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ASSESSMENT OF INDOOR AND OUTDOOR PARTICULATE MATTERS IN RESIDENTIAL AREAS: THE EFFECTS OF CLIMATIC CONDITIONS AND BUILDING CHARACTERISTICS

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Abstract

The aim of this study was to assess the indoor and outdoor particulate matters in residential areas, and to evaluate the effects of building characteristics and climatic conditions on indoor particle concentrations. The concentration of particles was measured simultaneously indoor and outdoor air during four seasons. Information on climatic conditions and building characteristics was collected through questionnaires during the sampling period. Linear regression models were adopted for determining the relationship between the dependent variable of I/O ratio and environmental factors. The I/O ratios of PM_1, $PM_{2.5}$, PM_4, PM_7, and PM_{10} were 0.67, 0.64, 0.61, 0.55, and 0.52, respectively. Moreover, the concentration of PM in the indoor air of the buildings were considerably lower than those of the outdoors ($p<0.05$). The results also suggest the ventilation mode and outside temperature had the most important role in the entrance of particles into the indoor environment.

Keywords: indoor air, outdoor air, outdoor temperature, particulate matters, regression model, ventilation mode

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1. Introduction

A serious environmental problem is the air pollution of indoor and outdoor environments. People spend more than 80-90 % of their lives at home (Cao et al., 2017). Particulate matters (PM) are one of the hazardous air pollutants (Fuzzi et al., 2015). Over the past decade, the amount of PM_{10}, $PM_{2.5}$, and PM_1 has increased in many metropolises (Raisi et al., 2010). Recent studies showed a relationship between fine particulate matters and certain noncommunicable diseases such as chronic obstructive pulmonary and cardiovascular diseases prevalence (Sun et al., 2019; Yang et al., 2019).

The World Health Organization (WHO) has identified ambient air pollution as one of the largest environmental health risks such as noncommunicable diseases and adverse health effects (WHO, 2016a). It was estimated that about 7 million deaths from the global disease burden were attributable to the effects of indoor and outdoor air pollutants in 2016 (WHO, 2016b). The indoor to outdoor (I/O) ratio has been commonly used to evaluate infiltration of air pollutants for buildings. This ratio seems to be the simplest way to study the influence of ambient air on the indoor air pollutions (Jodeh et al., 2018; Xiao et al., 2018). Sharma and Balasubramanian (2019) also showed that in naturally ventilated buildings, fine

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particulate matter in indoor air mainly originated from outdoor air pollution.

Many variables, such as frequency and methods of building cleaning, the concentration of particles outside of buildings, ambient meteorological conditions, season, the age of building, occupancy rate in buildings, building design, smoking, and cooking at home affect the indoor air particulate matter concentrations (Ji et al., 2015; Jodeh et al., 2018; Karimpour Roshan et al., 2019; Parajuli et al., 2016; Zhou et al., 2018). Several studies have reported ratios for particulate matter as 10>I/O>1 (Chen and Zhao, 2011; Shilton et al., 2002; Vicente et al., 2017). However, almost all of the studies focus on the effects of the ventilation systems, indoor occupants, type of building, and seasonal variations (Chen and Zhao, 2011; Tippayawong et al., 2009; Wallis et al., 2019). Liu and Zhang (2019) reported that ventilation modes such as mechanical and natural ventilation affect I/O ratio for $PM_{2.5}$, as open windows can increase the pollutant concentrations in buildings.

Human activities in indoor environment are significantly contributing to I/O ratio of PM concentrations in working and residential environments (Jodeh et al., 2018; Sajani et al., 2016; Wheeler et al., 2011). The studies of Parajuli et al. (2016) in rural areas of Nepal indicated that the type of kitchen fuel and ventilation affect the pollution of the residential buildings. In this study, ventilation correction is suggested as a solution for reducing the amount of pollutions in closed areas.

Another study made by Slezakova et al. (2019) also reported that the ultrafine particles concentration in school buildings were lower in ambient air and I/O ratio was lower than 1. They found that ventilation mode and building characteristics were identified as important variables contributing to overall indoor pollution levels. Ben-David and Waring (2016) analyzed the role of natural and artificial ventilation in the air quality of indoor environments. Their results indicated that natural ventilation increases the ratio of I/O for $PM_{2.5}$. The results of a study conducted in Beijing revealed that 54 to 63% of $PM_{2.5}$ in indoor buildings originated from open sources when the windows are closed; on the other hand, when the windows are open, this percentage reaches to 92% (Ji and Zhao, 2015). Some indoor air pollutants such as particulate matters may originate from the outdoor, which in turn, is influenced by climatic conditions and building characterization.

