in 5 schools in the Rural-Public category, 2 schools in the Rural-Private category, 5 schools in the Urban-Public category and 5 schools in the urban-Private category. This could be attributed mainly to the usage of chalkboards in most of these schools or to indoor penetration of outdoor $PM_{2.5}$ generated by outdoor sources. Furthermore, WHO guidelines and/or EPA/NAAQS standards for outdoor air quality are exceeded in 9 schools in the Rural-Public category, in 8 schools in the Rural-Private category, in 8 schools in the Urban-Public category and in 8 schools in the Urban-Private category. This was mostly associated with the location of the majority of these schools near construction sites, industries, smoking areas, traffic density and electrical generators. The results were compared with $PM_{2.5}$ concentrations observed in previous similar studies (Table 2). The average indoor $PM_{2.5}$ levels measured in this study ranged between 20 and 180 ug/m^3 with a mean of 62 ug/m^3. Most indoor concentrations ranged between 20 and 90 ug/$m^3$and fell within approximately the same range reported in the literature (Rivas et al, 2014; Alves et al, 2013; Ekmekcioglu, & Keskin, 2007; Amato et al, 2014; Fromme et al, 2007; Alves el al, 2013) (Table 2). The mean indoor value was nearly similar to concentrations previously observed in certain studies (Stranger et al, 2008; Ekmekcioglu, & Keskin, 2007) (Table 2). Moreover, the average outdoor $PM_{2.5}$ levels ranged between 20 and 170 ug/m^3 with a mean value of 50 ug/m^3. Most of the observed outdoor concentrations ranged between 20 and 100 ug/m^3 and fell within almost the same range reported in other studies (Rivas et al, 2014; Mohammadyan, & Shabankhani, 2013; Amato et al, 2014) (Table 2). The mean outdoor value (50 ug/m^3) fell in the range of outdoor means reported in other studies (9.7 to 72 ug/m^3) (Table 2). As for CO, the average concentrations are represented in Figure 3 and all indoor and outdoor CO levels were below threshold standards. Low indoor CO levels were expected in this study due to absence of significant CO sources inside classrooms. Literature reported indoor CO levels ranged between 1.05 and 6.03 ppm with a mean of 1.62 ppm (Table 2). Most of indoor CO levels ranged between 1.05 and 2.73 ppm, which are consistent with the range reported in the literature (Table 2). The mean indoor CO value (1.62 ppm) is similar to the means reported in the literature (Ajiboye et al, 2006) (Table 2). Furthermore, the average outdoor CO levels ranged between 0.7 and 6.43 ppm, where the majority of the observed outdoor concentrations ranged between 0.7 and 2.44 ppm. The mean outdoor CO value is equal to 1.4 ppm close to the one reported in the literature (1.2 ppm) (Razali et al, 2015) (Table 2).

Table 2. Comparison with literature reported studies

		$PM_{2.5}$ (ug/m^3)				CO (ppm)			Mean AER (h^{-1})
References	**Location**	**Mean Indoor**	**Range Indoor**	**Mean Outdoor**	**Range Outdoor**	**Mean Indoor**	**Range Indoor**	**Mean Outdoor**	
Razali et al. 2015	Malaysia	1.8	8-36	26		0.3	0-4.3	1.2	
Ajiboye et al. 2006	London, England					0.6-8.5[c]			
Wichmann et al. 2010	Stockholm, Sweden	8.1	2.8-13.9	9.7	5.2	24.2			1.64[a]
Alves et al. 2013	Aveiro, Portugal		44±3.2-117±16		37-42				≥0.2
Canha et al. 2015	Clermont-Ferrand, France	22±8	10-47						1.4±0.6[b]
Fromme et al. 2007	Munich, Germany	23	2.7-80.8						
Zwozdiak et al. 2013	Wroclaw, Poland	14		16					
Stranger et al. 2008	Antwerp, Belgium	61		72					
Rivas et al. 2014	Barcelona, Spain	37	13-84	29	10-111				
Mohammadyan & Shabankhani. 2013	Sari, Iran	46.6	29.1-69.1	36.9	15.5-115.8				
Almeida et al. 2011	Lisbon, Portugal	10	5-22		3-10				
Branis et al. 2005	Prague, Czech Republic	21.9	7.6-44						
Ekmekcioglu & Keskin. 2007	Istanbul, Turkey	70.9±3.6	45.6±2.3-95.2±4.8						
Amato et al. 2014	Barcelona, Spain		7-105		1-192				
Janssen et al. 2001	Netherlands	23	7.7-52.8	24.8	5.2-60.8				
This study	Beirut, Lebanon	62	20-180	50	20-170	1.62	1.05-6.03	1.4	

[a] Range between 0.41 and 3.45
[b] Range between 0.3 and 3.1 h^{-1}
[c] CO indoor mean in every assessed school

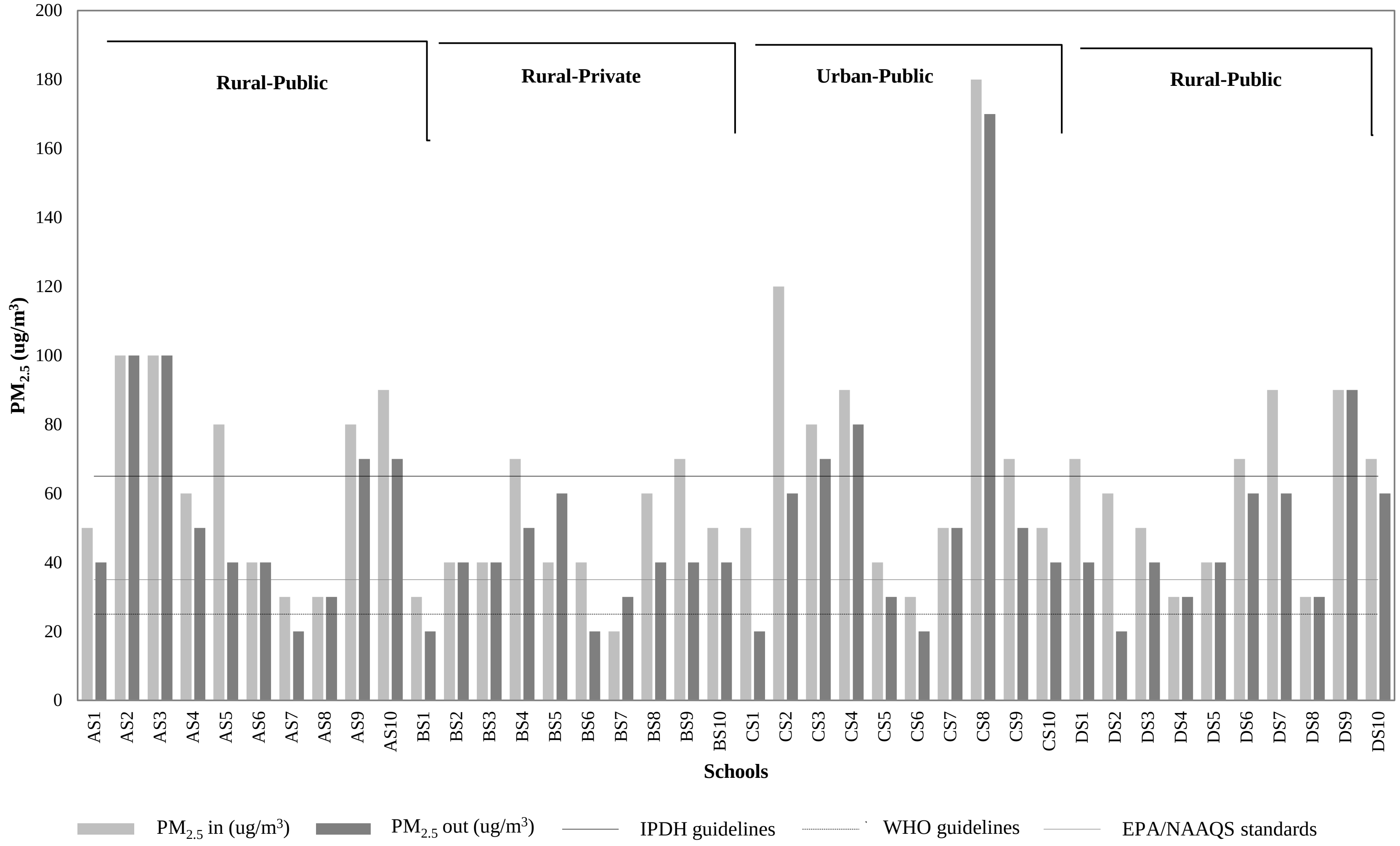

Figure 2. Comparison of $PM_{2.5}$ levels with international standards

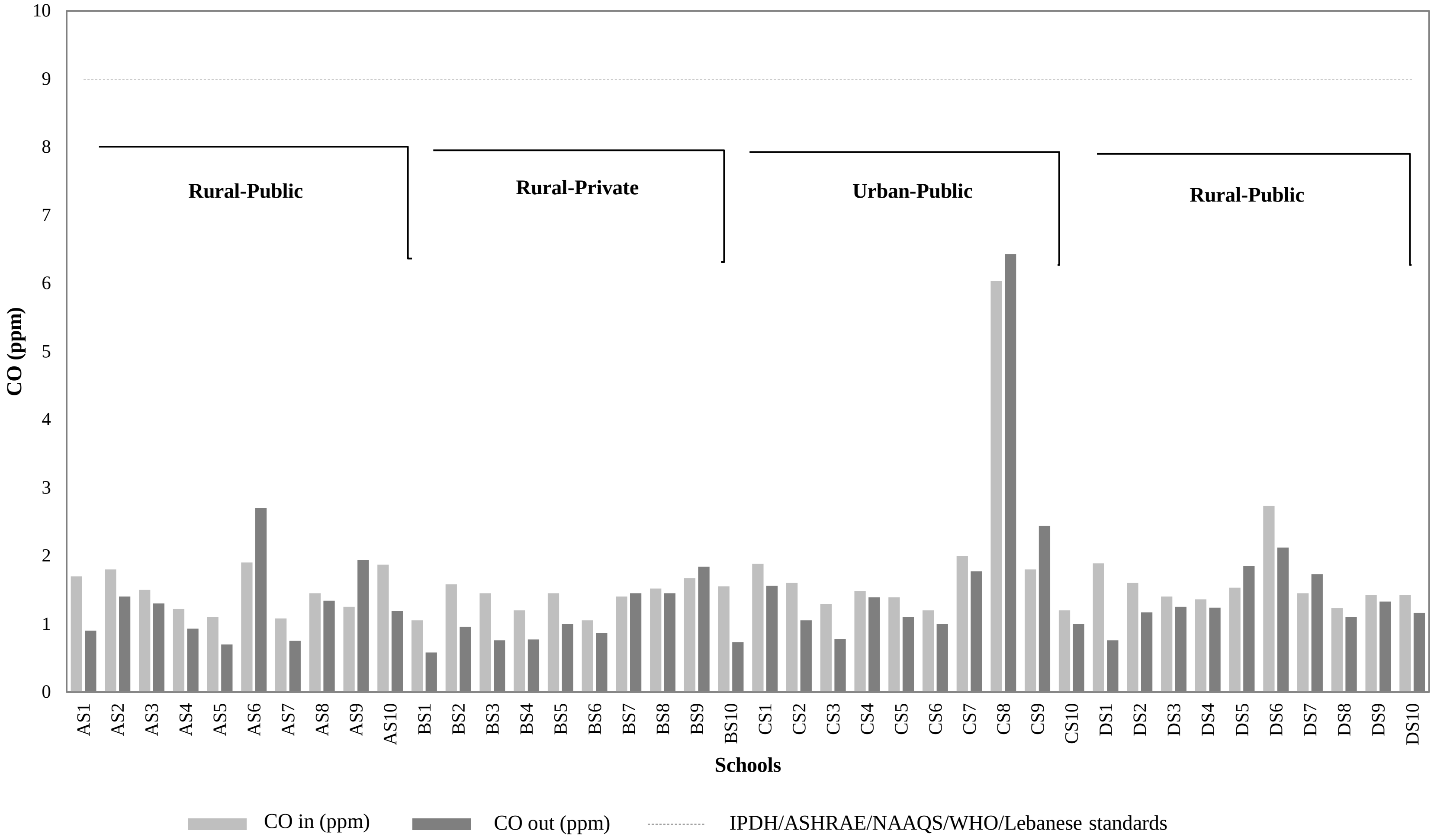

Figure 3. Comparison of CO levels with international and national standards

2. Comparison of Pollutants levels across categories

No statistically significant difference (p value by ANOVA= 0.645) was found between rural-outdoor and urban-outdoor $PM_{2.5}$ concentrations (Figure 4). Additionally, there was no statistically significant difference in outdoor $PM_{2.5}$ concentrations among the 4 different groups (rural-private, urban-private, rural-public, and urban-public schools) (Figure 4). For indoor concentrations (Figure 5) there was no significant difference (p value by ANOVA= 0.233) between rural-indoor and urban-indoor $PM_{2.5}$ levels. Moreover, no significant difference was found in indoor $PM_{2.5}$ levels among rural-private, urban-private, rural-public, and urban-public schools (Figure 5). Finally, $PM_{2.5}$ levels (Figures 6) showed no statistically significant difference between rural and urban indoor/outdoor $PM_{2.5}$ ratio (p value by Kruskal Wallis test=0.5199) and no statistically significant difference was found between the 4 different groups. The mean concentrations of $PM_{2.5}$ for each category are reported in Table 3. The absence of a significant difference between $PM_{2.5}$ levels among different groups was probably due to the existence of indoor and outdoor $PM_{2.5}$ sources in different schools categories.

