



Indoor exploratory analysis of gaseous pollutants and respirable particulate matter at residential homes of Delhi, India

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ABSTRACT

Biomass fuels are frequently used as a source of domestic energy in developing countries that may cause indoor air pollution. This study presents indoor and outdoor combustion pollutants (CO and NO_x) and respirable particulate matter–RSPM (PM₁₀, PM_{2.5} and PM_{1.0}) concentrations measured during winter and summer seasons in 8 homes in Delhi, India. CO₂ concentrations have been used to measure the outdoor airflow rates. This study further investigates variations in indoor/outdoor concentrations of the pollutants as a result of various activities in commercial (Site I) and institutional areas (Site II). The institutional area has been considered as the control site. Monitoring has been conducted at each site for 3 days in a week in both summer and winter seasons to investigate the diurnal variations of pollutant concentrations. Then, the I/O ratios have also been estimated. The correlation analysis of indoor pollutant concentrations with outdoor concentrations has been carried out. Winter/Summer (W/S) ratios have also been calculated and a two tailed t–test has been used to determine whether the winter and summer mean concentrations are significantly higher. The I/O ratios for PM₁₀, PM_{2.5} and PM_{1.0} at Site I homes, in winter season, have been found to be 1.43±0.84, 2.72±1.94 and 3.21±2.39, respectively. I/O ratio for CO has been found to be 2.99±2.19 in winters at Site I. The linear regression analysis results have revealed that usage of biomass fuels for cooking has increased the concentrations of RSPM and CO indoors, considerably in winter. W/S ratios for RSPM have also been found to be higher than 1.0 at almost all the homes indicating that the concentration of RSPM is higher in winter season. Regression analysis results indicated that the major sources for RSPM and CO exist indoors and that is principally, cooking using the biomass as fuels and also cleaning of homes manually, particularly at commercial site (NZM site). The results of this study also suggest that the indoor RSPM concentrations are mainly composed of the finer range of particles.

Keywords:

Indoor outdoor ratios
Biomass fuels
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Respirable particulate matter

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1. Introduction

Biomass remains the primary energy source in the developing countries in Asia. It contributes over a third of primary energy in India. Biomass fuels are predominantly used in rural households for cooking and water heating, as well as by traditional and artisan industries. It delivers most energy for the domestic use (rural, 90% and urban, 40%) in India (NCAER, 1992). Wood fuels contribute 56% of total biomass energy (Sinha et al., 1994). Consumption of wood has grown annually at two percent rate over the past two decades (FAO, 1981; FAO, 1986; FAO, 1996). Due to incomplete combustion, the use of biomass fuels in traditional stoves produce high level of indoor air pollutants which is responsible for more than 1.6 million of deaths and 2.7% of global burden of diseases (WHO, 2006).

It is estimated that residents in urban poor households (the households with an annual income of <\$ 535, NCAER, 1995) are exposed to the emissions coming out of burning low grade fuels (e.g. biomass, coal etc) in Chula (a native form of stove) for at least 3–7 h/day (Smith, 1987). Combustion of biomass fuels in poorly vented kitchens using poorly functioning stoves leads to the release of high concentrations of respirable particulates, gases including CO, SO₂, NO_x, toxic compounds like benzene, formaldehyde, and polycyclic aromatic compounds such as benzo[*a*]pyrene (Smith, 1987; Saksena et al., 1992). Exposure to these pollutants has been shown in many recent studies to be causally linked to several health effects especially in women who cook with these fuels and young children (Mishra and Rutherford,

1997; Bruce et al., 2000; Ezzati and Kammen, 2001a; Ezzati and Kammen, 2001b).

Increased indoor air pollution can occur because of poor air mixing in the stove especially when the stove is not well ventilated, with concentrations of RSPM often exceeding the ambient air quality standards set by Environment Protection Agency (EPA) and World Health Organization (WHO). Various studies for wood burning have found high indoor levels of particulate matter in Guatemala (Bruce et al., 2000; Naeher et al., 2001), PM_{2.5} in rural Mexico (Brauer et al., 1996), respirable particulate matter in Pakistan (Colbeck et al., 2010; Siddiqui et al., 2005a) and India (Balakrishnan et al., 2004; Kulshreshtha et al., 2008). Indoor source, including cooking, unventilated heating appliances and pets often make important contributions to exposure (Abt et al., 2000). Road traffic, however, provides one of the major sources of particulate pollution especially, PM₁₀ and lower ranges.

In developing countries, exposure to smoke is arguably the greatest indoor pollution problem. In a number of buildings, burning of wood, charcoal, crop residues, or animal dung is often undertaken without adequate ventilation (Gold, 1992). A Korean study has found indoor air concentrations to be consistently higher than outdoor, an observation that has been magnified during wintertime possibly due to heating (Baek et al., 1997). These studies have cited the difference between indoor and outdoor concentrations as attributable in part to human indoor activities, duration of human occupancy, ventilation, type of stove used for cooking and heating, and tobacco smoke (Baek et al., 1997). A

study by Akhtar et al. (2007) in the rural area of Peshawar, Pakistan revealed a strong association of biofuel smoke exposure with chronic bronchitis in women who are involved in cooking with biomass fuels. Another study has shown an independent effect of indoor air pollution on birth weight (Siddiqui et al., 2005b). In India, Pandey et al. (1989) have found that airborne particle concentrations, measured during cooking, are as high as $21\,000\text{ mg/m}^3$. Such figures are not typical of indoor exposures in the developed world whereas in developing countries they are a common phenomenon (Prasad et al., 2003; Dasgupta et al., 2006). India has among the largest burden of diseases due to use of low-grade fuels particularly in urban poor households. As a result, 28% of all mortality occurs due to polluted indoor air (Smith, 2000a; Smith, 2000b). Various hotels/homes in Pune city have been found to have higher NO_2 concentrations than the ambient air limit (Jayashree Mohan et al., 1992). Lawrence et al. (2004) have described that elevated levels of CO were due to the use of wood and coal during winter. Gadkari and Pervez (2008) have concluded that indoor activities and poor ventilation qualities are responsible for major portion of high level of indoor RSPM. The road traffic and soil born RSPMs are the dominating routes of personal exposure compared to ambient outdoor RSPM levels. Mishra et al. (1999) have reported prevalence of active pulmonary tuberculosis in 51% of persons aged 20 years and above who use biomass as their cooking fuel. It reflects that indoor air pollution in urban poor households in Indian slums is responsible for the high degree of morbidity and mortality, stressing the dire need for immediate interventions in India. Therefore the present work has been carried out to investigate the relationship between indoor/outdoor air quality and to assess the levels of particulate matter in indoor air in residences of India.

