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Particulate Air Pollution at Schools: Indoor-Outdoor Relationship and Determinants of Indoor Concentrations

Mahmoud Mohammadyan[1], Ahmad Alizadeh-Larimi[2], Siavash Etemadinejad[1], Mohd Talib Latif[3,4], Behzad Heibati[5*], Kaan Yetilmezsoy[6], Sabah Ahmed Abdul-Wahab[7], Payam Dadvand[8,9,10]

[1] *Health Sciences Research Center, Faculty of Health, Mazandaran University of Medical Sciences, Sari, Iran*
[2] *Faculty of Health, Mazandaran University of Medical Sciences, Sari, Iran*
[3] *School of Environmental and Natural Resource Sciences, Faculty of Science and Technology, Universiti Kebangsaan Malaysia, 43600 Bangi, Selangor, Malaysia*
[4] *Institute for Environment and Development (LESTARI), Universiti Kebangsaan Malaysia, Selangor, Malaysia*
[5] *Health Sciences Research Center, Faculty of Health, Student Research Committee, Mazandaran University of Medical Sciences, Sari, Iran*
[6] *Department of Environmental Engineering, Faculty of Civil Engineering, Yildiz Technical University, Istanbul, Turkey*
[7] *Department of Mechanical and Industrial Engineering, College of Engineering, Sultan Qaboos University, Muscat 123, Sultanate of Oman*
[8] *ISGlobal, Centre for Research in Environmental Epidemiology (CREAL), Barcelona 08003, Spain*
[9] *Pompeu Fabra University, Barcelona 08003, Spain*
[10] *Ciber on Epidemiology and Public Health (CIBERESP), Madrid 28029, Spain*

ABSTRACT

This study aimed to assess the relationship between indoor and outdoor particulate air pollution at primary schools, and identify the determinants of indoor pollution concentrations. The study was conducted in six classrooms within six primary schools in Sari, Northern Iran. Indoor concentrations of particulate matter (PM) with an aerodynamic diameter of less than 10 µm (PM_{10}), 2.5 µm ($PM_{2.5}$), and 1 µm ($PM_{1.0}$) were assessed in classrooms, and outdoor concentrations of $PM_{2.5}$ on the school playgrounds were monitored simultaneously by using two real-time and portable dust monitors during autumn, winter, and spring, yielding 26 sampling days for each school in total. The highest outdoor and indoor $PM_{2.5}$ concentrations were found in winter and spring, respectively. The mean indoor $PM_{2.5}$ concentration (46.9 ± 32.9 µg m^{-3}) was higher than that measured outdoors (36.8 ± 33.2 µg m^{-3}). Indoor $PM_{2.5}$ and $PM_{1.0}$ were moderately correlated with outdoor $PM_{2.5}$ concentrations, which was the main determinant for all indoor particulate concentrations, however, a distinct pattern was observed for PM_{10} and $PM_{2.5}$ compared to $PM_{1.0}$. While meteorological variables (i.e., ambient temperature, relative humidity) could predict indoor PM_{10} and $PM_{2.5}$ concentrations, the total area of the windows and the number of students in a classroom were predictors for $PM_{1.0}$ levels. The findings of this study could inform policymakers in implementing evidence-based targeted interventions aimed at reducing air pollution in school settings.

Keywords: Classrooms; Particulate matter; $PM_{2.5}$; PM_{10}; Iran.

INTRODUCTION

Air pollution is a major environmental contributor to the global burden of disease and is associated with a wide range of adverse health outcomes (Lim *et al.*, 2012). More recently, an emerging body of evidence has associated exposure to air pollution in schools with adverse health impacts in schoolchildren, and potential effects of elevated air pollution levels include impaired neurodevelopment (Sunyer *et al.*, 2015), behavioral and emotional problems, and respiratory problems (Forns *et al.*, 2016). Children spend a large part of their time at school during hours when traffic pollution is at its daytime peak, and children are likely to be physically active at school (e.g., during sports classes, and break times), which can increase their inhaled doses of air pollution (McConnell *et al.*, 2010). Consequently, air pollution concentrations at schools can play a large role in the total dose of airborne contaminants to which children

[*] Corresponding author.
Tel.: +98 11 33543493; Fax: +98 11 33542473
E-mail address: b.heibati@gmail.com

are routinely exposed (Hubal *et al.*, 2010; Buonanno *et al.*, 2012a; Borgini *et al.*, 2015).