Regarding CO levels, Figure 7 shows that there was no significant difference between rural-outdoor and urban-outdoor CO levels (p value obtained by Kruskal Wallis test= 0.08093) and between rural-private, urban-private, rural-public, and urban-public schools. As for indoor levels and as shown in Figure 8, there was no significant difference between rural and urban indoor CO concentrations (p value obtained by Kruskal Wallis =0.2972). Moreover, no significant difference was found in indoor CO levels among rural-private, urban-private, rural-public schools, and urban-public schools (Figure 8). Similarly, no significant difference was found between rural and urban indoor/outdoor CO ratio (p value by ANOVA =0.281) and no difference was present among the 4 different groups (Figure 9). Finally, neither the interaction between sector and setting (p value=0.469) nor the variance in sector (p value=0.365) or in setting (p value=0.282) were significant. The means concentrations of CO for each category are summarized in Table 3. The presence of CO sources in different schools categories was possibly the reason behind the absence of significant differences between indoor and outdoor CO levels among different groups.

Table 3. Means concentrations of $PM_{2.5}$ and CO for each category

School Category	**$PM_{2.5}$ Outdoor Average (ug/m^3)**	**$PM_{2.5}$ Indoor Average (ug/m^3)**	**$PM_{2.5}$ IO Ratio**	**CO Outdoor Average (ppm)**	**CO Indoor Average (ppm)**	**CO IO Ratio**
Rural	47±22.4	56±23.7	1.3±0.4	1.2±0.5	1.4±0.3	1.4±0.4
Urban	53±33	68±34.7	1.4±0.5	1.6±1.2	1.8±1.0	1.2±0.4
Rural-Private	38±11.7	46±15.6	1.3±0.4	1.0±0.4	1.4±0.2	1.5±0.4
Urban-Private	47±19.5	60±21	1.4±0.6	1.4±0.4	1.6±0.4	1.2±0.4
Rural-Public	56±11.7	66±26.2	1.2±0.3	1.3±0.6	1.5±0.3	1.3±0.4
Urban-Public	59±41.6	76±42.9	1.4±0.4	1.9±1.6	2.0±1.4	1.2±0.2

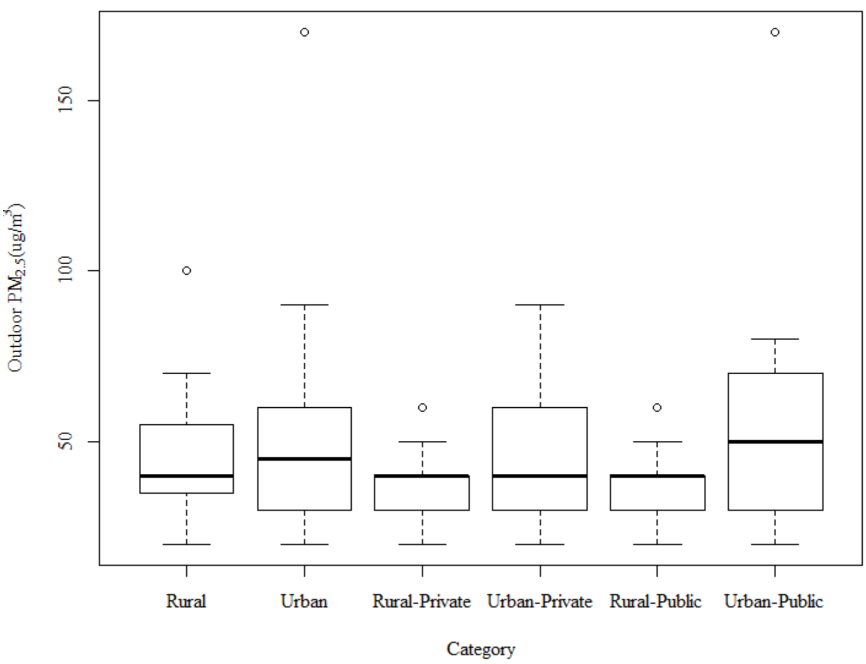

Figure 4. Comparison of outdoor $PM_{2.5}$ levels between different schools categories

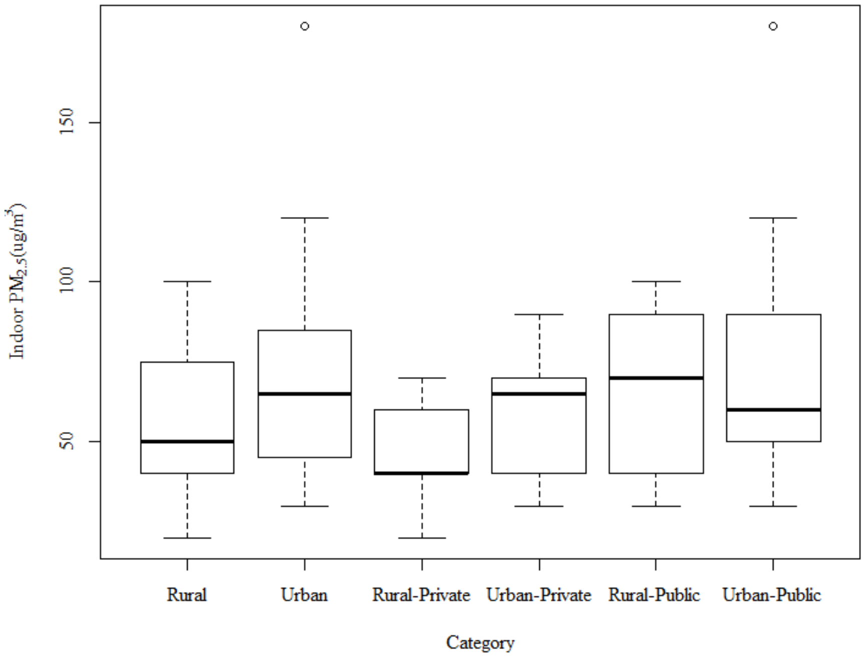

Figure 5. Comparison of indoor $PM_{2.5}$ levels between different schools categories

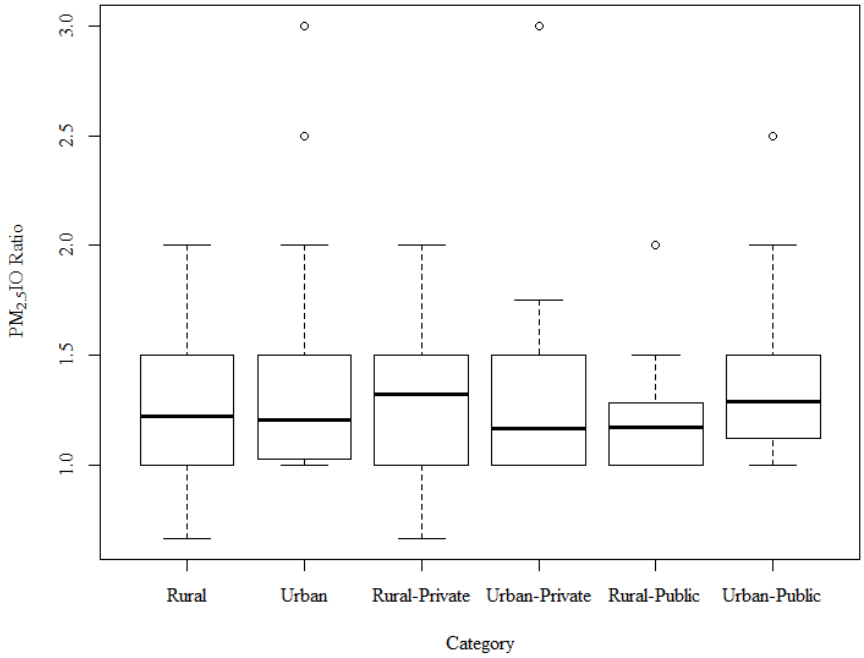

Figure 6. Comparison of $PM_{2.5}$ IO ratio between different schools categories

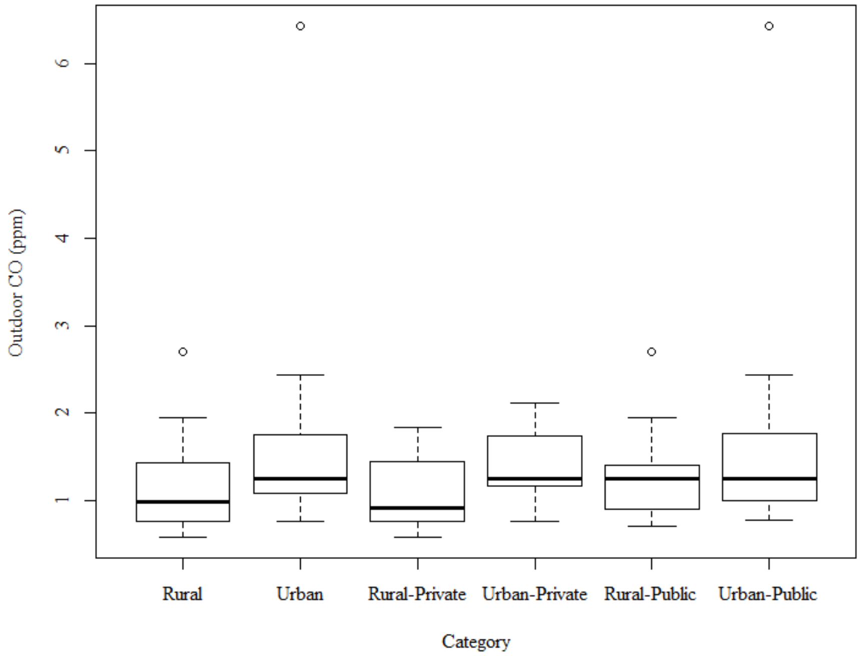

Figure 7. Comparison of outdoor CO levels between different schools categories

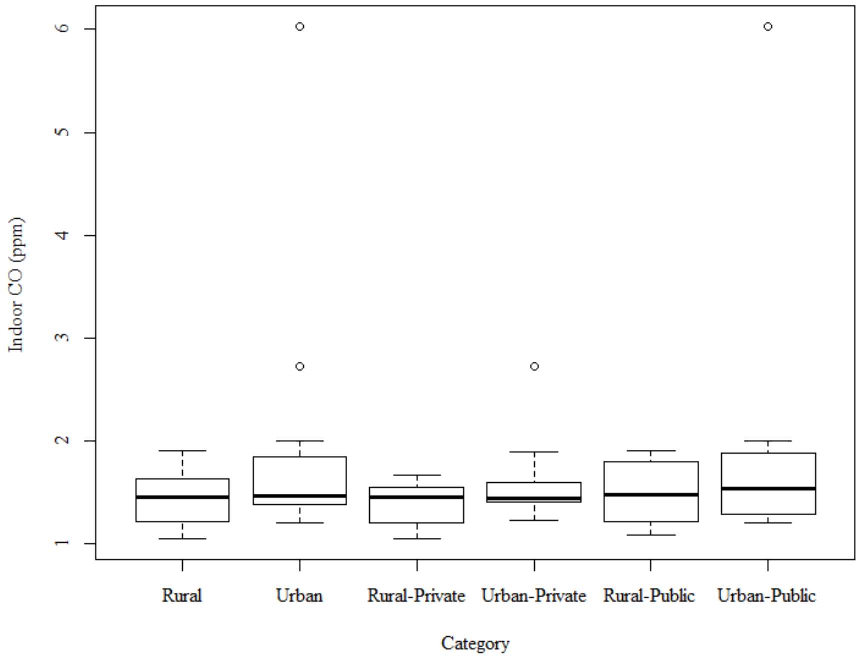

Figure 8. Comparison of indoor CO levels between different schools categories

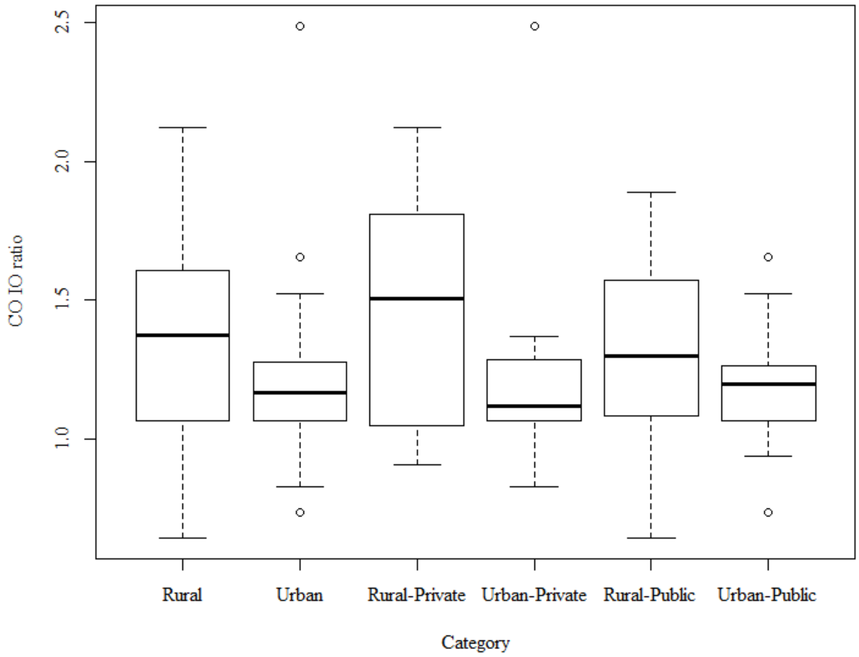

Figure 9. Comparison of CO IO ratio between different schools categories

3. Outdoor and Indoor $PM_{2.5}$ and CO assessment

Outdoor pollutants assessment

High outdoor $PM_{2.5}$ levels were encountered at several public and private schools, regardless of setting (Figure 2). Those schools were located near $PM_{2.5}$ sources such as construction sites, industries, smoking areas, high traffic streets, garages, parking lots, and electrical generators. In contrast, CO outdoor levels in the sampled schools were below standards (Figure 3). The highest CO concentrations were recorded at schools located near outdoor CO sources such as electrical generators, smoking areas, high traffic density, and gas stations. Table A1 in Annex A documents possible sources of $PM_{2.5}$ and CO near those schools.