Thus, investigating both indoor and outdoor air pollution can help understand and manage the effects of outdoor air pollution, climatic conditions and building characterization on indoor air pollution. Rapid industrialization and urbanization in Karaj, as a metropolis with a population of 3,000,000, has led to indoor and outdoor pollution problems that can be affected by climatic conditions and building characteristics. Meanwhile, there is scarcity of research on indoor and outdoor particulates in Karaj. Finally, further studies should be conducted with the aim of determining the concentration of the particles that are smaller than 10 microns in indoor environments, and comparing them with outdoor environment against existing standards. This study estimates infiltration of particulate matters from outdoor to indoor to devise and determine a suitable model that can detect their determinants. What makes this study unique is that we chose to investigate different sizes of PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP particles along with I/O ratios assessed for residential areas. According to previous studies (Clark et al., 2010; Hystad et al., 2009; Zhou et al., 2018), development of a model for I/O ratio varied with regions and ambient air and building characterization. Therefore, in this study a suitable model for I/O ratio and effective variables is introduced for enhancing our current knowledge.

2. Material and methods

2.1. Monitoring site

The monitoring location of particles was the urban area of Karaj in Iran. Karaj, as a metropolis, is located in Eastern longitude of 51 degrees and 0 minutes and 30 seconds, and Northern latitude of 35 degrees and 48 minutes and 45 seconds, with altitude at 1297 meters above the sea level. It is located in 48 km west of Tehran, Iran. This city, with 4.175 km^2 area, has a population of nearly 3,000,000. The metropolis of Karaj is divided into 10 municipal districts by Karj municipality based on the density and number of people in each municipal district. So, the sampling locations were randomly selected from the buildings in each municipal district. Residents of the selected buildings were invited to participate in the study. As most of the people are living in multistage buildings in this city, only apartment buildings were selected for the study. In each municipal district, three sampling stations were selected.

On the opposite side of each station, four buildings were chosen. The sampling was performed in a rotational method in different days during 12 months. The sampling process was performed 4 times a week in each station, with 9216 samples recorded for each particle size. The map of monitoring location and selected stations is illustrated in Fig. 1.

2.2. Monitoring particle concentrations

Experimental measurements were performed over the four-season period in 2017. The concentration of particles (PM_{10}, PM_7, PM_4, $PM_{2.5}$, and PM_1), temperature, and relative humidity of indoor and outdoor were evaluated simultaneously using a direct measurement device (AEROCET, 531S, MetOne Instrument, Inc. USA). This device, an optical particle counter, is a real-time PM sampler which is capable of measuring six different sizes of particulate matters (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP) in mass mode (μg/m^{-3}), as well as five popular cumulative particle sizes (>0.3, 0.5, 1.0, 5.0, and 10 microns) in count mode.