During the school time day, children spend much of their time in indoor classrooms, where the air pollution concentrations can be different from outdoor air pollution concentrations. The association between indoor and outdoor air pollution could, therefore be informative for epidemiological studies that mainly rely on estimates of ambient outdoor air pollution to assess total exposure to air pollution. Furthermore, characterizing the determinants of indoor concentrations of air pollutants are of importance for policymaking as it can inform policymakers' effective and targeted interventions. However, the available body of evidence on these determinants and the relation between indoor and outdoor air pollution in schools is still limited (Rivas *et al.*, 2014).

Air quality is deteriorating in several developing countries (Naerher *et al.*, 2000; Yetilmezsoy and Abdul-Wahab, 2012; Abdul-Wahab *et al.*, 2015). According to the World Health Organization (WHO) report published in 2014 (WHO, 2014), many cities in developing countries are currently in breach of WHO guidelines on air pollution levels. Although developing countries generally endure a greater burden of air pollution compared to developed countries (Wilkinson *et al.*, 2007), the available evidence on the scale and characteristics of this problem, particularly in relation to schools, is still limited. Therefore, the main objective of this study was to assess the relationship between indoor (i.e., within classrooms) and outdoor (i.e., playground) particulate air pollution concentrations at schools and to identify the main determinants of indoor air pollution concentrations in Sari, Northern Iran.

MATERIAL AND METHODS

Study Domain

The study was conducted in Sari, a city located in Northern Iran between the Alborz Mountains and the Caspian Sea (latitude 36°33′48″ north and longitude 53°3′36″ east). Sari is the capital of Mazandaran Province with approximately 300,000 people residing in town and 180,000 in the suburbs, for a population density of 135 people km^{-2}. Sari's average minimum and maximum temperatures in 2015 were –1°C and +32°C, respectively. In the same year, the total annual rainfall was 711.8 mm. There are two main industrial sources of air pollution in this area: a paper factory located in the north of the city, 10 km from the city center, and a gas and coal-fired power plant located about 20 km from the city center, south east of Sari. There is no fixed site station for air pollutant monitoring in Sari and, consequently, the general background concentrations of air pollutants are still unknown. In recent studies conducted in Sari, high levels of exposure to PM_{10} were found among taxi and bus drivers and also in shops located in Sari's city centre.

In consideration of the foregoing facts, exploring PM emissions in Sari's residential areas is vital to estimating environmental changes and evaluating future scenarios that include the impact of changing populations and new industrial developments.

Participating Schools

Indoor and outdoor air pollution evaluations were conducted in all six public primary schools located in Sari's city centre (Fig. 1). All schools were located in the vicinity of one of four major roads in the city center. School buildings were 10–40 years old, and each school had 8–11 classrooms accommodating between 27–32 pupils. The classrooms had similar designs with tile floors and total floor areas ranged from 24 m^2–34.2 m^2. No mechanical ventilation or air conditioning was in use during the monitoring periods. However, all classrooms were heated by a central heating system (radiators) in the cold months, with boilers located in separate rooms in schools' basements.