The present paper describes: (a) monitoring the mass concentrations of particulate matter (PM_{10} , $\text{PM}_{2.5}$, PM_1) and gaseous pollutants (CO , NO_x) along with CO_2 indoors and outdoors in dwellings situated in a commercial and non commercial areas of Delhi; (b) investigating the seasonal variations in I/O ratios of RSPM and gaseous pollutants; and (c) assessing the effect of outdoor pollutant concentrations on the indoor concentrations.

2. Materials and Methods

2.1. Study design

This study was conducted in Delhi, the capital of India which is geographically located in Central India with a total population of

23 200 000. As a rapidly expanding city, transportation, energy generation, construction, domestic burning, and industrial activities are contributing to the increasing air pollution and resulting in health and respiratory impacts. Apart from biomass burning and ambient dust, transportation and industries are the major contributors to air pollution in Delhi. With a growing city, the corresponding transportation needs are fuelling a rise in private cars, two and three wheelers, and taxis. Previous reported literature showed that apart from industrial emissions, automobile exhausts are well known for steep increase in gaseous pollutants and PM concentrations among Asian cities (BAQ, 2006). Figure 1 presents the results of source apportionment of the urban air pollution in Delhi (Chowdhury, 2004).

Higher concentration of particulates and gaseous pollutants tend to occur in the close vicinity of the roads, (Gulliver and Briggs, 2004). The present study has been undertaken in two different urban areas which differ in their characteristics and emission sources. Two residential areas have been selected, a sample site i.e. the Nizamuddin area (Site I) which, is located in close proximity to main railway station and adjacent to a commercial retail market (Figure 2); and a control site, the Indian Institute of Technology Delhi residential campus (Site II) (Figure 3), which is located far away from any major emission sources. Site II is a walled institutional area where the entry of general traffic is prohibited. Only a limited number of vehicles are allowed the entry. There are large green areas, which make the control site less polluted and the residential houses are spread across the 1.3 km^2 .

In most of the developing countries like India, the people belonging to the lower income group whose annual family income is $<\$535$ (NCAER, 1995) use biomass fuel such as cow-dung cake and wood as it is economically cheaper for them. The cost of cow-dung cake is $\$0.22/\text{kg}$ whereas the liquefied petroleum gas (LPG) costs $\$1.55/\text{L}$. The families whose annual family income is $<\$535$ cannot afford to use cleaner fuels (LPG, natural gas). A study by Laxmi et al. (Year?) conducted in a rural areas of Rajasthan in India shows that about 86% of the households using fuel wood gather it whereas the remaining 14% purchase it. The study also reveals that the economic status influences the choice and quantity of energy use. The survey also shows that about 22% of households have annual income below $\$200$ and almost 99% of households in rural areas of Rajasthan use bio-fuels for cooking.

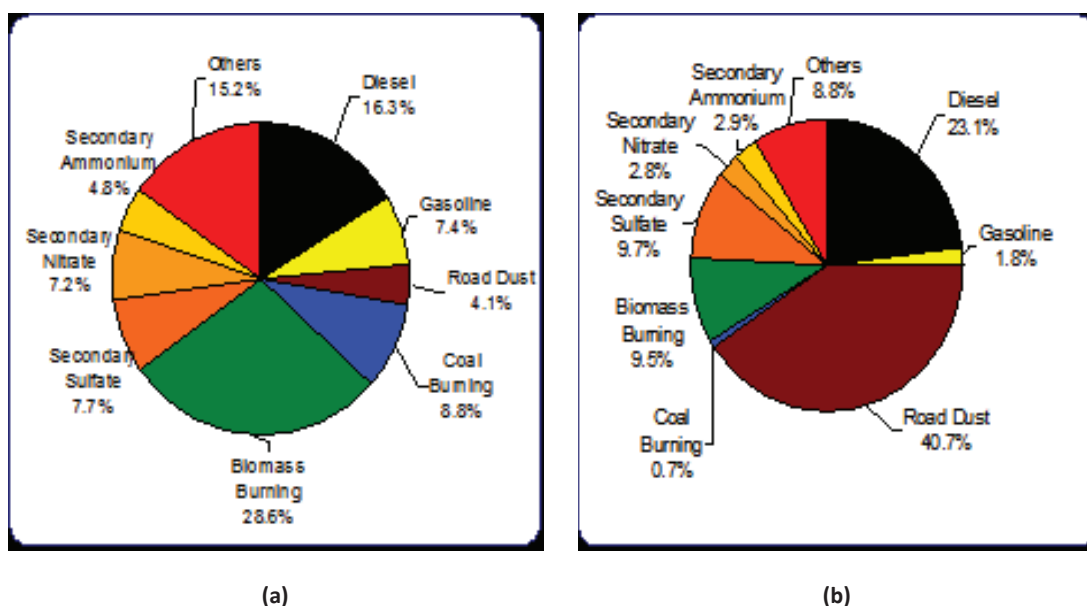


Figure 1. Source apportionment of the urban air pollution in Delhi in (a) winters (b) summers (Chowdhury, 2004).



Figure 2. Satellite map of Site I (Nizamuddin).



Figure 3. Satellite map of Site II (Indian Institute of Technology Delhi).