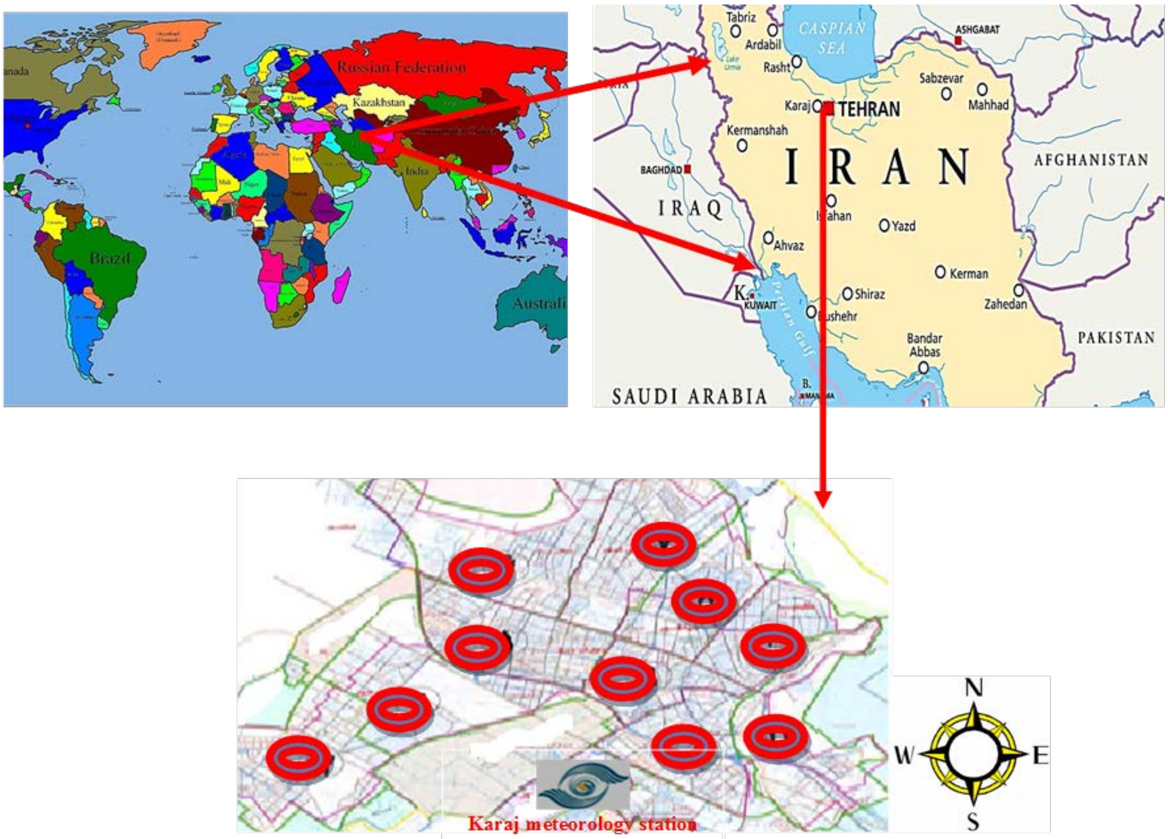

Fig. 1. Monitoring locations and the selected stations of Karaj

In recent years, the device has been used and evaluated by several studies (Akther et al., 2019; De Marco et al., 2016; Ghasemi et al., 2020; Okonkwo et al., 2018; Wang et al., 2020). This device was utilized at a flow rate of 2.831 L/min, with the device calibration conducted prior to the sampling operation by the manufacturer. The functioning range of this device was 0 to 1000 µg/m^3 with an accuracy of 0.1 µg/m^3. The measuring device was placed in monitoring locations, 1.5 meter above the ground surface and far from walls, and windows. In order to measure outdoor particles, balconies of the buildings were used. If there were no balcony, the sampling was conducted using room windows looking to the outdoor environment. These buildings were selected from municipal district as described above.

The characteristics of residential buildings, climatic characteristics of the studied area consisting of indoor and outdoor temperatures, relative humidity, wind speed, wind direction, and 24-hours precipitation before the sampling process were also surveyed and recorded in a questionnaire for each sampling site by the researchers during the sampling. Climatic characteristics were provided through direct measurements or from the Karaj weather observation station. In this study, the ventilation modes of buildings were compared in three forms of natural ventilation, mechanical ventilation, and non-ventilation. In winter, no natural ventilation existed in the studied areas. Natural gas heaters or central heating system with radiators were used for heating the buildings. Only smoking-free buildings were selected for this study.

2.3. Questionnaire

A standardized questionnaire was used to gather basic environmental information for each residential building and sampling site. The questions of this questionnaire included: building type; distance from street; demographic load of the building; ownership type; time of filling the questionnaire; open windows; cooking; type of ventilation; door and window materials; age of the building; geographical condition; indoor smoking; active hood in the kitchen; atmospheric conditions (temperature, humidity, wind speed, cloudy/rainy/clear/snowy and stormy).

Via observation, interview and measurement, researchers filled in this questionnaire at the same time of sampling. In this study, the relationship between the environmental variables and indoor and outdoor particle concentrations were analyzed.

2.4. I/O ratio determination

In this study, the ratio of I/O was assessed during four seasons and its relationship with climatic conditions and building characteristics variables was evaluated. The I/O ratio for each sample was calculated using Eq. (1) (Chatoutsidou et al., 2015).

$$I/O\ ratio = \frac{C_{in}}{C_{out}} \quad (1)$$

In this Equation, C_{in} - indoor particle concentration (µg/m^3), and C_{out} - outdoor particle concentration (µg/m^3).

2.5. Statistical analyses

Statistical analyses were performed with the SPSS software version 20. Considering that PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, I/O ratio, building characteristics, and certain environmental conditions variables were quantitative variables, we used Pearson correlation coefficient to estimate the association between these variables. Then, linear regression method was also used for evaluate the strength of the independent variables for predict the values of I/O ratio and for the modeling process. In all these analyses, P values of smaller than 0.05 were considered significant.

2.6. Modeling development for I/O ratio and independent variables

For the modeling development of I/O ratio and independent variables, a three-step method was followed. In the first step, linear regression model was examined for I/O ratio in relation to each independent variable. In this step, an independent variable with a higher R^2 was selected as the starting model.

In the second step, manually supervised forward regression analysis was utilized for evaluating the remaining variables which can improve R^2 of model. In this step, the remaining variables were those which changed the value of adjusted R^2 by at least 1 % and the coefficient of the variable. The remaining variables in the model should be compatible with a direct effect.

Finally, sampling time variables were added in order to control the unknown temporary processes of particle concentrations. Zhou et al. (2018) used this modeling method previously in a study conducted in Shanghai, China.

3. Results and discussion

3.1. Indoor and outdoor air quality monitoring

The descriptive statistics of the studied variables and PM levels (PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP) in indoor and outdoor environments are indicated in Table 1 and Fig. 2. The results revealed that annual mean of PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP particles for outdoor environments was 17.25, 33.23, 66.72, 119.41, 161.95, and 213.07 µg/m^3, respectively. For this group of particles, I/O ratios were 0.67, 0.64, 0.61, 0.55, 0.52, and 0.56, respectively. WHO guideline for PM_{10} and $PM_{2.5}$ are 20 and 10 µg/m^{-3}, respectively (WHO, 2016a). For these particles, Iran's standard is similar to the WHO guidelines.