Air Pollution Sampling

Indoor PM concentrations were measured with an aerodynamic diameter less than 10 µm (PM_{10}), 2.5 µm ($PM_{2.5}$), and 1 µm ($PM_{1.0}$) and outdoor concentrations of $PM_{2.5}$. Real-time monitoring was carried out simultaneously for indoors and outdoors in each school. Monitoring was conducted over 26 days of the school year including 10 days in the autumn, 11 days in the winter and 5 days in the spring. Because of the logistical limitations (such as limitations in monitoring instruments, accessibility to classrooms, and limitations in the numbers of technicians), we monitored indoor and outdoor PM concentrations in one school at a time. The indoor monitor was placed in the center of the classroom (about 0.8 m above the floor), which corresponds to the breathing zone of the sitting schoolchildren, and the outdoor monitor in the school yard at least 1 m away from any obstacle and 1.5 m above the ground. Both indoor and outdoor monitoring started and ended with the regular school time (from 8:00 a.m. to 12:30 p.m.). The average monitoring time was 4.4 hours (range: 3.0–4.7 hours), depending on the duration of a particular class.

For outdoor measurements, a real-time monitor (MicroDust Pro, Casella, Bedford, UK) was used to measure outdoor $PM_{2.5}$ concentrations. This instrument was calibrated to a known reference dust standard, or the Casella Measurement. This calibration involved the collection of a gravimetric (filtered) sample of dust after it had passed through the probe optics. To measure the $PM_{2.5}$ concentrations, a size-selective sampling cyclone was used in combination with a particle size adaptor (Casella) and a 7 mm Poly Urethane Foam (PUF) filter (Casella) that was designed for $PM_{2.5}$-size fraction monitoring. An Apex Pro personal sampling pump (Casella) was used to provide continuous airflow through the gravimetric adaptor and a photodetector (Cassella). For gravimetric calibration, particles were then collected on a 37 mm teflon polytetrafluoroethylene (PTFE) filter (Gelman Science), measuring 2.0 µm and 37 mm, and was assembled in the cassette behind the air sample stream. For the gravimetric analysis a microbalance with a high resolution of one µg was used. To obtain mean $PM_{2.5}$ concentrations, we divided particle mass (in µg) obtained by weighing the filter, with the volume of sampled air drawn through the instrument (in m^3). The average $PM_{2.5}$ concentration obtained from the direct reading from the MicroDust Pro monitor could then be compared with the mean $PM_{2.5}$ concentrations

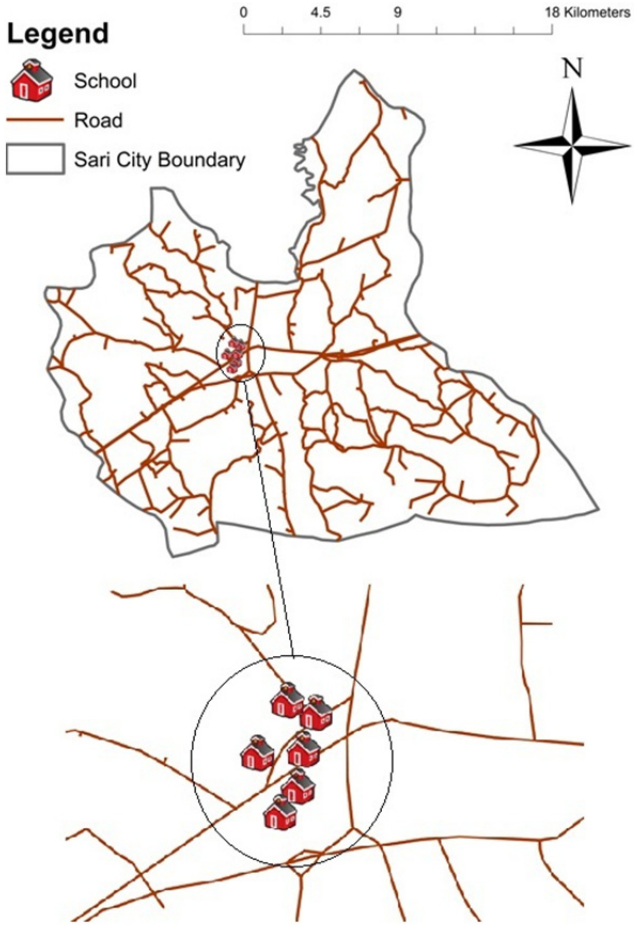

Fig. 1. Map of the study area showing the location of six public primary schools in Sari's city centre.

that were obtained by gravimetric measurements during the same continuous sampling and, if necessary, a correction factor could be applied. Finally, all real-time data were multiplied by the calibration factor obtained for instrument to calculate corrected particle concentrations.