2.2. Sampling design

Air samples have been collected within the dwellings at two sites: Site I, the NZM and Site II, the IITD. At both sites the sampling has been carried out in the kitchens of the dwellings. All the houses selected for the present study were naturally ventilated. Both sites have residential facilities belonging to high (annual income $> \$ 2\,300$), middle (annual income between $\$ 1\,070$ – $1\,550$) and low (annual income $< \$ 535$) income groups of people (NCAER, 1995). A study (Laxmi et al., Year?) conducted in rural areas of Rajasthan, India shows that about 86% of the households using fuel wood gather it whereas the remaining 14% purchase it. The study also reveals that the economic status influences the choice and quantity of energy use. About 22% of households have annual income below $\$ 200$ and almost 99% of households in rural areas of Rajasthan use bio-fuels for cooking. The participants in a recent study in Pakistan (Siddiqui et al., 2009) were stratified by type of fuel and by a median monthly income of less than or equal to or greater than $\$ 50$ per household. In the present study four kitchens

in different categories of the dwellings i.e. the lower income group (LIG 1, LIG 2, and LIG 3) and middle income group (MIG) have been selected for the sampling. These dwellings have been using the biomass as their cooking fuel. The other category of houses has been selected where the cooking fuel is mainly liquefied petroleum gas (LPG). These are categorized under high income group (HIG), (HIG-IITD), middle income group (MIG-IITD) and lower income group (LIG-IITD). The homes at Site I are generally made of mud, grasses and bricks. Monitoring of indoor and outdoor air pollutants has also been carried out covering different seasons of the year i.e. April–June 2005 (summer) and December–February 2005 (winter). The monitoring has been carried out for 6 h/day and three times during the week i.e. Monday, Wednesday and Friday (Kulshreshtha et al., 2008). The pollutants measured indoors are PM_{10} , $PM_{2.5}$ and $PM_{1.0}$, carbon monoxide (CO) and oxides of nitrogen (NO_x). CO_2 was also measured as a surrogate index for assessing the IAQ.

On all days of sampling, the occupants of the homes have been given a questionnaire to answer that consists of time activity diary. Thus it has provided information relating to the timing of activities such as cooking, cleaning, ventilation and if and when people are present in the home.

2.3. Instrumentation

The mass concentration of particles (PM_{10} , $PM_{2.5}$ and PM_1) has been monitored using two GRIMM Environmental Dust Monitors, both Model 1.107 (Grimm Aerosol Technik GmbH, Airing, Germany). The GRIMM monitors have a sensitivity of 1 particle/L with a reproducibility of $\pm 2\%$. The Grimm 1.107 monitor performs particulate size measurements by 90-degree laser light scattering. Air with multiple particle sizes passes through a flat laser beam produced by an ultra low maintenance laser diode. A 15-channel pulse height analyzer for size classification detects the scattering signals. Due to the lack of a sample heater inlet even aerosols and semi volatile liquid particles can be identified. These counts from each precisely sized pulse channel are converted to mass using a well-established equation and the data is then formatted for USA EPA categories of PM_{10} and $PM_{2.5}$. Inside the 1.107 unit is a removable PTFE 47 mm filter (in accordance to $PM_{2.5}$). All sampled dust is collected on the filter and a gravimetric and/or chemical analysis may be made later. Software allows the data to be viewed as counts/L or mass as $\mu g/m^3$. Both of these aerosol spectrometers were factory calibrated, prior to the sampling campaign. A gravimetric correlation was carried out with stearin and an optical calibration cross-reference was performed with spherical glass beads with a density of $2.8 g/cm^3$ and a refractive index of 1.36. For the present study, both of the spectrometers were used for reporting mass fraction in the environmental mode (PM_{10} , $PM_{2.5}$, and $PM_{1.0}$). Further, both of these monitors were operated side by side in each experimental setting for 12 h before the start of sampling. Intercomparison revealed a variation of $\pm 10\%$ with no obvious bias. Both of these instruments have been operated continuously for a period of 6 hours on 3 days in each setting and data recorded every 1 min. The data has been then averaged to 10 min and finally 1 hour. APM820 (Envirotech, New Delhi, India, 2004) handy sampler was used for measuring NO_x indoors. The modified Jacob-Hochheiser method (IS-5182 part-IV 1975) was used for NO_2 analysis, respectively. CO and CO_2 were monitored using Quest-5001 (Quest Technologies, Oconomowoc, WI, USA, 2000) IAQ monitor.

In the dwellings using biomass as fuels, the stoves in the kitchens are under the ground, having dimensions of approximately 30x15 cm. There was no chimney installed. The instruments were placed approximately 60 cm away from the stove, corresponding to the distance between the stove and the sitting position of the cooking person. The indoor sampling heights have been varying between 1–1.5 m above ground to simulate the breathing zone and to avoid potential interferences from re-suspension of particles. The outdoor sampling has been carried out in the courtyard of the dwellings and sited approximately 1.5 m away from the rooms. The activities of the occupants were documented during the sampling periods. Activities in the kitchen were divided in cooking (preparation for cooking, lighting and tending the fire etc), cleaning and other (doing outdoor work and no activity).

2.4. Ventilation parameters

Infiltration rates/outdoor air flow rate have been estimated using CO_2 concentration and occupancy data in ASHRAE formulation with an assumption that indoor CO_2 concentration is surrogate index of IAQ in terms of ventilation rates indoors (ASHRAE 1993; Scheff et al., 2000). Occupants generate CO_2 and consume oxygen at a rate that depends primarily on their level of physical activity and their size (ASHRAE, 1993; Scheff et al., 2000). The CO_2 concentrations have been discussed in detail by

Kulshreshtha et al. (2008). Therefore, CO_2 concentrations have been used as the surrogate index to evaluate the IAQ of a kitchen. The CO_2 generation rate of an individual occupant is calculated using Equation (1):

$$G = V_{O_2} RQ \quad (1)$$

where, V_{O_2} is the rate of oxygen consumption in L/s, and RQ is the respiratory quotient, i.e., the relative volumetric rates of CO_2 produced to O_2 consumed. The value of RQ depends on diet, the level of physical activity, and the physical condition of the person (ASHRAE, 1993; Persily, 1997; Scheff et al., 2000). Table 1 gives typical Met levels for various activities. Rate of oxygen consumption V_{O_2} can be calculated using Equation (2):

$$V_{O_2} = \frac{(0.00276 \text{ AD } M)}{(0.23 RQ + 0.77)} \quad (2)$$

where, M is the level of physical activity, or the metabolic rate per unit of surface area, in Mets; RQ is the Respiratory Quotient; AD is DuBois surface area in m^2 given by:

$$AD = 0.203 H_{0.725} W_{0.425} \quad (3)$$

where, H is the body height (m), W is the body mass (kg). Observing the physical activity of the occupants in the households during weekday, we can calculate CO_2 production by the occupants for every half hour period by taking suitable Met levels as given in Table 1.