Table 1. Descriptive statistics for the studied variables of Karaj in 2017 for 9216 samples

Variable	***Unit***	***Min***	***Max***	***Mean***	***SD***
PM_1(Indoor)	µg/m^3	0.5	127.30	10.31	10.46
$PM_{2.5}$ (Indoor)	µg/m^3	0.8	166.6	19.62	15.41
PM_4 (Indoor)	µg/m^3	1.2	257.10	35.84	27.33
PM_7 (Indoor)	µg/m^3	1	423.50	58.23	47.47
PM_{10} (Indoor)	µg/m^3	3.30	606	73.71	64.57
TSP (Indoor)	µg/m^3	7.70	966	99.58	86.15
PM_1(Outdoor)	µg/m^3	0.9	98.40	17.25	13.94
$PM_{2.5}$ (Outdoor)	µg/m^3	2.10	149.6	33.23	20.93
PM_4 (Outdoor)	µg/m^3	3.80	281.7	66.72	56.86
PM_7 (Outdoor)	µg/m^3	7.60	580.5	119.41	80.47
PM_{10} (Outdoor)	µg/m^3	9.30	990.1	161.95	125.86
TSP (Outdoor)	µg/m^3	10.4	981.4	213.07	147.17
Indoor temperature	ºC	10	31	24.87	9.83
Outdoor temperature	ºC	-5	39	18.66	14.85
Relative humidity (Indoor)	%	4	86	30.05	14.07
Relative humidity (Outdoor)	%	1	100	37.54	20.81
life of building	Year	1	35	14.83	8.40
Ventilation mode (with natural ventilation)	Number of buildings	-	-	2018	-
Ventilation mode (No natural ventilation or use of mechanical systems such as water cooler, gas cooler, and air conditioning)	Number of buildings	-	-	7198	-
Wind velocity	m/s	0	8	2.13	0.6
Ownership type of buildings: 1-Tenant 2-The owner	Number	-	-	1099 8117	-
Building type: 1- Residential 2- Commercial 3- Official	Number	-	-	5386 2510 1320	-