Correlation between indoor and outdoor pollutants

In order to identify the sources of $PM_{2.5}$ and CO in sampled classrooms, the temporal variations in indoor and outdoor pollutants were assessed (Figures B1 and B2 in Annex B). Correlation factors (CF) between indoor and outdoor $PM_{2.5}$ and CO levels were computed (Table 4) with a strong positive correlation discerned between indoor and outdoor $PM_{2.5}$ at schools located near $PM_{2.5}$ sources such as industries, construction sites, traffic, smoking areas…etc. (AS1, AS2, AS3, AS4, AS8, BS1, BS4, BS5, BS9, BS10, CS3, CS8, CS9, DS3, DS6 and DS10). Similarly, a strong correlation was discerned between indoor and outdoor CO levels, at schools located near CO sources such as traffic density, parking, garages, industries, solid waste open dump, smoking areas, electrical generators, or farms burning agricultural wastes (koppmann, 2005) (AS1, AS2, AS3, AS4, BS8, CS7, CS8, DS3, DS6, DS9 and DS10). Having a strong correlation factor between indoor and outdoor pollutants concentrations indicates that IAQ is affected by the outdoor air quality (Cyrys et al., 2004).

Table 4. Indoor/Outdoor $PM_{2.5}$ and CO correlation factors and I/O ratios

Category	School	$PM_{2.5}$ CF	CO CF	$PM_{2.5}$ I/O	CO I/O
Rural-Public	AS1	0.47	0.84	1.25	1.79
	AS2	0.58	0.74	1	1.37
	AS3	0.81	0.81	1	1.09
	AS4	0.73	0.41	1.2	1.32
	AS5	0.38	-0.13	2	1.47
	AS6	0.39	0.09	1	0.74
	AS7	0.26	-0.02	1.5	1.45
	AS8	0.79	0.08	1	1.07
	AS9	0.13	-0.42	1.14	0.65
	AS10	-0.23	-0.1	1.29	1.56
Rural-Private	BS1	0.62	0.05	1.5	1.77
	BS2	-0.33	-0.22	0.8	1.66
	BS3	-0.4	-0.41	1	1.91
	BS4	0.88	-0.39	1.4	1.56
	BS5	0.73	0.23	0.67	1.45
	BS6	0.46	0.17	2	1.21
	BS7	0.57	0.22	0.67	0.97
	BS8	0.27	0.54	1.5	1.04
	BS9	0.83	0.46	1.75	0.9
	BS10	0.63	0.75	1.25	2.29
Urban-Public	CS1	0.12	0.42	2.5	1.18
	CS2	-0.14	0.31	2	1.52
	CS3	0.59	0.37	1.14	1.69
	CS4	0.13	0.1	1.13	1.18
	CS5	-0.2	-0.22	1.33	1.44
	CS6	-0.13	-0.08	1.5	1.22
	CS7	0.35	0.61	1	1.1
	CS8	0.73	0.66	1.06	0.94
	CS9	0.58	0.41	1.4	0.74
	CS10	0.4	-0.08	1.25	1.2
Urban-Private	DS1	-0.21	-0.28	1.75	2.49
	DS2	-0.16	0.18	3	1.38
	DS3	0.9	0.6	1.25	1.12
	DS4	0.35	-0.16	1	1.15
	DS5	0.12	-0.05	1	0.8
	DS6	0.73	0.61	1.17	1.25
	DS7	0.15	0.13	1.5	0.87
	DS8	0.2	0.23	1	1.14
	DS9	0.27	0.7	1	1.09
	DS10	0.7	0.7	1.17	1.22

Indoor/Outdoor pollutants ratios

An indoor/outdoor ratio above 1 (I/O > 1) indicates potential indoor sources (Joseph et al., 2010). For instance, a major indoor source for $PM_{2.5}$ is the usage of chalkboards or the re-suspension of settled particles by students' movements (Blondeau et al., 2005). The results show that schools with indoor $PM_{2.5}$ levels that exceed threshold standards (Figure 2) use chalkboards (AS5, AS9, AS10, BS4, BS9, CS2, CS3, CS4, CS8, CS9, DS1, DS6, DS7 and DS10) (Annex A). These schools also tended to have $PM_{2.5}$ indoor/outdoor ratio greater than 1 (Table 4), ranging from 1.14 to 2. This highlights the role that chalks may play in the emissions of indoor $PM_{2.5}$. Moreover, several classrooms had occupancy (O) above the 1 student / 2 m^2 limit (ASHRAE, 2001) (Annex A). Under crowded conditions, re-suspension of settled particles (emitted from indoor or outdoor sources) by movement of the large number of students in relation to classroom area constitutes a source of $PM_{2.5}$ (Blondeau et al., 2005). Many schools with high occupancy had indoor/outdoor $PM_{2.5}$ ratio greater than 1 ranging between 1.13 and 3 (AS7, BS1, BS4, BS6, BS8, BS9, CS1, CS3, CS4, CS6, CS8, CS9, DS1, DS2, DS6 and DS7) (Table 4 and Annex A), reflecting on the relationship between classroom occupancy and indoor $PM_{2.5}$ irrespective of using chalkboards or whiteboards. Similar to $PM_{2.5}$, indoor/outdoor CO ratios were computed to check on the presence of indoor CO sources (I/O > 1) (Table 4). Smoking inside teachers' rooms or next to classrooms, using gas stoves in school kitchens, inefficient heating systems…etc. are all factors that play a role in CO emissions (WHO, 2000). Several schools exhibited an I/O CO > 1 ranging from 1.07 to 2.49 (AS1, AS2, AS3, AS4, AS5, AS7, AS8, AS10, BS1, BS2, BS3, BS4, BS5, BS6, BS8, BS10, CS1, CS2, CS3, CS4, DS5, CS6, CS7, CS10, DS1, DS2, DS3, DS4, DS6, S8, DS9 and DS10).

4. Physical control parameters

Air exchange rate (AER)

Indoor air quality is affected by the air exchange rate (AER) that is defined by the rate at which outdoor air replaces indoor air in a specific area, through infiltration, natural ventilation or mechanical ventilation (Adenin et al, 2015). During the assessment, doors were closed, A/Cs were off, fans were off and only one window was opened to ensure natural ventilation. The area of opened windows was estimated to be the same in all classrooms (approximately 1.5 m^2). The equivalent AER ranged from 0.01 to 23.35 h^{-1} with a mean value of 2 h^{-1}(Table 5). The AER is affected by many factors such as wind speed, direction and turbulence, size of ventilation openings, room volume, solar radiation, heat sources, temperature …etc. (Hussein & Kulmala, 2008). However, the mass balance model (Equation 1) accounts only for classroom volume due to lack of monitoring of other parameters that affects the AER. Figure 10 shows that the variation in AERs and the variation in classroom volumes are not correlated and this was expected since the AER depends on many parameters including room volume.

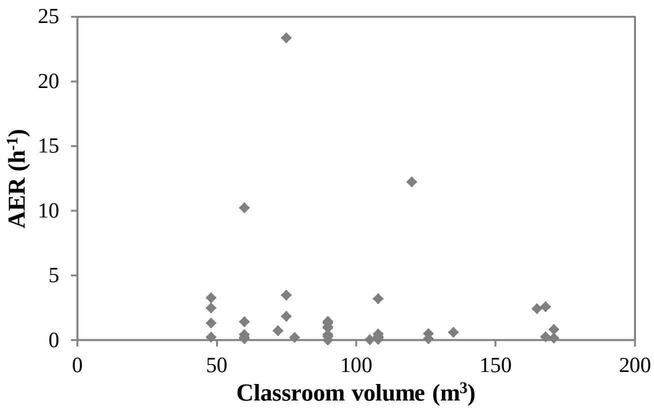

Figure 10. Equivalent AERs (h^{-1}) and classrooms volumes (m^3)

High AERs were estimated in certain classrooms such as AS2 (12.21 h^{-1}), BS8 (10.21 h^{-1}) and CS8 (23.35 h^{-1}) since those schools were assessed during windy days. On the other hand, very low AERs were encountered in AS9 (0.01 h^{-1}), CS2 (0.05 h^{-1}), CS3 (0.09 h^{-1}) and DS7 (0.03 h^{-1}). The mean estimated AER (2h^{-1}) is consistent with the literature reported means (Canha et al, 2015; Alves et al, 2013; Wichmann et al, 2014) (

Table 2). It is also important to mention that most visited schools had an AER lower than ASHRAE recommended AER for classrooms (3 h^{-1}) (Daisey et al, 2003). Furthermore, Figure 11 shows closer equilibrium between indoor and outdoor CO levels at higher AERs causing greater pollution when the outdoor air is polluted (Alves el al., 2014).

As for indoor $PM_{2.5}$ levels, they are affected by many factors such as indoor-outdoor exchange rate, penetration rate, deposition rate, re-suspension rate, indoor emission rate, formation of new particles, evaporation…etc. (Hussein & Kulmala, 2008). Taking into consideration only the AER factor, the results showed that classrooms with low AERs compared to others, tended to have high indoor $PM_{2.5}$, which was consistent with literature findings showing that indoor pollutants will increase with low AER, due to inefficiency of ventilation (Alves et al, 2014) (Figure 12). Similar to CO results, closer equilibrium between indoor and outdoor $PM_{2.5}$ levels at higher AERs is discerned causing greater pollution when the outdoor air is polluted (Figure 12). Consequently, the common intuition that IAQ is expected to improve with greater natural ventilation (higher AER), is accurate only in case the outdoor air quality is better than IAQ. Hence, decreasing the AER is required when the outdoor air is poorer in quality than the indoor air (Adenin et al, 2015).

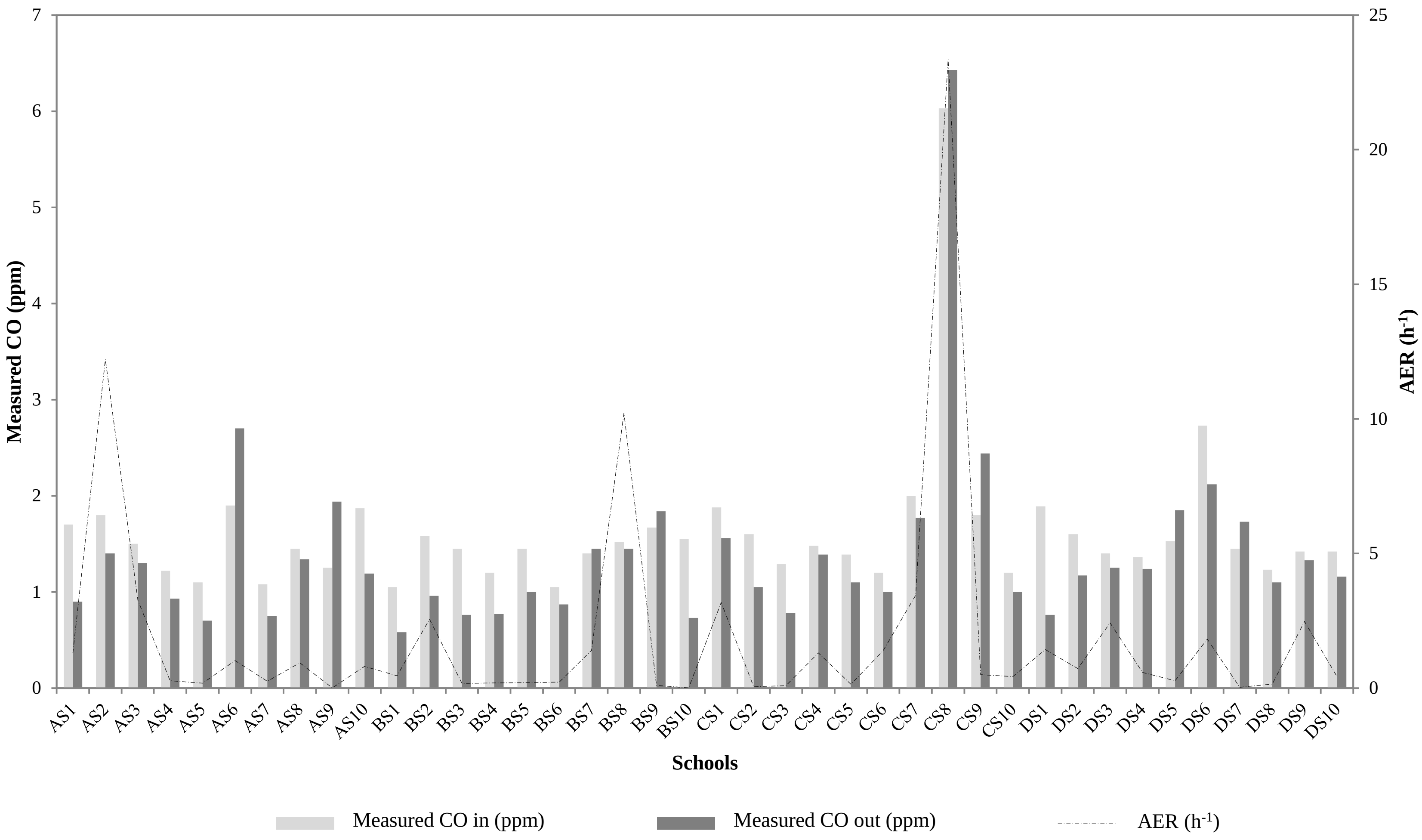

Figure 11. Equivalent AER (h^{-1}) and average CO (ppm) concentration at each school