For indoor measurements, a GRIMM dust monitor (GRIMM Aerosol Technik Gmbh & Co. KG, Ainrig, Germany, model 1.108) and a Microdust Pro monitor (Casella, Bedford, UK, model CEL-712) were used to measure $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations. These real-time and portable dust monitors were run side by side in six classrooms for 4.4 hours, one day a month over the study period. The correction factor for data displayed by the GRIMM dust monitor was then calculated as the average of the actual $PM_{2.5}$ concentrations obtained from the Microdust Pro monitor divided by the average $PM_{2.5}$ concentrations for the GRIMM monitor. All real-time data were multiplied by the correction factor to calculate the corrected concentrations. Mean correction factors of 1.03 and 1.14 were applied for the GRIMM and Microdust Pro monitor data, respectively.

Determinants of Indoor PM Concentrations

Data on potential determinants of indoor PM concentrations, including the number of students and the ventilation used in the classrooms, were obtained through a time-microenvironment-activity-diary via a questionnaire in one-minute time segments were recorded by a study technician who was present in the classroom through the entire sampling period. In the present study following information were recorded: (a) times and durations for which windows and doors were open; (b) the nature of students' activities; (c) the number of students in each classroom; (d) areas of the buildings in which classrooms were situated; (e) types of windows and doors, and heaters; and (f) types of mechanical ventilation systems. Since all schools in the study used central heating systems and none had air conditioners, these variables were not included as predictors in the multiple regression analysis performed within the scope of this study. The durations for which windows were open per hour were recorded by the study technician using a chronometer. The measured areas in m^2 of doors windows, and classrooms were obtained by a study technician using a retractable tape measure, as was the area occupied by doors and windows that were open to the outside during school hours. Information on daily wind speed, temperature and relative humidity (RH) were obtained from a nearby meteorological station.

Statistical Analyses

One-hour data on pollutant concentrations were used as the unit of analyses. Spearman's rank correlation coefficient (named after Charles Spearman, and often denoted by the Greek letter ρ (rho) or r_S, a non-parametric measure of correlation) was used to test the relationship between outdoor $PM_{2.5}$ and indoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations. It assesses how well an arbitrary monotonic function could describe the relationship between two variables, without making any assumptions about the frequency distribution of the variables. In other words, it is a non-parametric measure of the strength and direction of association that exists between two variables measured on at least an ordinal scale.

Spearman's rank correlation coefficient is calculated as follows (Spellerberg, 2005):

$$\rho = r_S = 1 - \frac{6\sum_{i=1}^{n} d_i^2}{n(n^2 - 1)} \quad (1)$$

where ρ (–1 to +1) is the Spearman's rank correlation coefficient, d_i is the difference between the two ranks of each ith observation, n is the total number of species in the paired comparison.

Mann-Whitney *U* test (named after Henry Berthold Mann and Donald Ramson Whitney, a non-parametric test that is used to compare two population means that come from the same population, and it is also used to test whether two population means are equal or not) was used to compare indoor and outdoor PM concentrations. All measured data were log-transformed to obtain a normal distribution. A stepwise multiple regression model was employed with indoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations as dependent variables (one at a time) and outdoor $PM_{2.5}$, meteorological variables, and class characteristics as independent variables. The stepwise criterion *Probability-of-F-to-enter* ≤ 0.05 or PIN(0.05) was used to enter a variable into the model, and the condition *Probability-of-F-to-remove* ≥ 0.10 or POUT(0.10) was used to remove a variable from the model. It is noted that the *Probability-of-F-to-enter* (or PIN) and the *Probability-of-F-to-remove* (or POUT) are two statistics that can be used as threshold values (the maximum acceptable significance levels), both for adding or removing variables from the model, respectively. For the *Probability-of-F-to-enter*, if the computed significance level (probability) is lower than the entered value, the variable is added, otherwise it is not. For the *Probability-of-F-to-remove*, if the computed significance level (probability) is higher than the entered value, the variable is removed (Huizingh, 2007). Statistical Package for the Social Sciences (SPSS) Version 19 (IBM Corp., Chicago, IL, USA) was used to perform these analyses.