The outdoor airflow rate is calculated using the following equation:

$$Q_0 = \frac{(1.8 \times 10^6 \text{ G})}{(C_{in,eq} - C_{out})} \quad (4)$$

where, Q_0 is the outdoor airflow rate into the space (L/s); G is the CO_2 generation rate in the space (L/s); $C_{in,eq}$ is the equilibrium CO_2 concentration in the space (mg/m^3); C_{out} is the outdoor CO_2 concentration (mg/m^3). CO_2 concentrations are measured in ppm. However, they are converted to mg/m^3 as follows:

$$(mg/m^3) = \frac{(ppm \times g \text{ mol mass} \times 10^6)}{(L/mol)} \quad (5)$$

At 273 K ($0^\circ C$) and 1 atm pressure (760 mm Hg), one mol of any gas occupies 22.4 L. However, air quality determinations are made in different temperature and pressure conditions. To convert to L/mol at different conditions, Equation (6) was used:

$$\frac{V_1 P_1}{T_1} = \frac{V_2 P_2}{T_2} \quad (6)$$

where, V_1 , P_1 , and T_1 relate to above conditions of 22.4 L/mol at 273 K and 760 mm Hg, and V_2 , P_2 , and T_2 relate to actual conditions being considered.

Thus, using average indoor and outdoor CO_2 concentrations obtained and average CO_2 generation rate as estimated by Equation (1), the outdoor airflow rate has been calculated which is an indicator of the ventilation in a room (Scheff et al., 2000). The calculated outdoor airflow rates of the selected households for every half an hour both in summer and winter periods are given in Table 2. It has been found that during winter period, the ventilation rate is less than in summer period (Goyal and Khare, 2009). During winters, the ventilation conditions at Site I were *poor* for 58% of times and *average* for remaining 42% of time. At Site II, the ventilation conditions are *good* for 67% of time in winters. In

summer period, the ventilation conditions are *excellent* for 58% of time at Site I and 100% at Site II.

Table 1. Typical Met levels for various activities

Activity	Met
Seated, quiet	1
Reading and writing, seated	1
Walking at 0.9 m/s	2
House cleaning	2.0-3.4
Exercise	3.0-4.0

2.5. Statistical analysis

Indoor/outdoor (I/O) ratios were calculated for all the pollutants in both seasons. Linear regression analysis was performed to investigate the effects of outdoor air on indoor air concentration of pollutants. Regression analysis for concentrations NO_x could not be performed as the number of samples collected were limited. Each house had six samples for NO_x (three for summer and three for winters). Two tailed t-test was applied to the winter and summer concentrations of RSPM and CO .

3. Results and Discussions

3.1. Descriptive statistics

The time activity diaries were filled by the occupants and by volunteers in LIG–NZM and MIG–NZM houses as some of the occupants were illiterate and faced problems in filling up the questionnaire. The occupants at LIG–NZM and MIG–NZM were the employees of Delhi railways and were living in the quarters allotted to them. These occupants were living in one room apartments and the mean number of occupants were $5.9(\pm 1.2)$ and $4.6(\pm 1.24)$ in

LIG–NZM and MIG–NZM, respectively (Table 3). Each family had 3–4 children on an average or the grandparents were also living together.

There was only one window in most of these houses which used to be closed during winters or blocked by water coolers (a room cooling system using an exhaust fan and drapes of moss grass moistened with water) during the summer season. This demonstrated unawareness amongst the occupants regarding ventilation and its benefits. New Delhi has to face extremes of temperatures during summer and winter seasons. The temperatures are as high as 45°C during summers whereas the winters record a low of $2\text{--}4^\circ\text{C}$. The use of room heaters during winters is not conventional in India and is financially costly for LIG and MIG families.

During winters, the doors and windows were found to be closed for most of the sampling hours. At LIG–NZM and MIG–NZM, only 2% and 15% houses had a separate kitchen, respectively (Table 3). Due to shortage of space, the cooking was carried out in that one room though the number of meals that were being cooked were more. Only male occupants were found to be smoking in all the households at Site I.

The cleaner fuel, prominently used in India, is Liquefied Petroleum gas (LPG) and it costs around \$ 1.55/L. This is a costly option for the families whose monthly income is less than \$ 40. The cheaper option for cooking fuel is cow dung cakes which can be procured at \$ 0.22/kg or twigs of wood which can be collected from farms and gardens. The LIG–NZM (97%) and MIG–NZM (78%) families were using either of these options (Table 3). This is also the reason for more time being spent by the occupants for fuel burning and cooking.

Table 2. Calculated outdoor airflow rate and evaluation of IAQ in homes

Time	Winter		Summer	
	Qo (CFM ^a /person)	Ventilation level	Qo (CFM ^a /person)	Ventilation level
Site I (Sampling site)				
10:00-10:30 a.m.	12.43	Poor	73.94	Excellent
10:30-11:00 a.m.	11.21	Poor	65.48	Excellent
11:00-11:30 a.m.	16.48	Average	32.44	Good
11:30-12:00 noon	17.43	Average	37.33	Good
12:00 noon-12:30 p.m.	10.23	Poor	43.65	Good
12:30-13:00 p.m.	18.67	Average	54.33	Excellent
13:00-13:30 p.m.	13.49	Poor	60.84	Excellent
13:30-14:00 p.m.	13.34	Poor	41.24	Good
14:00-14:30 p.m.	18.45	Average	38.98	Good
14:30-15:00 p.m.	12.32	poor	65.36	Excellent
15:00-15:30 p.m.	27.33	Average	58.44	Excellent
15:30-16:00 p.m.	25.33	Average	85.34	Excellent
Site II (Control site)				
10:00-10:30 a.m.	27.33	Average	93.46	Excellent
10:30-11:00 a.m.	32.67	Good	84.32	Excellent
11:00-11:30 a.m.	42.45	Good	100.45	Excellent
11:30-12:00 noon	28.73	Average	72.42	Excellent
12:00 noon-12:30 p.m.	38.17	Good	84.84	Excellent
12:30-13:00 p.m.	48.28	Good	69.01	Excellent
13:00-13:30 p.m.	36.51	Good	67.40	Excellent
13:30-14:00 p.m.	45.77	Good	73.56	Excellent
14:00-14:30 p.m.	56.22	Excellent	54.20	Excellent
14:30-15:00 p.m.	36.44	Good	62.37	Excellent
15:00-15:30 p.m.	39.03	Good	71.22	Excellent
15:30-16:00 p.m.	42.16	Good	84.88	Excellent