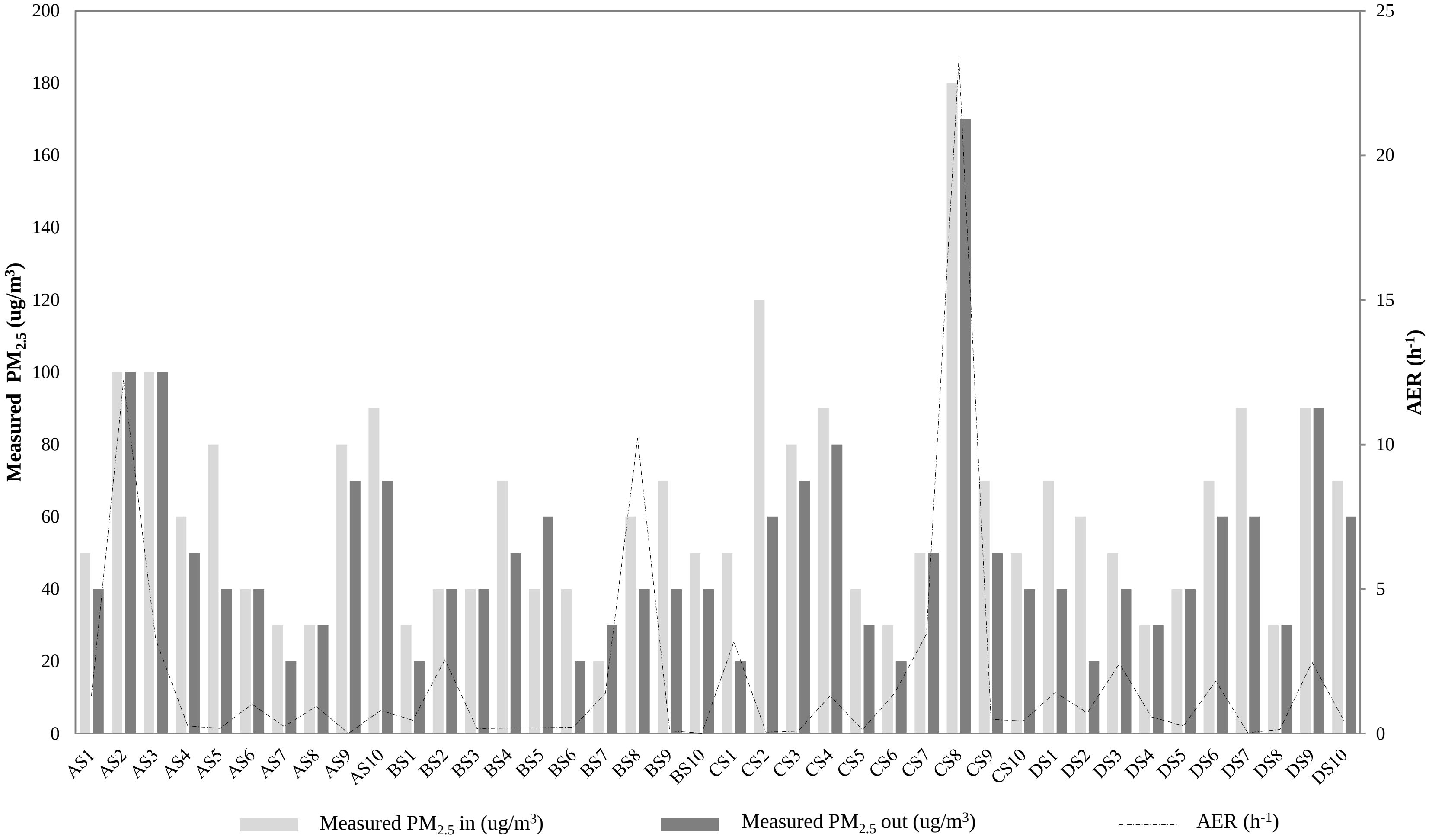

Figure 12. Equivalent AER (h^{-1}) and average $PM_{2.5}$ (ug/m^3) concentration at each school

Table 5. Estimated physical parameters

School Category	School ID	V (m^3)	AER (1/h)	ER_{CO} (mg/h)	$DR_{PM2.5}$ (1/h)	$ER_{PM2.5}$ (mg/h)	$RR_{PM2.5}$ (mg/h)
Rural-Public	AS1	90	1.31	6.00	0.46	0.00	0.44
	AS2	120	12.21	157.23	0.00	39.04	1.23
	AS3	48	3.26	18.00	0.37	2.52	0.50
	AS4	108	0.27	1.00	0.05	0.00	0.63
	AS5	108	0.18	0.08	0.00	14.51	1.08
	AS6	90	1.02	1.42	0.50	0.00	0.35
	AS7	168	0.25	0.00	0.02	0.73	0.47
	AS8	90	0.94	0.00	0.10	1.24	0.24
	AS9	90	0.01	1.15	0.01	2.61	0.70
	AS10	171	0.81	1.17	0.00	0.57	1.48
Rural-Private	BS1	108	0.46	0.18	0.22	4.46	0.30
	BS2	168	2.56	41.50	0.50	0.00	0.64
	BS3	108	0.17	0.00	0.00	0.34	0.39
	BS4	78	0.19	0.06	0.00	0.48	0.52
	BS5	60	0.20	0.24	0.00	0.68	0.22
	BS6	48	0.22	0.24	0.22	0.00	0.22
	BS7	60	1.40	0.00	0.50	0.00	0.14
	BS8	60	10.21	55.06	0.00	14.64	0.38
	BS9	60	0.10	0.00	0.00	1.50	0.41
	BS10	90	0.01	0.78	0.00	0.70	0.46
Urban-Public	CS1	108	3.18	0.00	0.00	0.84	0.55
	CS2	108	0.05	1.10	0.00	1.11	1.27
	CS3	126	0.09	0.11	0.00	0.91	1.07
	CS4	48	1.31	2.01	0.00	1.10	0.43
	CS5	171	0.14	0.00	0.00	1.15	0.75
	CS6	90	1.39	1.97	0.00	3.44	0.27
	CS7	75	3.45	9.05	0.00	3.26	0.42
	CS8	75	23.347	0.00	0.00	8.23	1.32
	CS9	126	0.50	0.00	0.00	0.95	0.94
	CS10	60	0.43	0.00	0.00	0.29	0.30
Urban-private	DS1	90	1.43	3.31	0.00	3.46	0.62
	DS2	72	0.72	0.15	0.01	0.95	0.41
	DS3	165	2.42	8.90	0.48	0.00	0.83
	DS4	135	0.58	0.25	0.01	0.00	0.37
	DS5	90	0.27	0.00	0.00	0.29	0.39
	DS6	75	1.82	3.99	0.40	0.00	0.55
	DS7	105	0.03	0.03	0.00	1.25	0.91
	DS8	60	0.15	0.21	0.00	0.27	0.21
	DS9	48	2.47	0.00	0.00	0.95	0.44
	DS10	90	0.43	0.00	0.00	0.08	0.63

V=classroom volume; AER=air exchange rate; ER=indoor generation rate; DR=deposition rate; RR=re-suspension rate

$PM_{2.5}$ deposition rate ($DR_{PM2.5}$) and re-suspension rate ($RR_{PM2.5}$)

Particles are removed from indoor air through deposition on indoor surfaces through gravitational settling, that's why it is essential to assess this process due to its role in reducing indoor $PM_{2.5}$ levels (Thatcher et al, 2002). $PM_{2.5}$ deposition rates were estimated using Equation 1 and they varied between 0 and 0.5 h^{-1} with a mean of 0.1 h^{-1}

(Table 5). The values were relatively lower than average deposition rates reported in the literature for particles size ranging between 2 and 3 um (2.55± 2.1 h^{-1} for minimum ventilation) (He et al, 2005). Several studies evaluated the relationship between AER and $PM_{2.5}$ deposition rates with some reporting a positive correlation between those two variables while others demonstrating a negative or no correlation between them. The difference between studies can be attributed to the fact that $PM_{2.5}$ deposition rates are affected by several factors such as particle size, type of surfaces, indoor activities, mixing process, coagulation, humidity level…etc., in addition to AER (He et al, 2005; Thatcher et al, 2002; Adeniran et al, 2015). Excluding outliers (windy days), the AER and the $DR_{PM2.5}$ exhibited a moderately positive correlation with correlation factor of 0.44 (Figure 13), implying that AER had an effect on the $DR_{PM2.5}$. Note that the $DR_{PM2.5}$ were less than AERs, reflecting a negligible effect of DR on $PM_{2.5}$ removal to the impact of AER (He et al, 2005).

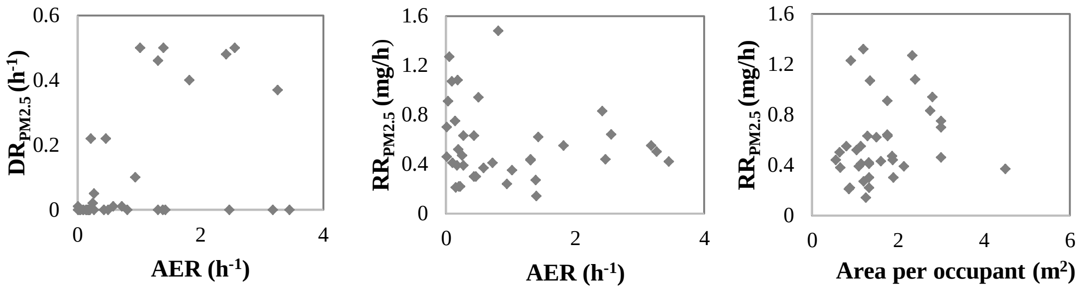

Figure 13. AER (h^{-1}), $DR_{PM2.5}$ (h^{-1}) and $RR_{PM2.5}$ (mg/h)

Indoor $PM_{2.5}$ levels are also affected by re-suspension of particles by indoor activities such as occupants' movement and cleaning (Hussein & Kulmala, 2008). The re-suspension of deposited particles constitutes a source of indoor $PM_{2.5}$. The maximum reachable re-suspension rates (mg/h) were estimated by multiplying indoor $PM_{2.5}$ levels (mg/m^3) by classroom volume (m^3) and by the maximum re-suspension rate of $PM_{2.5}$

from floor surfaces that is equal to 0.1 h^{-1} (El-Hougiri, 2001). The resulting values varied from 0.14 to 1.48 mg/h with a mean of 0.59 mg/h (Table 5). Figure 13 shows that no significant correlation existed between $PM_{2.5}$ re-suspension rates and AERs (correlation factor=-0.12) reflecting a contribution from other factors such as students movement consistent with other studies that demonstrated an increase in particles re-suspension with the increase in classroom occupancy (Rovelli et al, 2014). The correlation factor between particles re-suspension rate and the area allowed for each occupant was equal to 0.2, showing a minor correlation between the two factors. This weak correlation was expected since the re-suspension of particles is dependent as well on the intensity of indoor physical activities (Alves et al, 2013).

$PM_{2.5}$ and CO emission rate (ER)

Indoor/Outdoor pollution ratio may not an adequate indication of the presence of indoor sources (Wichmann et al, 2010), that's why $PM_{2.5}$ and CO indoor generation rates were estimated in each classroom. The indoor equivalent emission rates were estimated by reducing the difference between measured and simulated indoor levels (Equation 1). Annex B (Figures B1&B2) shows the model results after adding the emission rates. The emission rates ranged between 0 and 39.04 mg/h with a mean of 2.81mg/h for $PM_{2.5}$ and between 0 and 157.23 mg/h with a mean value of 7.89 mg/h for CO (Table 5). A review of the literature showed that the most important source of $PM_{2.5}$ in a classroom was wiping the board, and that the emission rates from this activity varied between 480 and 840 mg/h (Salma et al, 2013). In this study, the $PM_{2.5}$ emission rates were much lower than this range, since the chalkboards were not erased while taking measurements. $PM_{2.5}$ indoor generation is also due to writing with chalks and/or re-suspension of settled particles by indoor activities (Colome et al, 1992). Hence, most schools with high ERs used chalkboards, such as AS2, AS5, BS1, CS8, CS6, CS7 and DS1. On the other hand, the ERs were nil in certain classrooms, where whiteboards were used instead of chalkboards (AS4, BS6, BS7, DS3 and DS4). The difference between indoor emission rates (mg/h) and re-suspension rates (mg/h) can be used to estimate the indoor sources of $PM_{2.5}$ in the sampled classrooms. The emission rate exceeded the re-suspension rate in 23 schools reflecting an indoor $PM_{2.5}$ contribution from both chalks and re-suspension of settled particles in those classrooms. The re-suspension rate exceeded the emission rate in 17 schools, indicating that indoor $PM_{2.5}$ was mostly generated from re-suspension of settled particles in those classrooms. As for indoor CO emissions, the results showed that no indoor emissions were encountered in certain classrooms (AS7, AS8, BS7, BS9, CS1, CS5, CS8, CS9, CS10, DS5, DS9 and DS10) and the presence of indoor CO at these schools can be attributed to the infiltration of outdoor CO. Some classrooms had high CO indoor emission rates compared to others such as AS2, AS3, BS2, BS8 and DS3 which is mainly due to indoor CO sources such as smoking next to classrooms.

Model limitations

The analysis of physical control parameters was based on assuming similar ventilation conditions in all classrooms with one opened window with an area of ~1.5 m^2 without considering other factors that may affect the AER estimation such as wind velocity, temperature and humidity (Adeniran et al, 2015). Moreover, some factors were missing while estimating the deposition rates such as type of surfaces, coagulation, and humidity level (He et al, 2005). Finally, the analysis was based on the maximum reachable re-suspension rates and not the real re-suspension rates.

5. Management Measures

The results reflect concerns about IAQ and potential exposure of vulnerable children in classrooms particularly to $PM_{2.5}$ caused by outdoor sources, usage of chalkboards, and/or re-suspension of settled particles by indoor activities. CO was also encountered in the indoor air, as a consequence of infiltration of outdoor CO or due to smoking or having gas stoves next to classrooms but at levels below health standards. Higher AERs were deemed appropriate in some classrooms with existing AER lower than ASHRAE recommended values, particularly where the outdoor air exhibited relatively better quality than the indoor air. In the setting of this study, specific non-costly environmental risk management measures can be readily implemented towards IAQ control as outlined in Table 6. At a more general level, an IAQ management framework is imperative to guide stakeholders and decision makers in formulating and implementing strategies to minimize potential exposure of children in the classroom, as well as teachers and staff to prevent potential forced absenteeism and lowered productivity and performance (Bernstein, 2009). In this context, the key drivers to achieve an effective management framework in schools include organization, communication, assessment, planning, implementation, and evaluation (EPA, 2015) with proper monitoring, reporting, corrective measures, and penalties under institutional, parental and community commitments to comply with health standards and control IAQ at schools. The effectiveness of IAQ management framework for schools requires financial, legislative, administrative, and technical commitments (SEI, 2004) and consider both indoor and outdoor air quality near schools due to interactions between them and the contribution of the latter to indoor problems.