RESULTS

Description of PM Concentrations and Classroom Characteristics

In total, 136 one-hour indoor and outdoor PM concentration readings were obtained from the participating schools during one school year. Table 1 shows descriptive statistics of the outdoor $PM_{2.5}$ and indoor $PM_{1.0}$, $PM_{2.5}$ and PM_{10} concentrations. The mean indoor $PM_{2.5}$ concentrations (46.9 ± 32.9 µg m^{-3}) were higher (Mann-Whitney U test, p = 0.02) than the mean of outdoor $PM_{2.5}$ concentrations (36.8 ± 33.2 µg m^{-3}).

Table 2 describes characteristics of classrooms included in this study. The average measured classroom and door areas were about 29.8 m^2 and 1.6 m^2, respectively. The measured areas for windows and corridors, which exposed to outdoor and indoor atmosphere, were approximately 3.6 m^2, 0.5 m^2, and 0.63 m^2, respectively. The number of students in the classrooms during the monitoring periods ranged between 14–37. Similarly, Guo *et al.* (2010) studied particle and $PM_{2.5}$ concentration in a classroom with a measured area of 50 m^2 with 50 students. The mean reported ambient temperature, RH, and wind speed were 11.4°C, 77.8% and 2.96 m s^{-1}.

Table 1. Descriptive statistics of outdoor $PM_{2.5}$ and indoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations in classrooms.

Concentration (µg m^{-3})	*n*	Mean (µg m^{-3})	Range	25%	50%	75%
Outdoor $PM_{2.5}$	136	36.8	0.0–418.0	5.9	18.1	43.1
Indoor $PM_{1.0}$	136	17.9	3.1–83.7	8.7	13.6	24.3
Indoor $PM_{2.5}$	136	46.9	10.2–251.8	25.5	40.4	59.7
Indoor PM_{10}	136	397.2	117.0–1606.5	79.7	323.9	511.0

Table 2. Descriptive statistics of the environmental air pollution related variables in schools.

Variable	Mean	SD[a]	Minimum	Maximum
Classroom's area (m^2)	29.8	4.5	24.0	34.2
Door area (m^2)	1.6	0.2	1.30	2.0
Windows' area (m^2)	3.6	1.0	2.0	4.5
Corridor to outdoor (m^2)	0.5	1.11	0.0	4.3
Corridor to indoor (m^2)	0.63	0.54	0.0	2.0
Number of students	30	5.0	14	37
Ambient temperature (°C)	11.8	7.3	2.7	26.0
Ambient RH (%)	77.8	8.6	58.0	94.0
Ambient wind speed (m s^{-1})	3.0	2.2	0.0	10.0

[a] Standard deviation.