If $Q_o < 15$ CFM/person, IAQ is poor in homes (ASHRAE 1993)

^a CFM: cubic feet per minute

Excellent: goal for predisposed or sensitized occupants

Good: goal for most occupants; minimum standard for predisposed occupants

Average: goal for most occupants; complaints of stale air and odors are still possible

Poor: indicates inadequate ventilation and a high potential for complaints

Table 3. Demographic and household characteristics of the occupants

Variable	Site I			Site II		
	LIG-NZM(30) Mean± SD	MIG-NZM(30) Mean± SD	HIG-NZM(30) Mean± SD	LIG-I.I.T(30) Mean± SD	MIG-I.I.T(30) Mean± SD	HIG-I.I.T(30) Mean± SD
Age(years) of occupants	40.2±7.7	41.1±7.2	38.8±7.4	41.3±7.4	41.9±6.3	41.4±5.5
Number of rooms	1±0.0	1.63±0.4	2.67±0.4	2.1±0.8	3.5±1.1	4.2±1.4
Number of occupants	5.9±1.2	4.6±1.24	3.9±0.9	4.0±1.0	3.3±0.9	2.6±0.6
Number of windows in the house	0.73±0.5	0.80±0.5	2.73±0.4	2±0.0	4±0	6.2±1.6
Number of doors in the house	1.03±0.1	1.03±0.1	3.62±1.6	2.0±1.18	3.0±0.88	5.2±1.2
Fuel burning duration(min/day)	254±76	246±57	115±52	97±32	112±45	122±34
Occupant's time spent in kitchen during fuel burning on sampling day(min/day)	241±67	199±82	102±71	84±22	78±26	72±28
Duration of doors and windows openings on the day of sampling(min/day)						
a. Summers	356±72	289±61	343±59	312±47	289±71	141±62
b. Winters	68±22	52±19	74±26	72±31	59±22	43±17
Percent (%)						
Cooking done in separate kitchen	02	15	96	97	100	100
Frequency of cooking 3-4 times/day	78	64	38	34	22	28
Presence of smoker in home	37	39	22	21	15	32
Number of houses using biomass fuel	97	78	02	None	None	None

At Site II, the questionnaire was duly filled by the occupants as they were employed in the educational institution. LIG–IIT occupants were allotted two room houses with a separate kitchen (97%) with an exception of 3% who preferred to have kitchen with partition in one of the rooms (Table 1). None of the families were found to be using biomass fuels for cooking. They were all using LPG for cooking and had at least one window in the kitchen. MIG (3.5) and HIG (4.2) houses had 3–4 rooms whereas the number of occupants varied between 2–3 persons.

The cooking time was also shortened considerably at Site II (72–84 min/day) due to use of cleaner fuels. As most of the families were nuclear with both the parents working the frequency of cooking done 3–4 times in a day was less and only 22–34% families used to cook 3–4 meals a day.

3.2. Indoor and outdoor pollutant concentration

Table 4 shows a summary of mean concentration of pollutants at both sampling sites. Maximum variation is observed in mass concentration of particulate matter during cooking with concentrations in the range of 1 000–2 500 $\mu\text{g}/\text{m}^3$. The high concentration levels of aerosols are a common feature in south Asian countries. A study (Dasgupta et al., 2006) carried out in Bangladesh suggests that household variation is strongly affected by structural arrangements: cooking locations, construction materials, cooking fuel and ventilation practices. A large variation in PM_{10} was also found during the 24-h cycle within households. For example, within the dirtiest firewood using household readings over the 24-h cycle vary from 68 to 4 864 $\mu\text{g}/\text{m}^3$. Such variation occurs because houses can recycle air very quickly in Bangladesh.

During summers, PM_{10} outdoors is higher than indoors because of enhanced dispersion due to unstable atmospheric conditions as shown in Figure 4. During winters, the concentration indoors is higher than outdoors (Table 4). Ezzati and Kammen (2002) have mentioned in their study that a typical 24-h average concentration of PM_{10} in homes using biomass fuels may range from 200–500 $\mu\text{g}/\text{m}^3$ or more throughout the year depending on the type of fuel, stove and housing. The concentration of fine particles is higher during cooking indoors in winters as shown in Figure 4. LIG (1, 2 and 3) and MIG dwellings in the Site I have been using cow dung cake and wood as the cooking fuel, which on combustion releases coarse and fine particulate matter. In winters,

the occupants burn wood and coal to keep them warm which increases the particulate matter concentration in the indoor air. Such variations are primarily dependent on the quality (dryness) of biomass fuel used, duration of cooking, degree of incomplete combustion and ventilation (Colbeck et al., 2010). The concentration of finer particles is higher during the cooking time (Figure. 4). This finding is similar to the results of Park and Lee (2003) who pointed out that particulate matter increases rapidly during cooking and decreases quickly after cooking. It has been seen that in kitchens, it can take up to an hour for the indoor air to reasonably clear after cooking (Colbeck et al., 2010). The coarser particles settle down faster whereas the fine particles remain suspended in the air for a longer duration. The concentration of CO is much higher in Site I due to the proximity of the homes to railway station and the heavy vehicular traffic especially during the morning hours from 10:00 to 14:00. The high concentration of CO outdoors is infiltrated indoors more during summers as the doors and windows are mostly open.

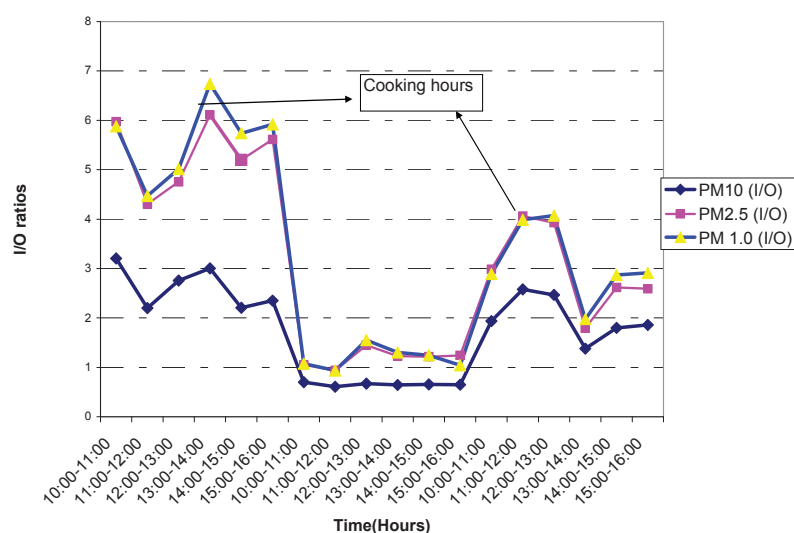
The concentration of CO is comparatively less in Site II. This can be attributed to the fact that there is negligible commercial activity in this area and the vehicular traffic is also lower than the Site II. The concentration of particulate matter is not considerably lower but the origin of particles are the activities being carried out indoors like children playing, burning of incense sticks and cleaning.