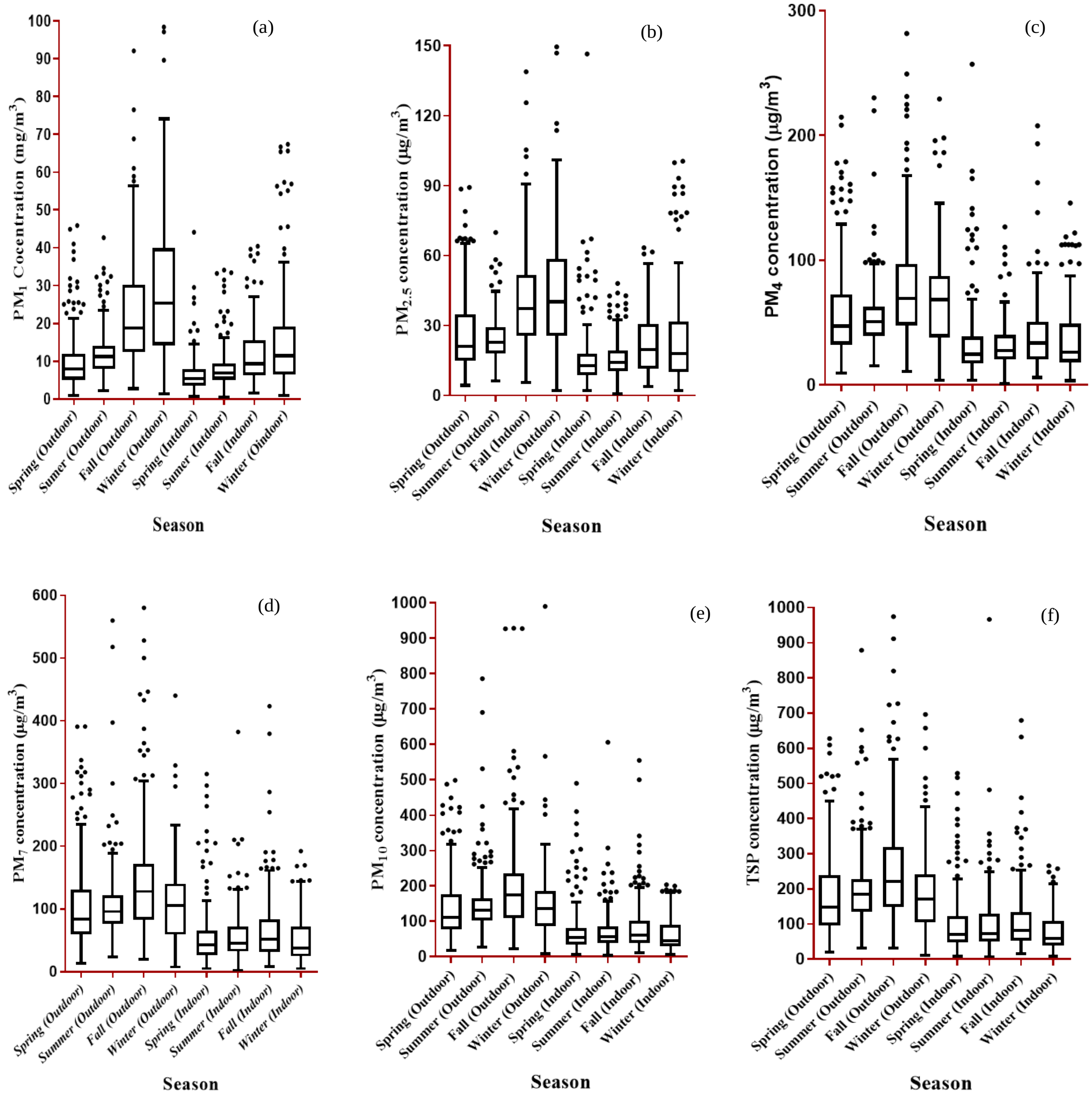

Fig. 2. PM levels in indoor and outdoor environments in different seasons (mean; 25-75%; range):
(a) PM_1, (b) $PM_{2.5}$, (c) PM_4, (d) PM_7, (e) PM_{10}, (f) TSP

All the measured mean values of concentrations were higher than those of World Health Organization guidelines. Since World Health Organization (2013) recently declared that outdoor air pollution as a group 1 carcinogen to human, a suitable planning is necessary for reducing the amount of atmospheric pollutants of Karaj metropolis and preventing the entrance of pollutants into the indoor environments. As shown in Fig. 2, the outdoor particles have a noticeable effect on indoor particles, which is more effective in PM_1 and $PM_{2.5}$ particles. Table 3 clearly shows the correlation between the indoor and outdoor particles concentrations.

However, most exposure to particulate matter occurs in indoor environments, where people spend about 80% of their time. Indoor air quality is affected by outdoor air pollutants through natural ventilation and infiltration, so outdoor pollutants are a major threat to human health (Bai et al., 2019).

The annual average of ambient temperature and relative humidity were 14.85^{o}C and 20.81%, respectively that the maximum temperatures (39^{o}C) and minimum relative humidity are occurred during summer season. These meteorological parameters were considered to be effective on indoor and outdoor particulate matters concentrations (Zhou et al., 2018).

3.2. Indoor/outdoor ratios

The annual mean of I/O ratio of particles with different aerodynamic diameters is presented in Fig. 3. The highest value of this ratio belonged to PM_1, and with larger aerodynamic diameter of the particles, the I/O ratio reduced as well. As depicted in Fig. 3, the annual mean and 75th percentile of I/O ratio is lower than 1 in all studied particle types, which indicate a dominance of outdoor sources (Wallis et al., 2019).

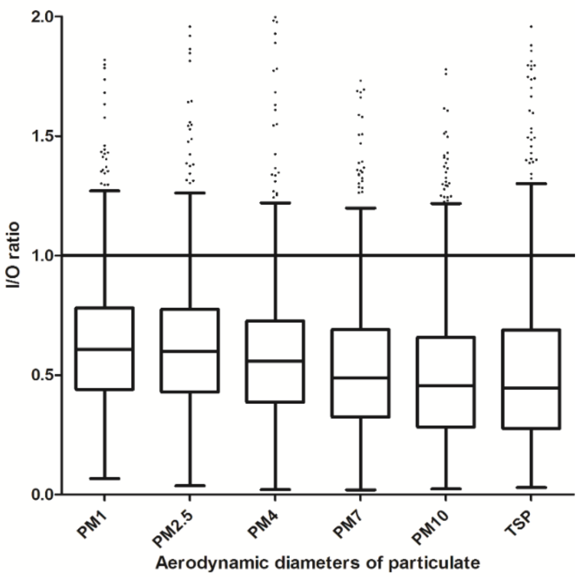

Fig. 3. Annual average of I/O ratio for PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP particles

The I/O ratio was reported in literature to describe indoor air pollution origin and indicated that value of greater than 1 may suggest the existence of indoor sources (Jodeh et al., 2018; Xiao et al., 2018).

The results presented here are agree with most studies conducted on residential areas for I/O ratio (Ben-David and Waring, 2016; Guo et al., 2008; Majewski et al., 2016; Sajani et al., 2016; Vicente et al., 2017). Some indicated that if the I/O ratio is less than 1, the indoor pollution can be related to the outdoor pollution (Chen and Zhao, 2011). Nevertheless, in the study of Diapouli, the ratio of I/O was estimated to be higher than 1 (Diapouli et al., 2011); this value was higher than 1 for crowded buildings and less than 1 for low-population buildings. Similar results were reported for PM_{10} by Vicente et al. (2017). Higher ratios of I/O for PM_1, $PM_{2.5}$, PM_{10}, and TSP (nearly 2 to 18, except PM_1 ratio which is from 0.98 to 8.9) have been identified in research stations of the South Pole (Pagel et al., 2016). The highest values of I/O ratio were estimated in a classroom, as reported by Guo et al. (2008) for cleaning hours and rainy conditions. In some studies, pollutant concentrations in outdoor environments were higher than those of indoor pollutants (Riesenfeld et al., 2000). Therefore, as one of the main objectives of this research we designed a suitable model for analyzing the effects of outdoor pollutants on indoor pollutants, and controlled and removed effective indoor factors of the building studied by other researchers (Ben-David and Waring, 2016; Chen et al., 2011; Jodeh et al., 2018; Lu et al., 2017; Majewski et al., 2016; Riesenfeld et al., 2000). Hence, building without major indoor sources such as cooking and smoking selected for assessment. Thus, expectedly the concentration of indoor pollutants was lower than that of outdoor pollutants in this study (I/O ratio < 1).