Relationship between Indoor and Outdoor Concentrations

As presented in Table 3, the Spearman's rank correlation coefficient (ρ) between outdoor $PM_{2.5}$ and indoor $PM_{1.0}$, $PM_{2.5}$, and PM_{10} concentrations ranged from 0.13 for PM_{10} to 0.60 for $PM_{1.0}$. There was a moderate to strong correlation ($p \leq 0.01$) between indoor PM levels with Spearman's correlation coefficients ranging from 0.37 between $PM_{1.0}$ and PM_{10} to 0.82 between $PM_{2.5}$ and $PM_{1.0}$. There was also a moderate significant correlation ($p < 0.01$) between indoor and outdoor $PM_{2.5}$ concentrations. Higher relationship between outdoor $PM_{2.5}$ and $PM_{1.0}$ was due to penetration of fine particles from outdoor to the classrooms through openings. However, lower correlation coeficient between outdoor $PM_{2.5}$ and PM_{10} could be explained by indoor source of coarse fraction of PM because of the resuspension of particles during individuals activities in the classroom. A lower correlation between indoor fine and coarse fractions of PM could be also explain by indoor activities that increase coarse fraction of PM.

Determinants of Indoor PM Concentrations

A multiple regression analysis showed that indoor $PM_{2.5}$ concentrations were best predicted by outdoor $PM_{2.5}$ concentrations and ambient temperature (Table 4). These two variables could predict about one-fourth ($R^2 = 0.24$) of the variation in indoor $PM_{2.5}$ concentrations. Other environmental variables had no significant effect on indoor $PM_{2.5}$ concentrations. Ambient temperature and RH, and outdoor $PM_{2.5}$ concentrations were the strongest predictors for indoor PM_{10} concentrations (Table 4). These three variables could predict 23% ($R^2 = 0.23$) of the variation in indoor PM_{10} concentrations. Indoor $PM_{1.0}$ concentrations were best predicted by outdoor $PM_{2.5}$ level, measured window area, and the number of students in the classroom (Table 4). These variables could predict 38% ($R^2 = 0.38$) of the variation in indoor $PM_{1.0}$ concentrations. The result of the multiple regression model showed that these variables did not predict a high fraction of indoor PM concentrations. This was mainly due to different indoor activities of children. Moreover, it could also attributed to the fact that temporal variations in all of the PM fractions in classrooms were very high, and did not follow the outdoor PM concentrations and other air pollution related variables.

DISCUSSION

We evaluated the relationship between indoor and outdoor particulate pollution and determinants of the indoor particulate air pollution at six schools across Sari, Northern Iran, based on simultaneous measurements of indoor and outdoor particulate pollution during different seasons over a school year. We observed weak to moderate correlations between outdoor $PM_{2.5}$ and indoor PM concentrations and moderate to strong correlations between indoor PM

Table 3. Spearman's correlation coefficient (ρ) between indoor PM_{10}, $PM_{2.5}$, and $PM_{1.0}$ concentrations and outdoor $PM_{2.5}$ concentration.

Particulate matter (PM)	PM_{10}	$PM_{2.5}$ (indoor)	$PM_{1.0}$	$PM_{2.5}$ (outdoor)
PM_{10} (indoor)	1.00			
$PM_{2.5}$ (indoor)	0.77*	1.00		
$PM_{1.0}$ (indoor)	0.37*	0.82*	1.00	
$PM_{2.5}$ (outdoor)	0.13	0.48*	0.60*	1.00

* *p*-value < 0.01.

Table 4. Multiple regression results of the best-fit models for indoor $PM_{2.5}$, PM_{10} and $PM_{1.0}$ concentrations predicted by outdoor $PM_{2.5}$ concentrations (both log-transformed) and environmental characteristics.

Models	Unstandardized coefficients		Standardized coefficients	*t*-ratio	*p*-value[b]
	B	*SE*[a]	*β*		
Indoor $PM_{2.5}$					
Constant	1.45	0.04		32.69	
Outdoor $PM_{2.5}$	0.20	0.03	0.525	6.36	0.00
Temperature	–0.007	0.003	–0.203	–2.46	0.01
Indoor PM_{10}					
Constant	3.16	0.19		16.95	0.00
Outdoor $PM_{2.5}$	–0.02	0.003	–0.51	–5.70	0.00
Temperature	0.11	0.028	0.33	3.95	0.00
Relative humidty	–0.007	0.002	–0.27	–3.21	0.00
Indoor $PM_{1.0}$					
Constant	0.80	0.16		4.99	0.00
Outdoor $PM_{2.5}$	0.23	0.03	0.52	7.62	0.00
Windows' area	–0.07	0.02	–0.23	–3.30	0.00
Number of student	0.01	0.004	0.18	2.67	0.00

[a] Standard error.