Table 6. Specific risk factors and management measures
(European Commission, 2014; Stanke, 2002; WHO, 2004; Adams, 2009; CISCA, 2009)

Risk	Factor	Management control measures
Indoor air pollution	Chalkboard	Substitute chalkboards with whiteboards or clean chalkboards with a wet cloth that must be cleaned daily using hot water.
		Vacuum classrooms at the end of each day using high efficiency filter or wet steam.
		Clean classrooms regularly at the end of each school day using non-hazardous cleaning products while students are not present and while proper ventilation is ensured.
		Prohibit running inside classrooms to avoid re-suspension of settled particles while making students aware.
	Ventilation	Open windows/doors in order to provide fresh air from the outside during lessons, in case outdoor air is clean.
		Provide mechanical ventilation in case natural ventilation isn't possible because of weather conditions, outdoor noise, and outdoor pollution.
		Check regularly the mechanical ventilation system especially to make sure that infiltration of outdoor air is reduced, stable and adequate temperature and humidity are maintained and that indoor air pressure is maintained higher than outdoor pressure in order to prevent the infiltration of outdoor air.
		Change air filters present in the ventilation system in a regular way.
	Carpets	Clean carpets regularly using vacuum, especially to remove settled particles matters.
	Flooring	Use low emission flooring materials during the construction phase of a school.
		Use door and entrance mats to catch and reduce the pollutants that can be spread by foot traffic all over the school.
	Smoking	Prohibit Smoking must be prohibited in schools (also for teachers and staff).
	Classroom occupancy	Maintain occupancy less or equal to the 1 students/2m^2 limit recommended by ASHRAE
Outdoor air pollution		Locate schools away from pollution sources such as highways, industrial areas, waste disposal sites…etc.
		Prohibit the passage of vehicles near air intakes.
		Take into account weather conditions, outdoor activities and rush hours (if near high traffic areas) before applying natural ventilation.
		Dilute polluted outdoor air through mechanical ventilation before replacing indoor air by outdoor air.
		Planting Trees near schools

CONCLUSION

This study assessed indoor and outdoor air quality ($PM_{2.5}$ and CO) in 40 schools located in the Greater Beirut area and nearby rural areas. No significant difference was found between rural and urban areas, in terms of CO and $PM_{2.5}$ exposure. Also, no difference in air pollutants levels was identified between rural-private, rural-public, urban-private and urban public schools. The results showed that the AER had an effect on indoor air quality. For instance, in certain classrooms, an increase in the AERs, caused an increase in indoor $PM_{2.5}$ and CO levels when outdoor levels are relatively high. Significant correlation between indoor and outdoor pollutants was discerned at schools located near pollutants sources reflecting on the penetration and infiltration of outdoor pollutants to the inside. On the other hand, in certain cases, the low AER associated with inefficient ventilation, triggered high levels of indoor $PM_{2.5}$. In short, the major concern in schools was $PM_{2.5}$ at elevated concentrations because of outdoor sources (i.e. emissions from construction or industrial activities or vehicle-induced emissions), indoor sources such as usage of chalkboards and re-suspension of settled particles as ascertained by the analysis of the equivalent indoor generation and re-suspension rates. As for CO, all levels were below standards and indoor CO was mostly of outdoor origin, except in some schools, where indoor CO emission rates reflected the presence of indoor sources such as smoking near classrooms. Non-costly environmental risk management measures were defined alongside general guidelines for the development of a management framework towards controlling IAQ in schools.

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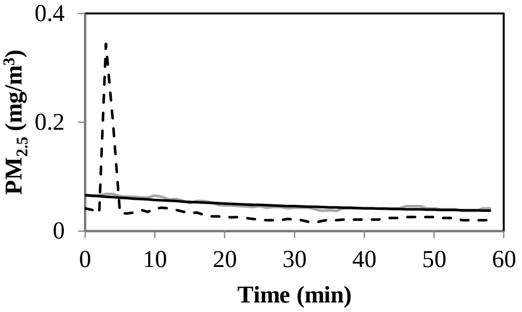
ANNEX A: Schools characteristics

Category	ID	Location	Date	Time	Surrounding	Weather	Temperature (^0C)	Area (m^2)	Students Number	Occupancy (m^2/person)	Board type
Rural-Public	AS1	Jal El dib	20,11,2014	09:53-10:53	Residential, low traffic density	Sunny	O: 17; I: 16	30	16	1.88	Chalkboard
	AS2	Mazraat Yachoue	12,11,2014	10:52-11:42	Residential, construction site, low traffic density, farm	Sunny	O: 19.3;I: 20	40	44	0.9	Chalkboard
	AS3	Choueifet	24,3,2015	10:00-11:00	Residential area, construction site, industry, trees, smoking area	Sunny Windy	O: 22; I: 22.3	16	25	0.64	Whiteboard
	AS4	Kfarchima	30,3,2015	09:45-10:45	Medium traffic density	Sunny	O: 21; I: 20.2	36	28	1.29	Whiteboard
	AS5	Damour	21,4,2015	11:54-12:50	Low traffic density, trees	Sunny	O: 22.2; I: 20	36	15	2.4	Chalkboard
	AS6	Beit Meri	28,4,2015	09:58 11:00	Inside a monastery, low traffic density, trees	Sunny	O: 22.2; I: 22.9	30	5	6	Chalkboard
	AS7	Baaklin	13,5,2015	10:05-11:05	Low traffic density, trees	Sunny low wind	O: 21.7; I: 21.1	56	30	1.86	Chalkboard
	AS8	Hemena	19,5,2015	12:21-13:21	Low traffic density, mechanic workshop, trees	Sunny windy	O: 24.9; I: 24.7	30	5	6	Chalkboard
	AS9	Achkout	1,6,2015	10:14-11:14	Residential, medium traffic density, cement industry	Sunny	O: 19.1; I: 19.4	30	10	3	Chalkboard
	AS10	Aley	4, 6,2015	10:30-11:30	Medium traffic density, gas station	Windy	O: 20.5; I: 20.8	57	10	5.7	Chalkboard
Rural-Private	BS1	Dik El Mehdi	28,11,2014	11:08-12:00	Very low traffic density, trees	Rainy	O: 18.1; I: 16.9	36	19	1.89	Chalkboard
	BS2	Baabda	7,11,2014	11:02-12:32	Low traffic density, construction site, power plant, trees	Sunny Windy	O: 16.5; I:17	56	32	1.75	Chalkboard
	BS3	Broumana	28,4,2015	12:20-13:30	Residential area, Medium traffic density, trees	Sunny	O: 23.9; I: 24.2	36	33	1.09	Chalkboard
	BS4	Damour	21,4, 2015	10.05-11:13	Medium traffic density, trees	Sunny	O: 22.2; I: 21.3	26	25	1.04	Chalkboard
	BS5	Baaklin	13,5, 2015	12:05-13:05	Medium traffic density, garage, parking, trees	Cloudy low wind	O: 20.3; I: 21.6	20	15	1.33	Whiteboard
	BS6	Bekfaya	14,5,2015	10:51-	Low traffic density, trees, bushes	Rainy	O: 18.8; I: 17.9	16	18	0.88	Whiteboard

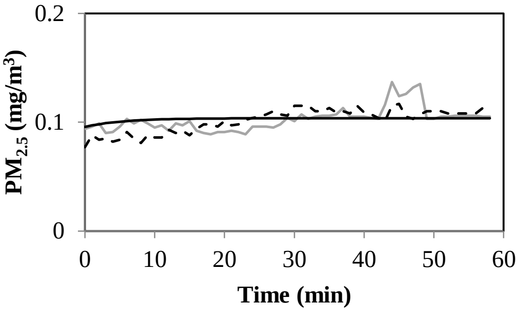
Category	ID	Location	Date	Time	Surrounding	Weather	Temperature (^0C)	Area (m^2)	Students Number	Occupancy (m^2/person)	Board type
				11:51		low wind					
	BS7	Hemena	19,5,2015	10:32-11:32	Low traffic density, parking, Trees	Sunny low wind	O:20.1; I: 20.4	20	16	1.25	Whiteboard
	BS8	Kfour	28,5,2015	10:03-11:03	Inside a monastery, Medium traffic density, Trees	Sunny windy	O: 20.3; I: 20.1	20	30	0.66	Whiteboard
	BS9	Adma	28,5,2015	11:58-12:58	Medium traffic density, Forest	Sunny	O: 21.5; I: 19.3	20	15	1.33	Whiteboard
	BS10	Faytroun	1,6, 2015	12:47-13:47	On a hill Parking	Sunny	O: 21; I: 19	30	10	3	Chalkboard
Urban-Public	CS1	Manara,	30,10,2014	10:13-11:06	Residential, high traffic, smoking area	Sunny	O: 18.6; I: 17	36	45	0.8	Chalkboard
	CS2	Zalka	11,112014	14:44-15:56	Residential, low traffic, construction, garage, smoking	Sunny windy	O: 22.9; I: 21.4	36	15	2.33	Chalkboard
	CS3	Ashrafieh	29,10,2014	11:45-12:45	Low traffic, construction	Sunny	O: 19.7; I: 19	42	31	1.35	Chalkboard
	CS4	Zidanieh	29,10,2014	13:52-14:32	High traffic	Sunny low wind	O: 19.1; I: 18.7	16	10	1.6	Chalkboard
	CS5	Dekwane	5,11,2014	12:38-13:32	Low traffic, Aluminum factory	Sunny	O: 20.1; I: 19.9	57	19	3	Chalkboard
	CS6	Verdun	5,2,2015	10:21-11:21	Highway, medium traffic, garage	Rainy	O: 19.4; I: 19.1	30	25	1.2	Chalkboard
	CS7	Ghobeiry	26,2,2015	10:21-11:21	Medium traffic, garage, electrical generators	Sunny	O: 18.4; I: 19	25	19	1.32	Whiteboard
	CS8	Bachoura	24,2,2015	09:23-10:29	Residential, medium traffic, Construction site, smoking	Sunny Windy	O: 17.3; I: 17	25	21	1.19	Chalkboard
	CS9	Ain Remane	11,3,2015	10:38-11:38	Residential, highway, high traffic, electrical generator	Sunny low wind	O: 21.4; I: 20.8	42	15	2.8	Chalkboard
	CS10	Bir Hassan	16,3,2015	11:35-12:30	Highway, medium traffic	Sunny little windy	O: 20.4; I: 20.8	20	15	1.33	Chalkboard

Category	ID	Location	Date	Time	Surrounding	Weather	Temperature (^0C)	Area (m^2)	Students Number	Occupancy (m^2/person)	Board type
Urban-Private	DS1	Ashrafieh	28,10,2014	10:03-10:25	Residential, low traffic, construction	Sunny	O: 22.2; I: 22.5	30	20	1.5	Chalkboard
	DS2	Hamra	27,10,2014	13:47-14:53	High traffic	Sunny	O: 24; I: 23.3	24	21	1.14	Chalkboard
	DS3	Msaytbe	17,2,2015	11:49-12:43	Residential, medium traffic, electrical generator	Sunny windy rainy	O: 18; I: 18.3	55	20	2.75	Whiteboard
	DS4	Mina El Hosn	4,3,2015	11:19-11:58	Low traffic, construction	Windy rainy	O: 21; I: 21.2	45	10	4.5	Whiteboard
	DS5	Ouzai	5,3,2015	09:49-10:59	Residential, medium traffic	Sunny windy	O: 18.3; I: 18.6	30	14	2.14	Whiteboard
	DS6	UNESCO	6,11,2015	10:00-10:52	Highway, high traffic, gas station	Sunny	O: 21; I: 21.3	25	22	1.13	Chalkboard
	DS7	Ain Remaneh	11,3,2015	13:00-13:45	Medium traffic	Sunny windy	O: 21; I: 20.5	35	20	1.75	Chalkboard
	DS8	Bir Hassan	16,3,2015	09:00-10:00	Medium traffic, trees, parking	Rainy low wind	O: 22.4; I: 22	20	23	0.86	Chalkboard
	DS9	Camp Chatila	18,3,2015	11:20-11:57	Low traffic, industries, construction, waste disposal	Sunny	O: 22; I: 22.3	16	29	0.55	Whiteboard
	DS10	Badaro	18,3,2015	09:59-11:00	Medium traffic, trees	Sunny	O: 20.1; I: 20.4	30	17	1.76	Whiteboard

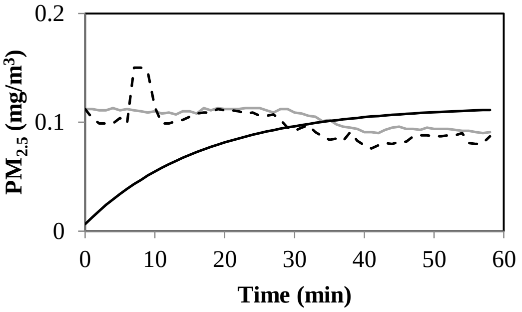
ANNEX B: Variation of measured and simulated indoor and outdoor indicators