In Table 2, indoor to outdoor ratio of particulate matters are reported for all seasons. Based on the results, the mean I/O ratio was lower in fall (0.52), while it was higher in summer (0.68). In the previous decade, particulate matters ($PM_{2.5}$ and PM_{10}) were widely considered for I/O ratio determination, due to people's health effects and WHO recommendations (Chatoutsidou et al., 2015; Vicente et al., 2017). However, one of the characteristics of this study was utilizing a wide range of particle sizes along with a high number of samples for estimating the I/O ratio.

The highest average values of I/O ratio belonged to PM_1, as well as Pearson correlation coefficient (all Correlation was significant at the 0.05 level) which were lowered with elevation of diameter of the particulates (Tables 2 and 3). These results agree well with the results presented by Lu et al. (2017). The low size particles can be penetrating to indoor from outdoor air due to the temperature difference (Bekö et al., 2015) that can be caused by the Brown diffusion effect (Lu et al., 2017). According to Ye et al. (2017), the ratio of I/O was affected by season and method of ventilation.

3.3. Pearson correlation coefficient of variables

In Tables 3 and 4, Pearson correlation coefficient is provided for quantitative variables used in this study. The results showed that correlation coefficient for particles varied from 0.21 to 0.86 for outdoor concentrations; with the increase in particle size, the value of correlation coefficient decreased. This coefficient for indoor concentrations varied from 0.32 to 0.74 decreased with larger aerodynamic sizes. Pearson correlation coefficients were larger in aerodynamic diameters of smaller indoor and outdoor particles. Outdoor temperature had a higher correlation with the indoor concentrations having smaller aerodynamic diameters. Correlation coefficients of indoor and outdoor concentrations of PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP particles were 0.643, 0.620, 0.432, 0.574, 0.446, and 0.431, respectively. These results show that the indoor and outdoor PM_1 concentrations were significantly correlated than particulate matters with higher aerodynamic diameter.

In this study, a significant correlation ($P<0.05$) was found between precipitation, season, ventilation mode, indoor temperature, wind speed with I/O ratio for different particulate matters. However, no significant differences ($P>0.05$) were found for other climatic conditions and building characteristics with I/O ratio for different particulate matters.

As suggested by the results in Fig. 2 and Table 2, the I/O ratios for particulate matters were higher in warmer and mild seasons due to penetration of outdoor particles by natural ventilation (Sharma and Balasubramanian, 2019).

Table 2. I/O ratio of particles for each season

Particle	Winter				Fall				Summer				Spring			
	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max	Mean	SD	Min	Max
PM_1	0.62	0.86	0.57	1.29	0.53	0.55	0.438	0.59	0.68	0.89	0.23	0.80	0.63	0.63	0.38	0.96
$PM_{2.5}$	0.58	0.84	0.40	0.95	0.55	0.60	0.46	0.70	0.64	0.84	0.13	0.79	0.62	0.90	0.45	1.8
PM_4	0.48	0.29	0.12	0.87	0.51	0.58	0.43	0.64	0.59	0.69	0.08	0.75	0.57	0.78	0.40	1.2
PM_7	0.47	0.60	0.44	0.68	0.45	0.53	0.33	0.55	0.51	0.66	0.09	0.68	0.53	0.68	0.38	0.81
PM_{10}	0.43	0.56	0.36	0.68	0.42	0.51	0.29	0.59	0.48	0.67	0.13	0.77	0.52	0.74	0.35	0.98
TSP	0.42	0.49	0.38	0.82	0.42	0.49	0.31	0.52	0.49	0.75	0.25	0.91	0.54	0.71	0.39	0.84

Table 3. Pearson correlation coefficient for quantitative variables of the studied samples