3.3. Indoor/outdoor ratios

The I/O ratio PM_{10} , $\text{PM}_{2.5}$ and PM_{1} is more than unity in all the homes during winters indicating that the concentration of RSPM is higher indoors than outdoors (Table 5). One of the main reasons for this is the fact that during winters the doors and windows are closed. In India, heating of the homes is not a common practice so the occupants close the doors and windows to avoid the entry of cold wind. The finer the particles, the higher are the I/O ratios at both sampling sites. It can therefore, be inferred that the higher I/O ratios of finer particles ($\text{PM}_{2.5}$ and $\text{PM}_{1.0}$) are the result of indoor generated activities. In Site I, the homes have been using cow dung cake and wood as the cooking fuel that results in generation and rise in the concentration of particles. Burning of incense sticks, cleaning and playing of kids indoors during winters are the other factors which result into higher particulate matter concentrations (Figure 5). The I/O ratio of NO_x is higher than unity.

Table 4. Summary of mean hourly indoor and outdoor pollutant concentrations and standard deviation (SD) for the two sites

Seasons	PM ₁₀ (µg/m ³)		PM _{2.5} (µg/m ³)		PM _{1.0} (µg/m ³)		CO (ppm)		NO _x (µg/m ³)	
	I±SD	O±SD	I±SD	O±SD	I±SD	O±SD	I±SD	O±SD	I±SD	O±SD
Summer										
LIG 1	192±67	322±96	45±31	53±43	30±24	36±36	4±1.07	5±0.6	245±32	163±23
LIG 2	143±32	218±67	57±10	59±18	36±7.5	35±12	6±1.4	7±1.1	220±10	237±22
LIG 3	199±73	285±82	53±23	68±40	29±14	41±33	5±0.7	7±1.69	223±11	169±16
MIG	136±36	357±174	60±116	73±12	36±13.4	41±5	8±1.1	7±1.6	179±12	141±17
HIG	107±93	288±111	34±24	48±44	23±17	31±36	3±0.8	7±0.67	65±11	88±6
LIG-IITD	345±156	598±207	98±13	113±16	47±9	55±13	1.6±0.5	3.6±1.1	73±7	81±6
MIG-IITD	506±305	135±36	110±58	61±15	47±27	36±14	1.2±0.6	3±0.9	65±9	62±15
HIG-IITD	104±87	100±53	43±24	52±20	29±18	38±14	1.80±0.4	2±0.5	62±14	59±5
Winter										
LIG 1	1 022±1 009	391±204	936±970	166±106	823±804	139±92	5.2±1.2	3.7±0.7	117±13	78±4.5
LIG 2	396±210	617±254	227±152	201±89	200±145	172±80	6±1.2	5±0.9	104±16	81±18
LIG 3	894±924	653±338	713±933	287±274	623±782	252±247	5.5±0.7	5±2	86±4	71±7
MIG	373±185	579±230	232±94	267±109	200±84	232±97	5±1.1	4±1	95±12	70±9
HIG	586±239	310±107	197±87	56±43	169±79	37±35	2±0.8	3.6±1	95±5	71±7
LIG-IITD	241±124	207±105	90±65	69±48	75±60	53±38	0.2±0.4	1.8±0.7	52±5	77±16
MIG-IITD	350±351	207±86	145±115	74±45	121±102	57±40	0.61±0.2	3±0.93	46±6.6	42±6.5
HIG-IITD	507±141	261±120	230±107	112±53	200±96	90±44	0.24±0.1	1.3±0.5	62±5.5	72±5.6

**Figure 4.** The observed peaks during the cooking hours while using biomass fuel in winters.

It may be due to the use of gas stoves that were not being properly cleaned and maintained by the occupants. The I/O ratios of CO has been found to be less than one during winters suggesting that the major source of CO is heavy outdoor sources like vehicular traffic (Figure 5h).

The coefficient of determination (R^2) between indoor and outdoor data is used as an indicator of the degree to which RSPM and CO measured indoors is attributed to infiltration from outdoors (Colome et al., 1992; Clayton et al., 1993; Geller et al., 2002; Chaloulakou et al., 2003). It is important to note that the sample size used for the univariate regression curves in this study is relatively small ($n=36$) and there is a possibility that the correlation coefficients are significantly affected by one or two extremely high data points. For these reasons, interpretation of the correlation results should be taken as suggestive rather than definitive. Figure 5a, 5c, and 5e shows weak correlations between outdoor and indoor RSPM data ($R^2=0.03$, $R^2=0.34$ and $R^2=0.32$, respectively) at Site I. The weak indoor to outdoor RSPM association at Site I suggests that a substantial fraction of both coarse and fine particles are generated by indoor sources and activities such as cooking, cleaning, dusting, burning of incense sticks and re-suspension, all of which depend on the occupants of each home.