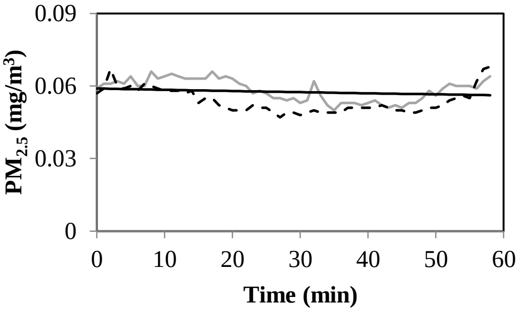
AS1



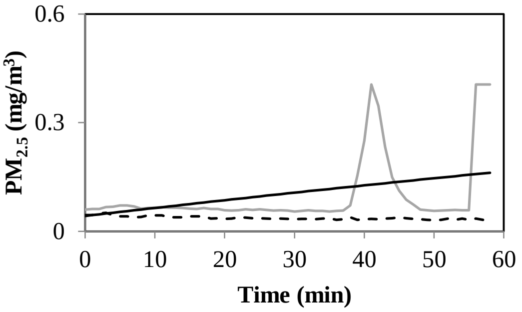
AS2



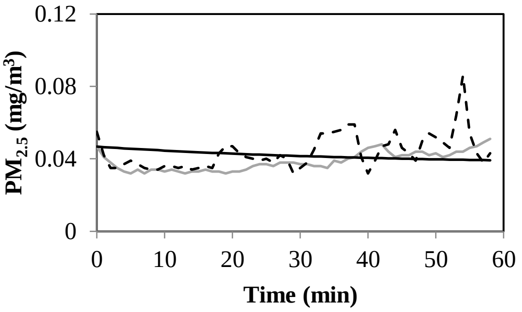
AS3



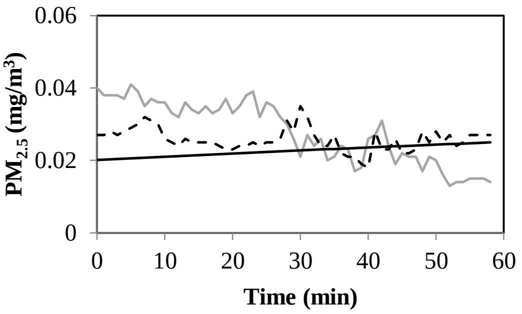
AS4



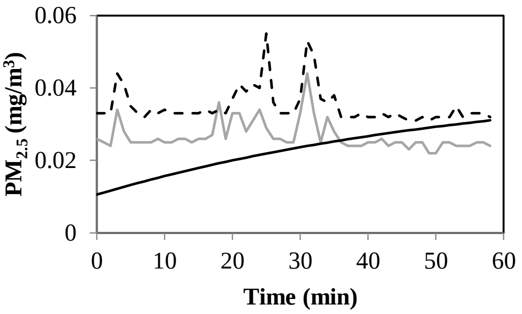
AS5



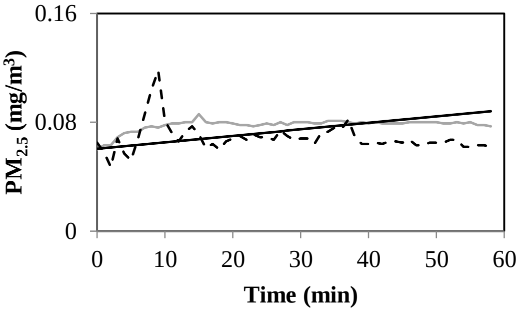
AS6



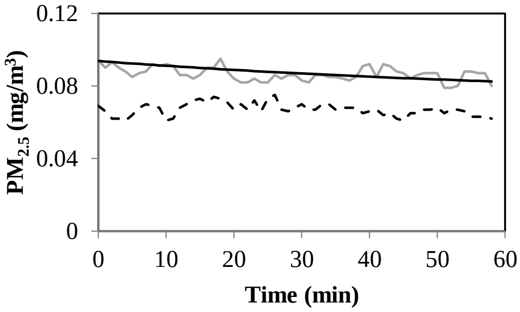
AS7



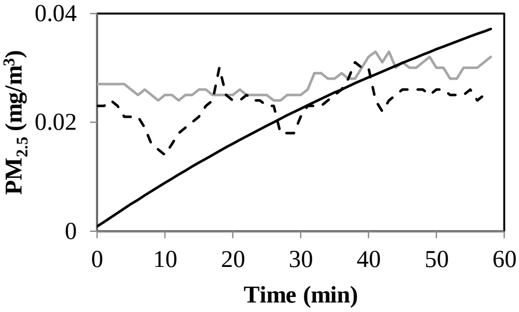
AS8



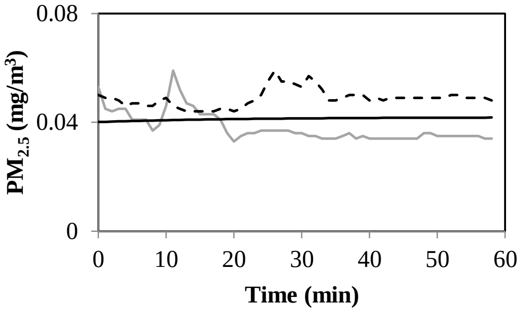
AS9



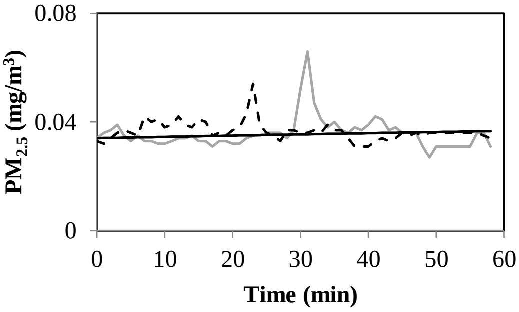
AS10



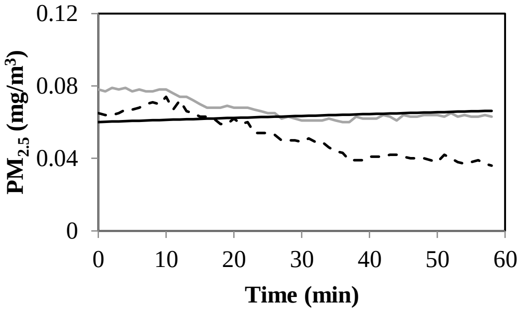
BS1



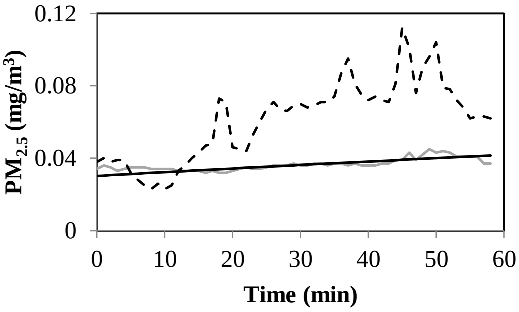
BS2



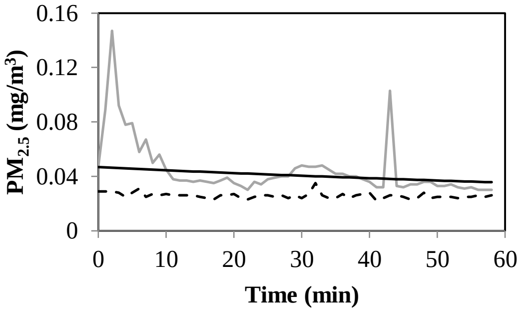
BS3



BS4



BS5



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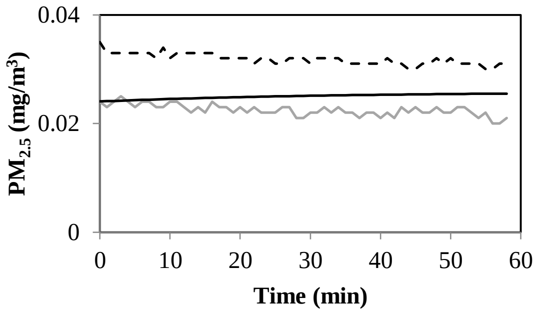
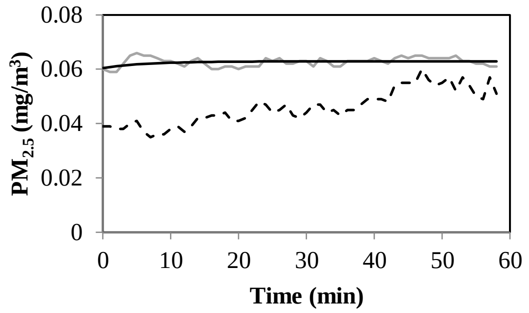


BS7



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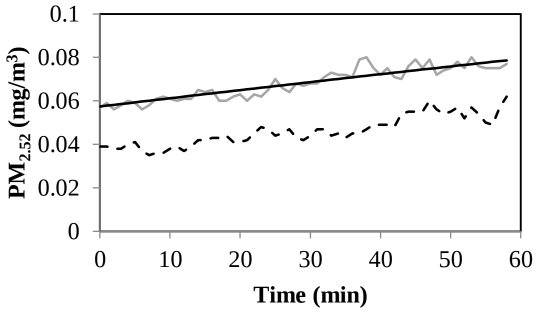
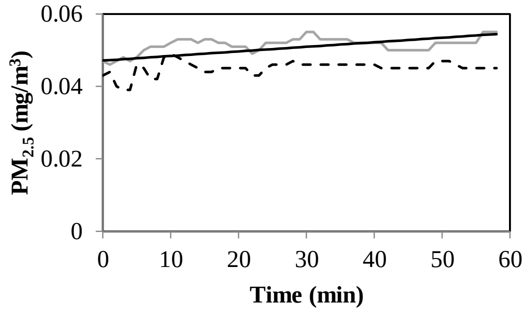
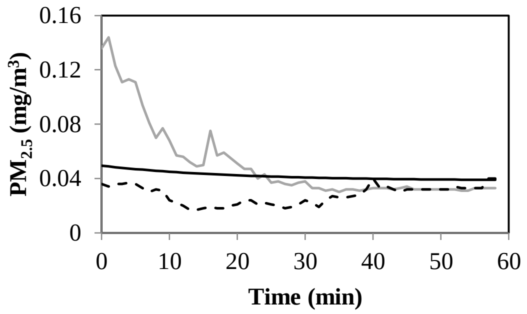