[b] *p*-values < 0.01 were considered to be significant.

concentrations. $PM_{2.5}$ concentration was the main determinant for indoor different sizes particulate concentrations.

The mean outdoor $PM_{2.5}$ levels in the study schools was slightly higher than the 24-hour $PM_{2.5}$ standards (35 µg m^{-3}) recommended by the United States Environmental Protection Agency (US EPA, 2006). The mean indoor $PM_{2.5}$ and PM_{10} concentrations were also higher than the EPA's 24-hour standards (US EPA, 2006). The observed indoor $PM_{2.5}$ concentration (47 µg m^{-3}) was comparable to the 42 µg m^{-3} indoor $PM_{2.5}$ concentration reported for classrooms in Tehran, Iran. Similar studies conducted in Barcelona, Spain and Stockholm, Sweden, have found considerably lower indoor $PM_{2.5}$ concentrations in classrooms (16.3 µg m^{-3} and 8.3 µg m^{-3}), respectively.

Wichmann *et al.* (2010) studied indoor and outdoor $PM_{2.5}$ concentrations in 18 homes, six schools and 10 daycares in Stockholm, Sweden, and concluded that the median indoor $PM_{2.5}$ concentration was lower than outdoor levels. Rovelli *et al.* (2014) measured $PM_{2.5}$ and PM_{10} in seven schools in Milan, Italy, and concluded that, in general, the mean $PM_{2.5}$ indoor concentrations were lower than the average outdoor $PM_{2.5}$ levels, with indoor/outdoor (I/O) ratios being generally < 1. Rivas *et al.* (2014) studied indoor and outdoor air quality in 36 schools in Barcelona, Spain, and concluded that indoor mean $PM_{2.5}$ concentrations were higher than urban background levels. In the present study, mean indoor $PM_{2.5}$ levels were higher than the mean outdoor $PM_{2.5}$ concentrations. The use of chalk on blackboards and the lack of air conditioning systems in our participating schools might explain, at least in part, the higher indoor PM concentrations observed in this study. Thus, it is noted that students and teaching activities in the classroom may cause the higher PM concentrations in classroom than those in outdoor environment. In comparison, the use of filtration systems at participating schools in the Stockholm study might explain lower indoor $PM_{2.5}$ levels in those schools.

There were moderate correlations between indoor $PM_{1.0}$ and outdoor $PM_{2.5}$ concentrations ($\rho = 0.60$, $p < 0.01$), and indoor $PM_{2.5}$ and outdoor $PM_{2.5}$ concentrations ($\rho = 0.48$, $p < 0.01$). However, outdoor $PM_{2.5}$ concentrations had no significant relationship with indoor PM_{10} concentrations. Different sources of coarse (PM_{10}) and fine particles ($PM_{2.5}$) are the main reason of the poor relationship between PM_{10} and $PM_{2.5}$. Small particles also can be emitted to indoor environment due to other sources such from industrial and vehicular emissions. Resuspension mechanism of particle with different size due to student activities will determine the variability of particle exist in indoor air. Coarse particle is more prone to exist in short time compare to fine particles which are able to float within longer period. In line with findings of the present study, Hassanvand *et al.* (2014) reported a significant relationship between outdoor $PM_{2.5}$ and indoor $PM_{2.5}$ and $PM_{1.0}$ concentrations in a school dormitory and a retirement home in Tehran, Iran in 2012–2013. Wichmann *et al.* (2010) also found a significant association between indoor and outdoor $PM_{2.5}$ concentrations in classrooms located in Stockholm's city center.