	TSP (Out)×	PM_{10} (Out)	PM_7 (Out)	PM_4 (Out)	$PM_{2.5}$ (Out)	PM_1 (Out)	TSP (In)+	PM_{10} (In)	PM_7 (In)	PM_4 (In)	$PM_{2.5}$ (In)	PM_1 (In)
PM_1(Outdoor)	0.212*	0.208*	0.278*	0.42*	0.861*	1	0.066*	0.112*	0.155*	0.289*	0.532*	0.643*
$PM_{2.5}$(Outdoor)	0.552*	0.530*	0.666*	0.663*	1	0.861*	0.267*	0.349*	0.394*	0.518*	0.620*	0.553*
PM_4(Outdoor)	0.606*	0.565*	0.691*	1	0.663*	0.425*	0.294*	0.361*	0.390*	0.432*	0.372*	0.218*
PM_7(Outdoor)	0.949*	0.846*	1	0.691*	0.666*	0.278*	0.461*	0.547*	0.574*	0.583*	0.424*	0.175*
PM_{10}(Outdoor)	0.842*	1	0.846*	0.565*	0.530*	0.208*	0.375*	0.446*	0.468*	0.468*	0.333*	0.134*
TSP (Outdoor)	1	0.842*	0.949*	0.606*	0.552*	0.212*	0.431*	0.504*	0.524*	0.512*	0.364*	0.158*
PM_1(Indoor)	0.158*	0.134*	0.175*	0.218*	0.553*	0.643*	0.258*	0.317*	0.362*	0.512*	0.736*	1
$PM_{2.5}$(Indoor)	0.364*	0.333*	0.424*	0.372*	0.620*	0.532*	0.561*	0.652*	0.709*	0.885*	1	0.736*
PM_4(Indoor)	0.512*	0.468*	0.583*	0.432*	0.518*	0.289*	0.809*	0.895*	0.920*	1	0.885*	0.512*
PM_7(Indoor)	0.524*	0.468*	0.574*	0.390*	0.394*	0.155*	0.910*	0.951*	1	0.920*	0.709*	0.362*
PM_{10}(Indoor)	0.504*	0.446*	0.547*	0.361*	0.349*	0.112*	0.967*	1	0.951*	0.895*	0.652*	0.317*
TSP (Indoor)	0.431*	0.375*	0.461*	0.294*	0.267*	0.066*	1	0.967*	0.910*	0.809*	0.561*	0.258*
Temperature(Outdoor)	0.055	0.029	0.017	-0.10*	-0.33*	-0.47*	0.144*	0.133*	0.115*	0.036*	0.17*	0.29*
Temperature(Indoor)	0.073*	0.044	0.057	-0.042	-0.14*	-0.22*	0.146*	0.124*	0.116*	0.089*	0.008	-0.063
Relative Humidity(Outdoor)	-0.128*	-.095	-0.077	0.055	0.121*	0.191*	-0.13*	-0.14*	-0.137	-0.12*	-0.051	0.016
Relative Humidity(Indoor)	-0.015	-0.002	0.001	0.018	0.083*	0.141*	0.039	0.024	0.029	0.012	0.021	0.026
Age of structure	0.150*	0.134*	0.154*	0.111*	0.119*	0.043	0.086*	0.168*	0.165*	0.166*	0.108*	0.065*
precipitation	-0.132*	-0.10*	-0.10*	-0.033	-0.004	0.012	-0.12*	-0.12*	-0.11*	-0.09*	-0.051	-0.035
Ventilation	0.043	0.014	0.024	-0.063	-0.23*	-0.32*	0.246*	0.259*	0.244*	0.169*	-0.006	-0.14*

**Correlation is significant at the 0.05 level (two-tailed), × outdoor, + indoor*

Table 4. Pearson correlation coefficient for I/O ratio and certain climatic conditions and building characteristics

	I/O ratio	Sig. (1-tailed)
Type of use (residential, commercial, or official)	.049	.082
Heating and cooling device	.021	.279
Type of doors and windows	.059	.056
Age of building	-.029	.165
Relative outdoor humidity	-.010	.392
Wind direction	-.061	.052
Heating and cooling device	.021	.279
Relative indoor humidity	.004	.459
Building floor	-.016	.328
Season	-.067	.028
Precipitation	-.065	.033
Indoor temperature	.012	.137
Outdoor temperature	.201	.036
Ventilation mode	.095	.000
Wind speed	.098	.063

The lowest value of I/O ratio belonged to TSP and PM_{10}, with 0.44 – 0.42 values, in fall and winter. The results indicated that with the increase in particle size, the ratio of I/O decreased in all seasons. Sharma and Balasubramanian (2019) also showed that in naturally ventilated buildings, fine particulate matters in indoor air mainly originated from outdoor air pollution. Stasiulaitiene et al. (2019) also suggested that the I/O ratio were highly correlated with seasonal and ventilating situations. Ben David and Waring (2016) evaluated the performance of natural and artificial ventilations in indoor air quality. The results of their study demonstrated that natural ventilation increased the value of I/O ratio for $PM_{2.5}$ particles. In

Beijing, it was observed that 54 to 63% of the $PM_{2.5}$ particles entered the indoor environment from open sources when the windows were closed. When the windows were open, this percentage reached 92% (Ji and Zhao, 2015).

Another factor influencing the I/O ratio was the difference between indoor and outdoor temperature. In this study, the outdoor temperature in cold seasons (fall and winter) was less than the indoor temperature. Lu et al. (2017) studied the effects of indoor and outdoor temperature differences on the penetrability of particles into the indoor environment. In this study, $PM_{2.5}$ and PM_{10} indoor and outdoor concentrations were analyzed when the doors and windows were closed and no indoor pollutant source existed. The results of their study showed that indoor and outdoor temperature differences affect the penetrability of small particles. With the widening of this temperature difference, penetrability increased as well. Furthermore, the extent of temperature difference affected I/O ratio, which was higher on $PM_{2.5}$ than on PM_{10}.