Table 5. Summary of I/O ratios of pollutants at both sites in winter and summer seasons

Season	PM ₁₀ (µg/m ³) (I/O)	PM _{2.5} (µg/m ³) (I/O)	PM _{1.0} (µg/m ³) (I/O)	CO (ppm) (I/O)	NO _x (µg/m ³) (I/O)
Summer					
LIG 1	0.60±0.12	0.85±0.26	0.83±0.30	0.8±0.18	1.5±0.38
LIG 2	0.66±0.22	0.97±0.38	1.03±0.68	0.8±0.09	0.9±0.09
LIG 3	0.70±0.30	0.78±0.43	0.71±0.39	0.71±0.18	1.31±0.08
MIG	0.38±0.19	0.82±0.18	0.88±0.35	1.14±0.14	1.26±0.06
HIG	0.37±0.27	0.71±0.64	0.74±0.75	0.43±0.18	0.73±0.07
LIG-IITD	0.58±0.23	0.87±0.05	0.87±0.13	0.53±0.22	0.90±0.14
MIG-IITD	3.75±2.35	1.80±1.34	1.72±1.31	0.40±0.24	1.04±0.17
HIG-IITD	1.04±0.70	0.83±0.33	0.77±0.33	0.90±0.20	1.05±0.28
Winter					
LIG 1	2.61±2.7	5.64±4.9	5.64±5.2	5.92±0.12	1.28±0.07
LIG 2	0.64±0.18	1.13±0.79	1.29±0.90	1.16±0.10	1.21±0.12
LIG 3	1.37±1.56	2.48±2.11	2.40±2.19	2.47±0.11	1.00±0.08
MIG	0.64±0.15	0.87±0.16	0.86±0.16	0.86±0.11	1.36±0.07
HIG	1.89±0.85	3.52±1.83	5.88±2.75	4.57±0.06	1.34±0.06
LIG-IITD	1.16±0.95	1.30±0.52	1.42±0.61	0.11±0.39	0.68±0.52
MIG-IITD	1.69±1.27	1.96±2.31	2.12±3.23	0.20±0.09	1.10±0.02
HIG-IITD	1.94±1.37	2.05±1.31	2.22±1.41	0.17±0.08	0.86±0.02

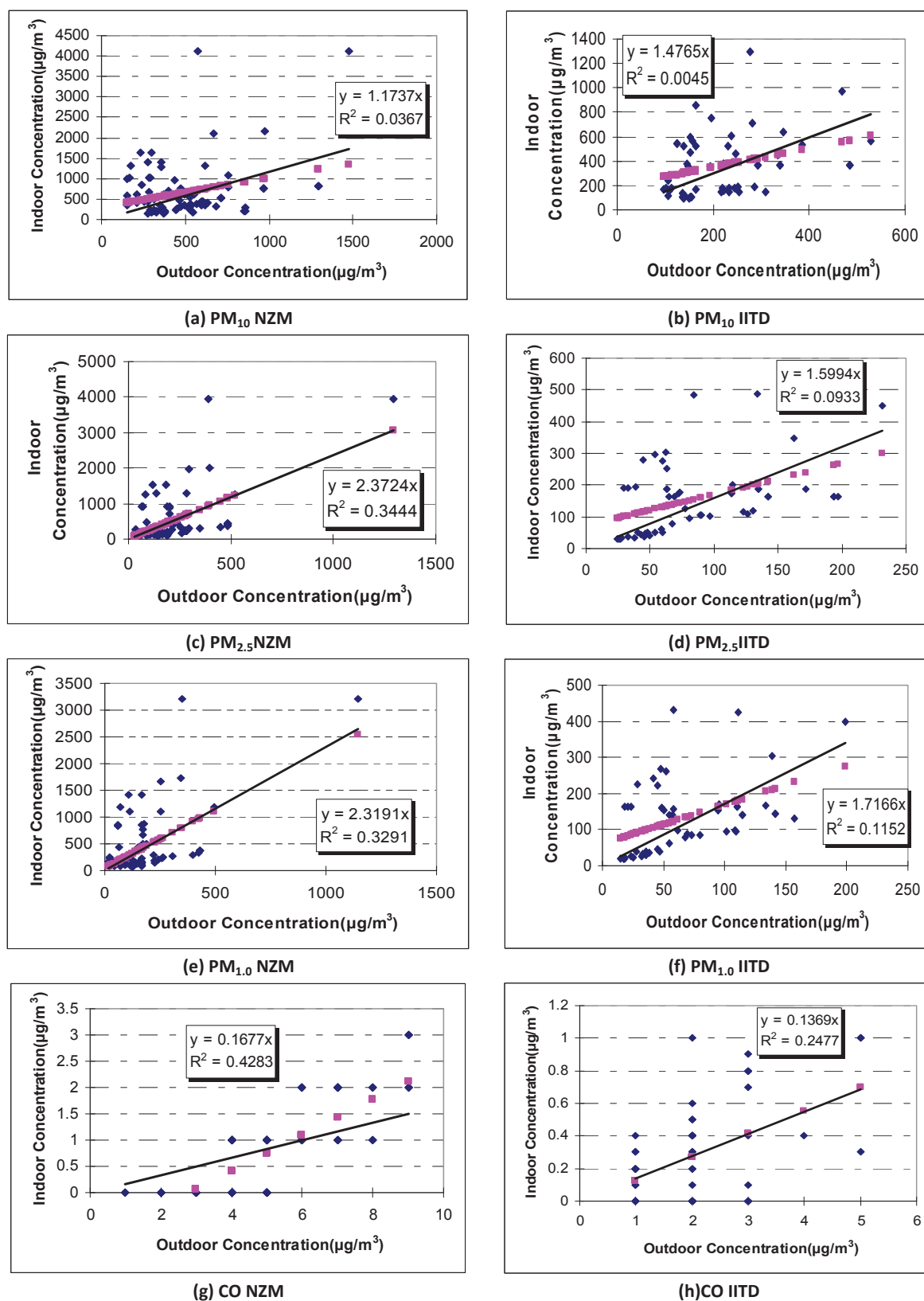


Figure 5. Indoor/outdoor comparison of pollutants during winter season by sites: (a) and (b) PM_{10} , (c) and (d) $PM_{2.5}$, (e) and (f) $PM_{1.0}$, and (g) and (h) CO