Outdoor $PM_{2.5}$ level was the only determinant among our studied factors that remained a predictor in the final best-fit model for all three indoor particulate pollutants. It should be noted that a distinct pattern was observed for the rest of the determinants. For PM_{10} and $PM_{2.5}$ concentrations meteorological factors including ambient temperature and RH were the main predictors. On the other hand, the windows' measured area and the number of students in the classroom were predictors for $PM_{1.0}$ in the final model. It was observed that ambient temperature during the monitoring period had an inverse association with indoor $PM_{2.5}$ and PM_{10} particle concentrations. One explanation could be that in cold conditions, the windows were closed, therefore, the presence of indoor sources and activities/movements of the occupants could generate higher indoor $PM_{2.5}$ and PM_{10} concentrations. Relative humidity has also an inverse effect on indoor PM_{10} levels. Higher humidity in wet seasons may cause lower level of resuspension of coarse fraction of PM and therefore, lower indoor PM_{10} concentrations.

The study showed that number of students did not affect indoor PM_{10} and $PM_{2.5}$, but had a weak effect of indoor $PM_{1.0}$ (see Table 4). The main reason of high concentration of $PM_{1.0}$ in classrooms was resuspension of of PM due to the students' movements. Buonanno *et al.* (2012b) characterized there suspension of particles in school gyms and concluded that student activity was the main predictor of particle resuspension and among the various PM fractions, coarse particles ($PM_{2.5}$ and PM_{10}) were found to be the most relevant. Guo *et al.* (2010) did not find any influence on indoor $PM_{2.5}$ concentrations of the number of students in the classroom, which is consistent with our findings. The observed impact of the measured window area on indoor $PM_{1.0}$ concentrations is in line with findings by Zwozdziak *et al.* (2015), which showed that indoor $PM_{1.0}$ concentrations at schools were mainly influenced by the infiltration of ambient particles, and the classrooms' measured windows area showed a negative association with indoor $PM_{1.0}$ concentrations.

Finally, it should be noted that the present study faced a number of limitations. We used different instruments for measuring indoor and outdoor PM concentrations which might have affected the present comparison of indoor and outdoor $PM_{2.5}$ concentrations. However, in this study, we applied correction factors by running these two monitors side by side in order to obtain comparable measurements. Because of logistic limitations, we could not obtain measurements simultaneously in all schools.

CONCLUSIONS

In this research, we measured the indoor and outdoor concentrations of particulate air pollution in six schools in Sari, Northern Iran, to evaluate the association between the indoor and outdoor PM levels and identify the predictors of the indoor levels. Indoor $PM_{2.5}$ concentrations were higher than outdoor $PM_{2.5}$ levels. We observed weak to moderate correlations ($\rho = 0.13$–0.60) between outdoor $PM_{2.5}$ and indoor PM concentrations. Outdoor $PM_{2.5}$ was the main predictor for all indoor particulate pollutants. Meteorological variables were also among the predictors for indoor $PM_{2.5}$ and PM_{10} concentrations but not for indoor $PM_{1.0}$ concentrations.

On the other hand, windows' measured area and the number of students in a classroom predicted indoor $PM_{1.0}$ concentrations but not indoor PM_{10} or $PM_{2.5}$ concentrations. The observed moderate correlation between indoor and outdoor $PM_{2.5}$ levels have implications for epidemiological studies of the health effects of school air pollution that, to date, have mainly relied on measurements of outdoor levels.

The findings of this study indicated that some specific control measures, such as installation of ventilation or heating systems in the classroom, decreasing the number of students or windows areas in one classroom, may need to be considered to control PM concentrations in classrooms. Future studies are required to replicate the reported findings in other settings while characterizing source/composition of particulate air pollution and including other air pollutants such as nitric oxides, ozone, and volatile organic compounds (VOCs) in their analyses. Seasonal and temporal variations of particles in the classrooms also need to be considered to investigate the influence of background activities and meteorological factors on the variation of indoor dust. Since that was beyond the scope of the present study, this has been left for future studies.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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