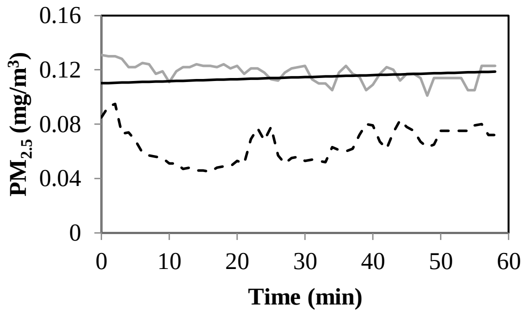
BS9



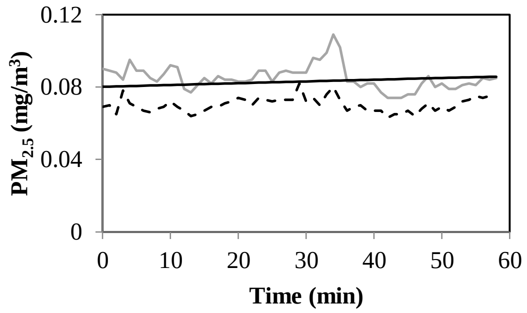
BS10



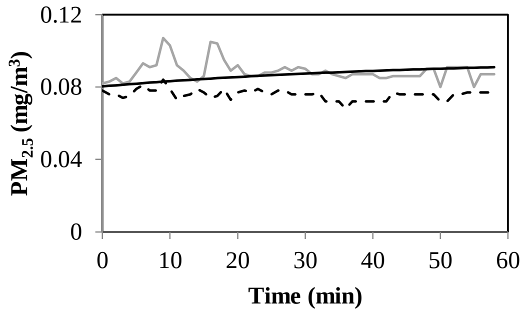
CS1



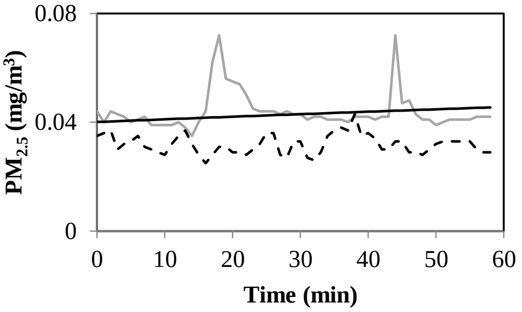
CS2



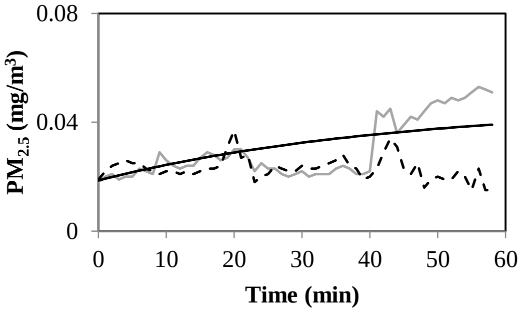
CS3



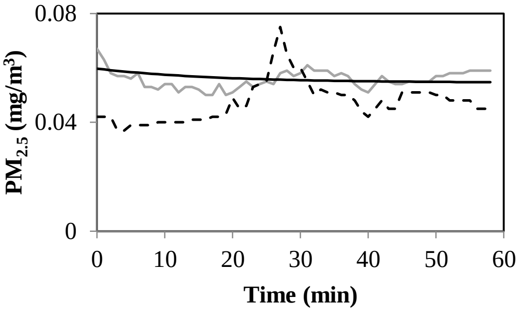
CS4



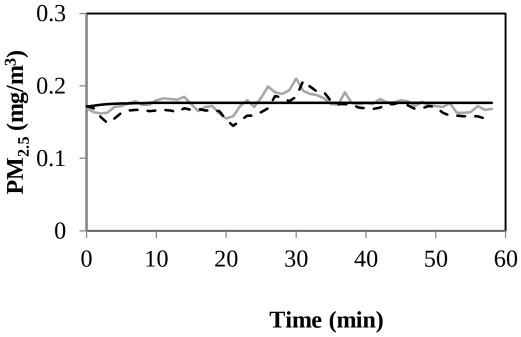
CS5



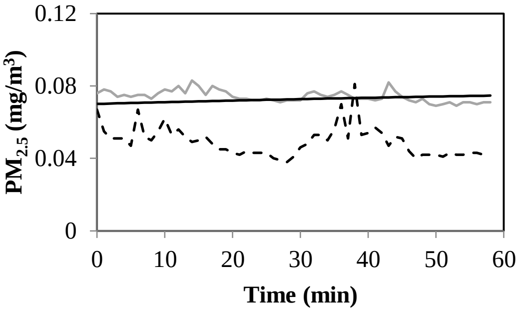
CS6



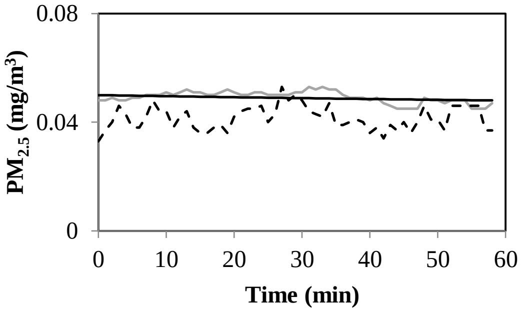
CS7



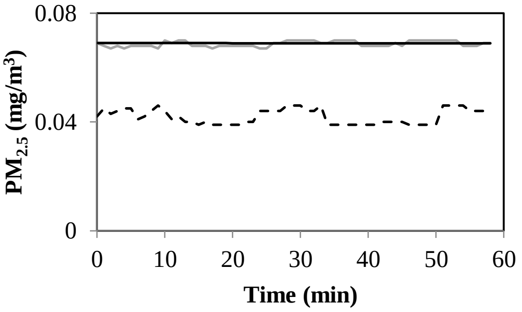
CS8



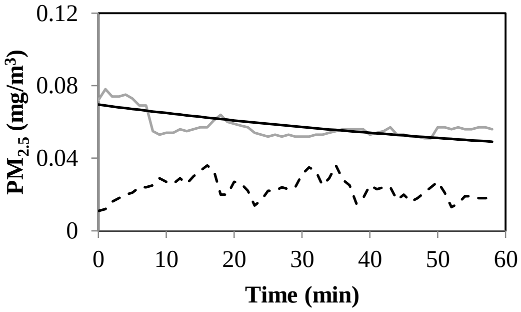
CS9



CS10



DS1



DS2

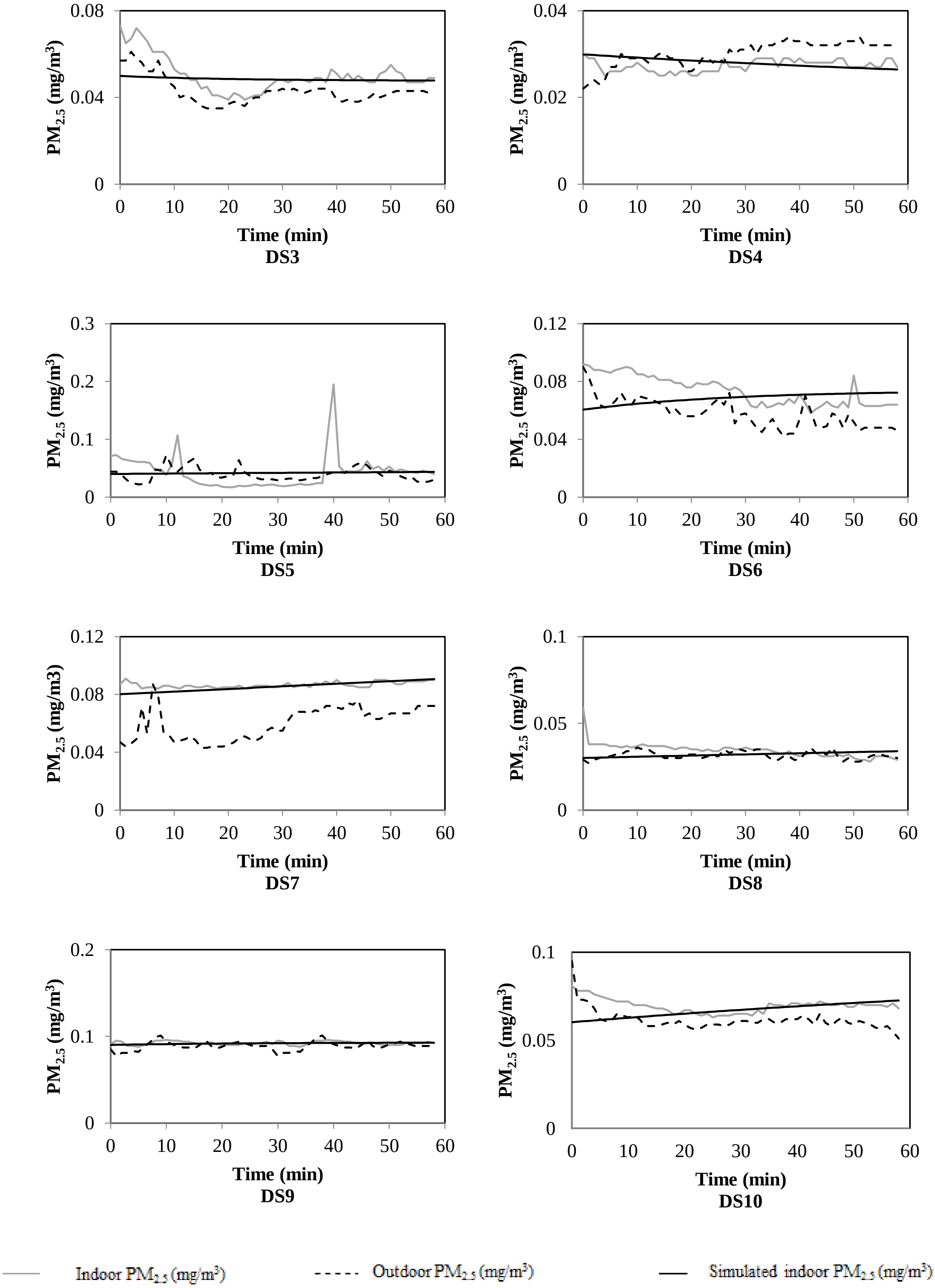
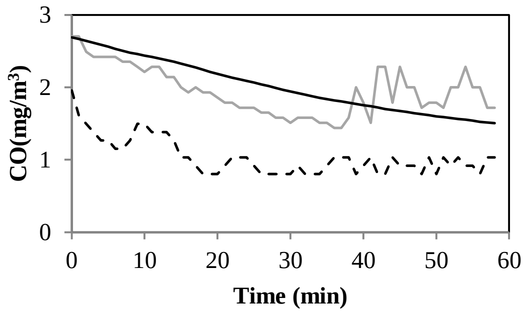


Figure B1. Variation of measured and simulated indoor $PM_{2.5}$ and measured outdoor $PM_{2.5}$



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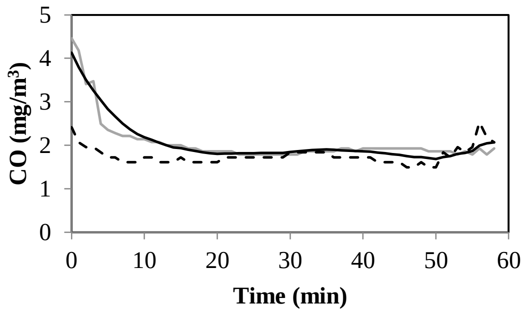

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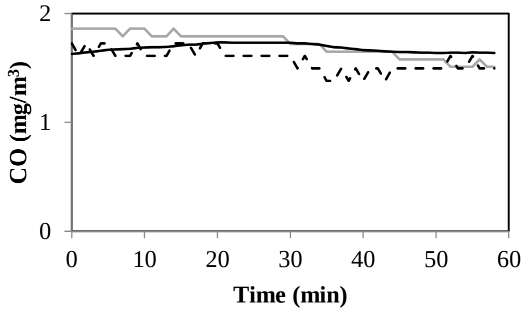

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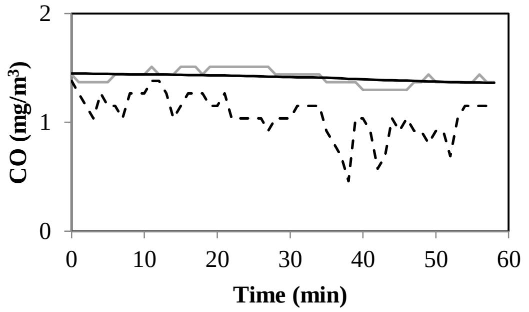

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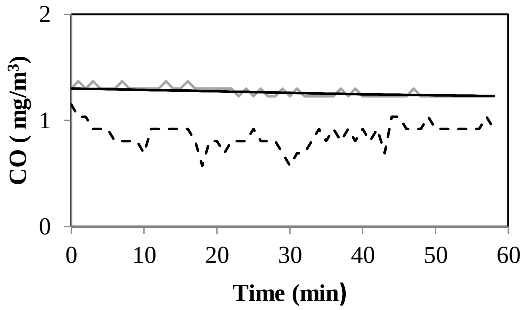

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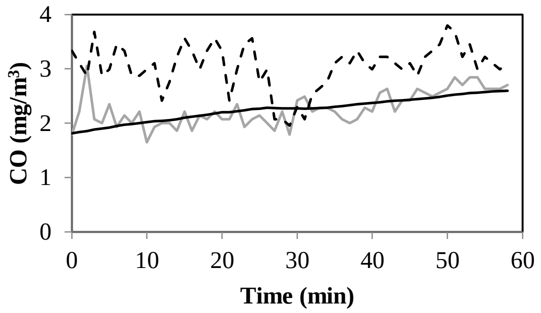

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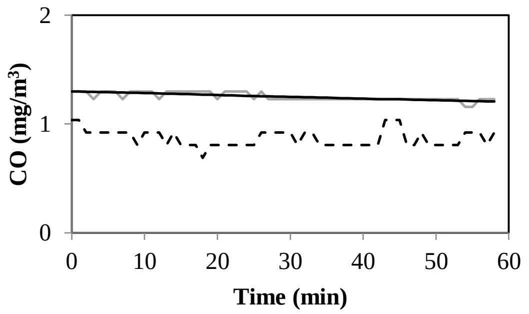

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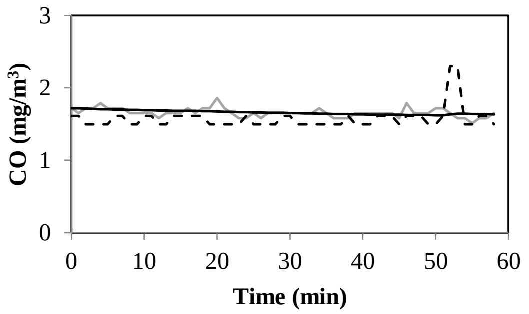

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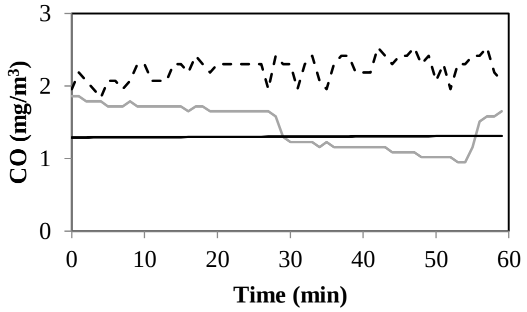

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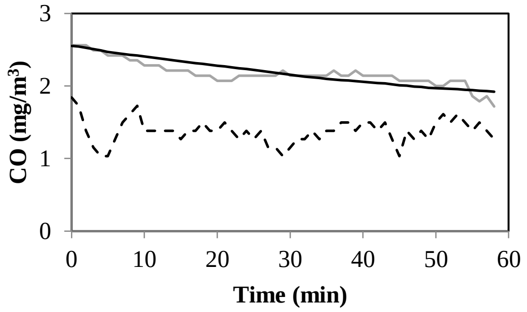

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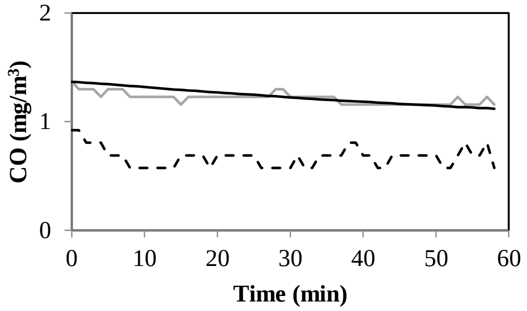

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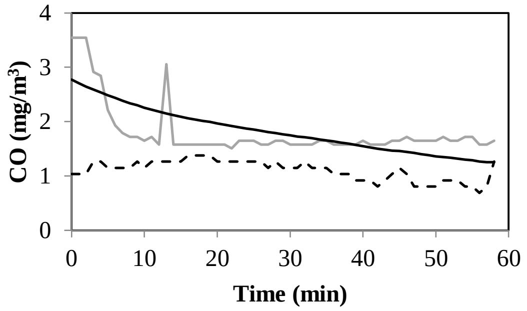

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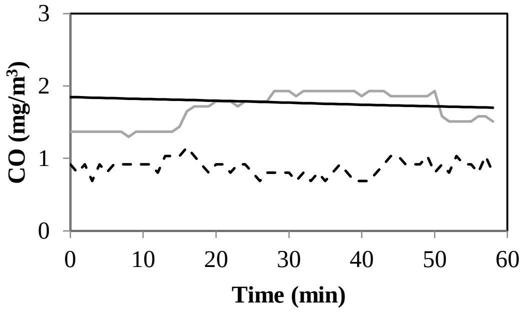

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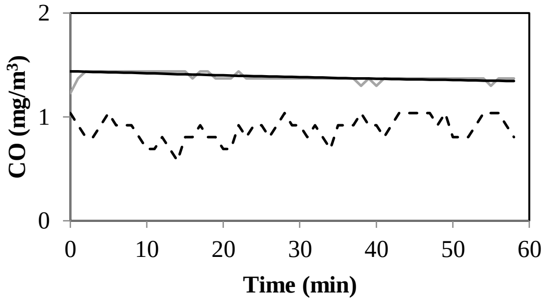