3.4. The developed model of I/O ratio changes and independent variables

Based on the Pearson correlation coefficient for I/O ratio and certain climatic conditions and building characteristics (Table 4), the outdoor temperature, ventilation mode, season and precipitation were correlated with I/O ratio ($p < 0.05$). Other variables, such as the type of doors and windows, age of building, relative outdoor humidity, wind direction, heating and cooling device, relative indoor humidity, building floor, indoor temperature, and wind speed, did not show significant associations. Therefore, these characteristics were not selected as predictors.

The developed model of I/O ratio changes and independent variables is summarized in Table 5. The results of this study, based on the correlation analyses and linear regression analyses, revealed that ventilation and outdoor temperature variables were more effective in the developed model than season and precipitation variables; and this model is more applicable for smaller particles, where R^2 of PM_1 and $PM_{2.5}$ particles are 0.485 and 0.316. However, this model showed less validity for larger particles (R^2 values for PM_4, PM_7, PM_{10}, and TSP particles were 0.320, 0.256, 0.227, and 0.133, respectively). Therefore, with an increase in particles size, the validity of this model decreased.

The current developed model was in line with a previous model developed by Zhou et al. (2018). In this study, R^2 value for $PM_{2.5}$ particles in summer was nearly 0.45. One of the main characteristics of our study for the modeling procedure was that more samples were used and more variables were analyzed. In a similar study, Zhou et al. (2018) indicated the penetrability of small particles in residential areas of Shanghai, China.

In their study, the variables of temperature, relative humidity, ventilation, and building floors were considered to be effective variables. However, in our study, outdoor temperature and ventilation type were the most influential variables. In addition, R^2 value of their study was slightly higher than our estimated value which can be influenced by geographical and atmospheric conditions. Another difference between our study and the study mentioned above was the consideration of a wide range of particle sizes providing the opportunity for comparing the models for different particles. Lee et al. (2016) developed an I/O ratio model for $PM_{2.5}$ and PM_{10} and introduced the indoor pollutant sources in the model. The most important predictor variables in their model were temperature and floor level

4. Conclusions

Overall, annual concentration means of PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP particles for outdoor environments were 17.23, 33.23, 66.72, 119.41, 161.95, and 213.17 µg/m^3, respectively. These values were significantly higher than national standards and World Health Organization guidelines. For the above-mentioned particles, I/O ratios were 0.67, 0.64, 0.61, 0.55, 0.52, and 0.56, respectively. We also observed that indoor concentration was significantly positively correlated with the outdoor concentration.

Table 5. Linear regression model for dependent variable of I/O ratio and independent variables (outdoor temperature and type of ventilation)

Dependent variables (I/O ratio)	*Independent variables*	*Slope*	*Intercept*	*β*	*R*	*R^2*	*P*
PM_1	Outdoor temperature	0.005	0.317	0.139	0.697	0.485	0.007
	Ventilation mode	0.401		0.596			0.000
$PM_{2.5}$	Outdoor temperature	0.003	0.361	0.085	0.562	0.316	0.152
	Ventilation mode	0.368		0.520			0.007
PM_4	Outdoor temperature	0.045	0.363	0.139	0.565	0.320	0.443
	Ventilation mode	0.534		0.596			0.000
PM_7	Outdoor temperature	0.001	0.345	0.033	0.506	0.256	0.593
	Ventilation mode	0.345		0.483			0.000
PM_{10}	Outdoor temperature	0.001	0.329	0.023	0.477	0.227	0.717
	Ventilation mode	0.352		0.461			0.000
TSP	Outdoor temperature	0.05	0.358	0.050	0.365	0.133	0.459
	Ventilation mode	0.330		0.330			0.000

In this study, the I/O ratios for particulate matters were highly influenced by the ventilation mode, outdoor temperature, and seasonal variations. On the contrary, the correlation coefficient was not significant between I/O ratio and other climatic and building variables such as building ownership, heating and cooling equipment of buildings, door and window materials, age of building and relative humidity. Thus, according to our data, higher levels of I/O ratio belonged to PM_1 and there was a negative correlation between I/O ratio and the aerodynamic particle size.

I/O ratios in spring and summer had the maximum values, while they showed minimum values in cold seasons, which can be due to the reduction of natural ventilation time in cold seasons. For the dependent variable, the ratio of I/O to independent variables – including atmospheric and area conditions – was measured using linear regression model. Among all the independent variables of this study, ventilation type and outdoor temperature presented the greatest affectability for the linear regression model. This model was more valid for smaller particles. R^2 values for PM_1, $PM_{2.5}$, PM_4, PM_7, PM_{10}, and TSP particles were 0.485, 0.316, 0.320, 0.256, 0.227, and 0.133, respectively. Based on this study, with an increase in aerodynamic particle size, the validity of this model decreased.

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