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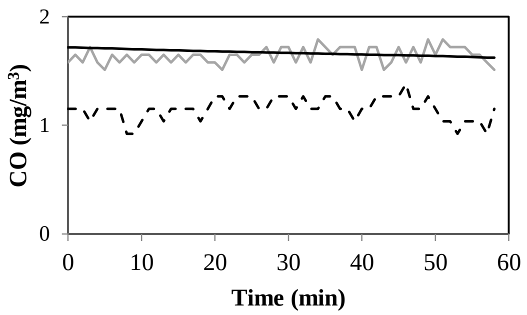

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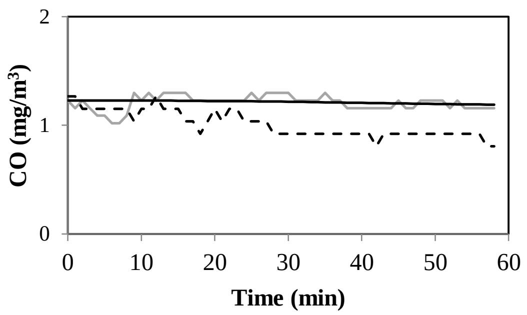

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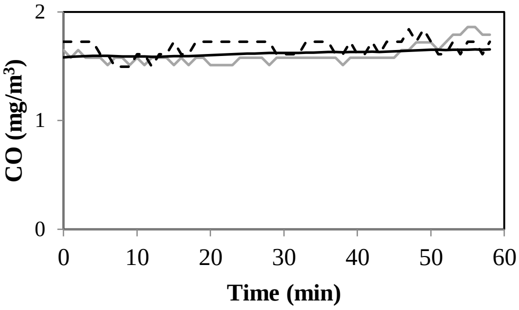

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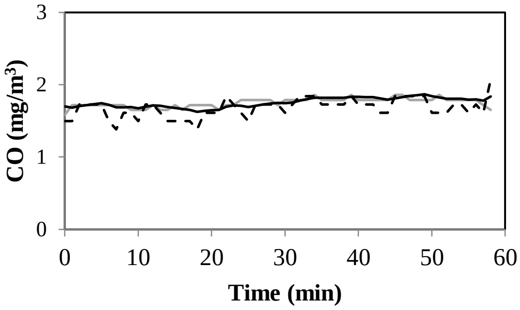

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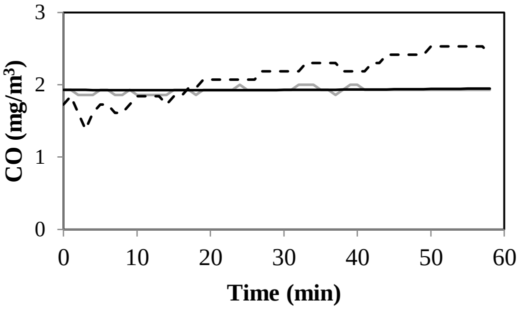

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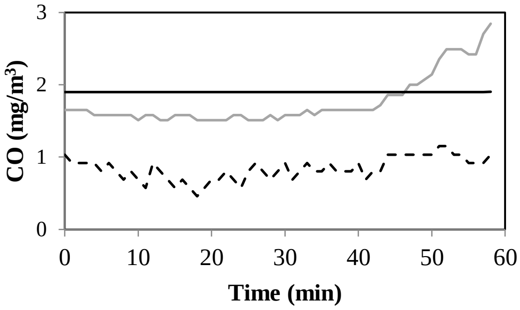

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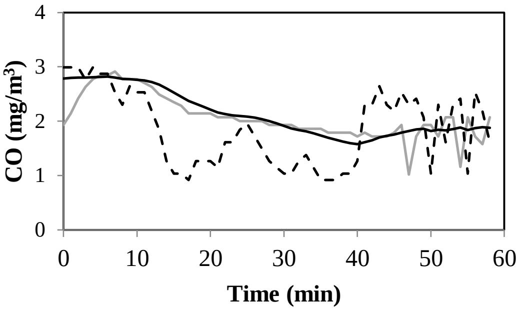

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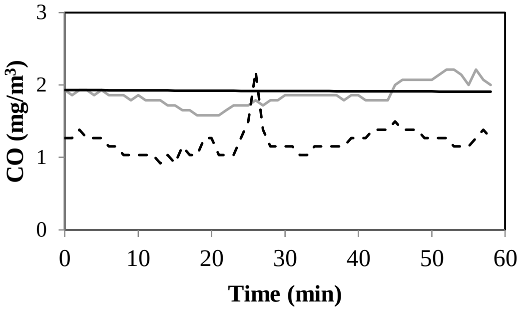

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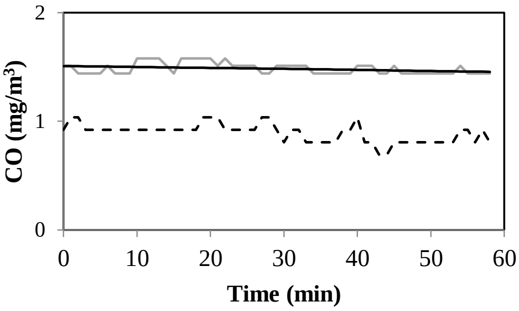

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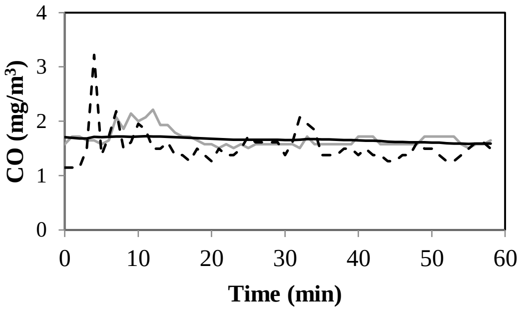

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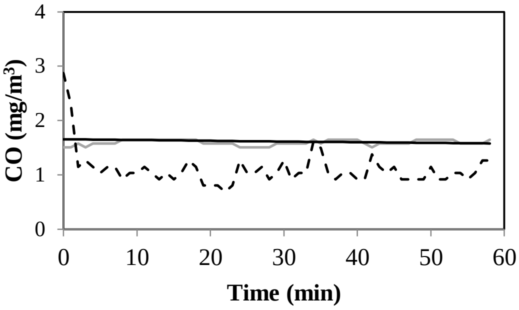

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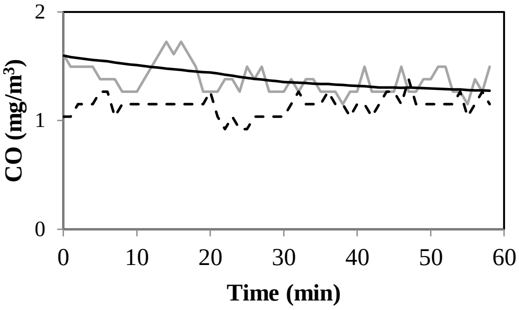

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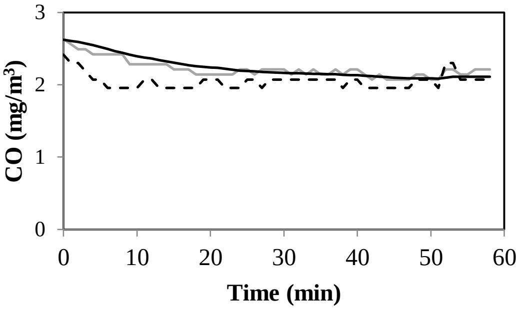

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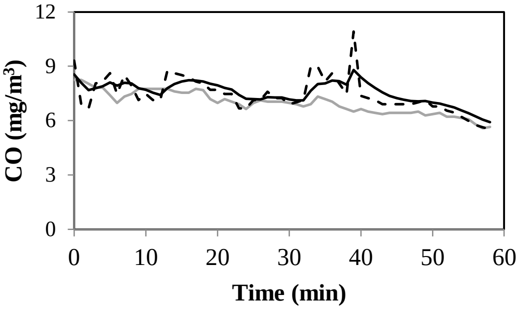

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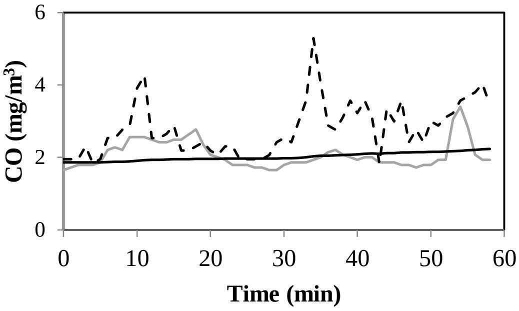

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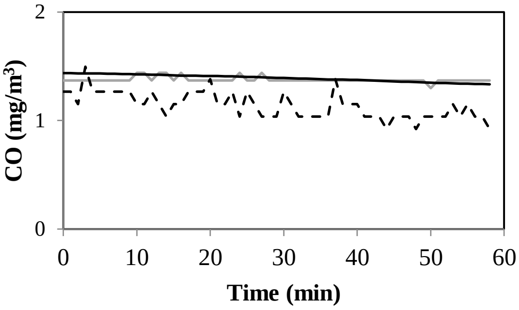

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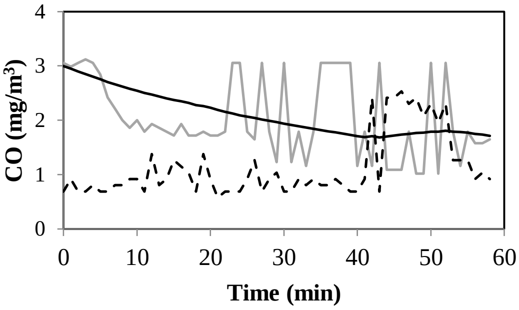

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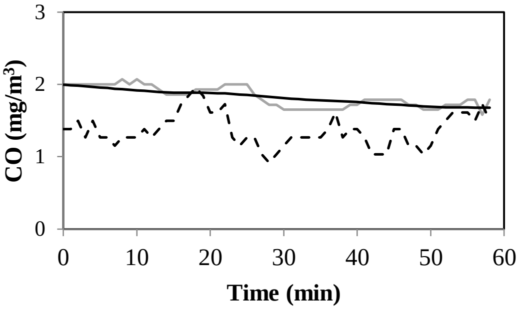

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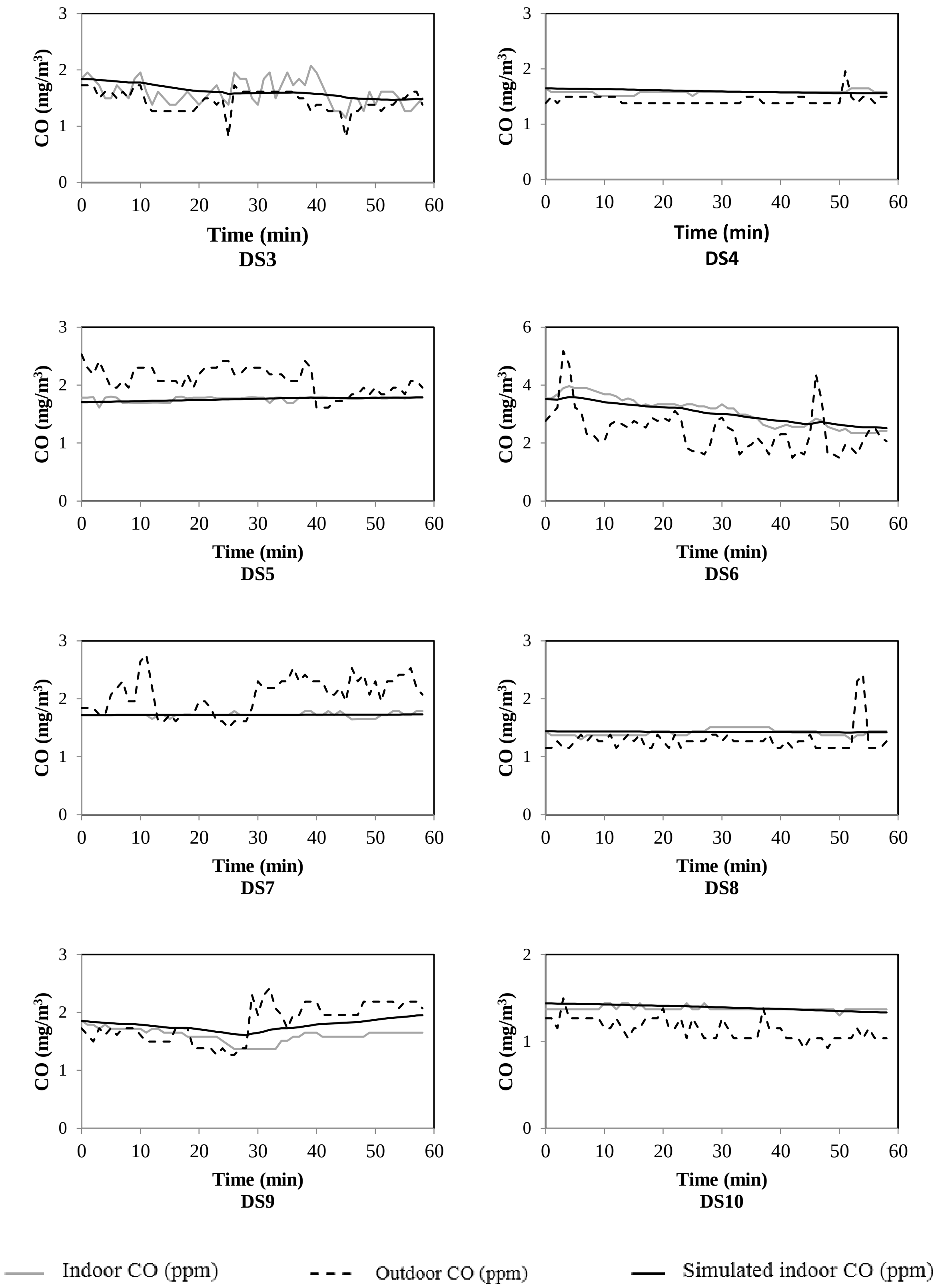

Figure B2: Variation of measured and simulated indoor CO, and measured outdoor CO