Figure 5g shows the indoor versus outdoor concentrations for CO. The average indoor to outdoor CO mass concentration ratio is 2.99 ± 2.19 at Site I in winters. The high concentration of CO indoors implies that several additional factors related to indoor activities influence IAQ during the winters, in addition to penetration of outdoor air and meteorological factors. These include indoor activities, duration of human occupancy and ventilation (Baek et al., 1997). This observation is similar to a study conducted in Korea, where homes rely on coal briquettes as heating and cooking fuels leading to elevated indoor CO levels particularly during cold winter months (Son et al., 1990). The data plotted in Figure 5g indicate that outdoor concentrations can explain only 42% of the variation of the indoor concentrations thereby suggesting that there may be significant contributions by indoor sources to the CO concentrations in the five homes at Site I monitored during the study. The main source which is indicated from the time activity diary is the burning of biomass fuel for cooking especially in the LIG homes. The cooking is done with either cow dung cakes or wood, as they are much cheaper, than the clean fuels but take longer duration to burn. The occupants of LIG houses are living in one room and keep the window closed during winters, which increases the concentration of indoor pollutants. Figures 5b, 5d, and 5f show the plots of the indoor versus outdoor concentrations for PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ in Site II homes. Wintertime I/O ratios of RSPM were 1.59, 1.77 and 1.92 respectively for PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ at Site II suggesting the presence of an indoor source. The data plotted in Figure 5 indicate that the outdoor concentrations can explain only about 0.4%, 9% and 11% of the variation of indoor concentrations at Site II, thereby, suggesting that there may be significant contributions by indoor sources to the overall RSPM. During sampling hours in winters at Site II the occupancy of the houses is high as the winter vacations were going on and the children were at home. The doors and windows were mostly closed during winters which increased the accumulation of RSPM inside the houses. Additional differences in the home structural characteristics, number of occupants and activity patterns of individuals in each of these homes also contribute to the overall variability in the indoor RSPM concentrations. Similar findings have been reported in a recent study (Dasgupta et al., 2006) conducted in Bangladesh, suggesting that cross-household variation is strongly affected by structural arrangements: cooking locations, construction materials, and ventilation practices. Other studies also show that cooking generated substantial amounts of super-micrometer particles (Siddiqui et al., 2009; Colbeck et al., 2010).

I/O ratio for CO in Site II homes is found to be 0.16 ± 0.04 indicating that the concentration of CO indoors may be primarily due to infiltration from outdoors. Figure 5h suggests that only 24% of the variation in indoor concentrations can be explained by outdoor concentrations. CO is a pollutant emitted by traffic and no indoor CO sources were present at Site II. As Site II is primarily an institutional area, the density of vehicular traffic is low compared to Site I.

Table 5 shows that I/O ratios of RSPM in Site I during summers is found to be less than one in all the homes though the fraction of finer particles is very close to unity. Since, the outdoor values are very low during summer, the I/O ratio is close to unity. Figure 6a, 6c, and 6e also show a weak correlation between the outdoor and indoor data ($R^2=0.10$, $R^2=0.09$, $R^2=0.04$) of PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ respectively. The I/O ratios of CO were observed to be 0.77 in Site I during the summer season suggesting that the prominent fraction of CO infiltrates from outdoors. As already noted earlier, this is attributed mainly to the fact that Site I is in very close proximity to a railway station due to which the vehicular traffic density in that area is high. Figure 6g shows that 32% of variation in the indoor concentration of CO can be attributed to outdoor air ($R^2=0.325$). The I/O ratio of NO_x is 0.75 (Table 3) which suggests the presence of outdoor source. In summers, due to the frequent failure of electricity, heavy generators are used outside the homes, which also contribute to higher concentration outdoors.

The I/O ratios PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ at Site II during summer season were found to be higher than 1.0 indicating a presence of an indoor source. The main reason for this was identified as the increase in occupancy levels along with activity levels of the occupants. The children were having their summer vacations when the monitoring was carried out in the homes which can be an important reason for increase in concentration of particulate matter indoors (Table 5). These findings are strongly supported by the linear regression analysis results (Figure 6b, 6d, and 6f) showing that a very weak correlation exists between indoor and outdoor data i.e. PM_{10} ($R^2=0.03$), $PM_{2.5}$ ($R^2=0.007$) and $PM_{1.0}$ ($R^2=0.003$). I/O ratio of CO was found to be 0.61 in summers suggesting the infiltration of pollutant from outdoors. Figure 6h shows the plot which indicated that only 8% of the indoor environment is being affected by outdoor air concentrations. This finding is supported by findings of Lawrence et al (2004) where only 0.5% correlation was established between indoor and outdoor CO concentration at roadside homes in Agra.

A comparison between indoor and outdoor concentration of pollutants in a house using biomass fuel at Site I and a house using LPG at Site II is shown in Figures 7 and 8. The data plotted in Figure 7 indicate that outdoor concentration can explain only 34% and 32% of the variation in indoor concentration of the finer particles i.e., $PM_{2.5}$ and $PM_{1.0}$. The data in Figure 8 suggests that 93% of variation in fine particulate matter concentration results from outdoor air. The concentration of particulate matter in winters at Site II is less than that at Site I. The main reason for this difference is attributed to the type of cooking fuel used. The occupants at Site I use cow dung cake or wood for cooking whereas the occupants at Site II use LPG for cooking.

3.4. Winter/summer ratios

Seasonal variations of pollutants are evaluated using the winter/summer (W/S) concentration ratios shown in Table 6. A winter–summer paired sample t-test is also applied to determine whether the summer or winter mean concentration is significantly higher. PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ showed W/S ratios to be higher than 1.0 in all the households in Site I, indicating that both ambient and indoor concentrations are higher in winters than in summer. Results revealed that there is a statistically significant difference between winter and summer outdoor $PM_{2.5}$ and CO concentrations (paired t-test, $p<0.05$) in LIG 1, outdoor CO concentrations in LIG 2, outdoor PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ concentrations in LIG 3 and outdoor PM_{10} and CO concentrations in MIG at Nizamuddin site (Table 4). The W/S ratios for PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ are found to be higher than 1.0 in all the homes at Site I suggesting that the indoor pollutant concentrations are worse in winters. Use of biomass fuels indoors in winters, burning of incense sticks and cleaning activities were found to be the main sources. Besides, as heating of homes is not a convention in India during winters, the occupants have to keep the doors and windows closed which further worsened the condition.

Summer concentrations of outdoor $PM_{2.5}$ in LIG Site II, PM_{10} in MIG Site II and PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ in HIG Site II were significantly higher than the winter concentrations. The condition is observed to be much more within control at Site II (with the exception of HIG house). This can be attributed to the fact that Site II has large open playing grounds, greenery and is less congested than Site I. The W/S ratio for CO reveals that at Site I outdoors the concentration of CO is higher as compared to Site II and the reason for this can be low traffic density at Site II. These results are in agreement with Pekey et al. (2009) who analyzed the variations in PM_{10} and $PM_{2.5}$ and their elemental compositions in summer and winter and indicated that winter concentrations of

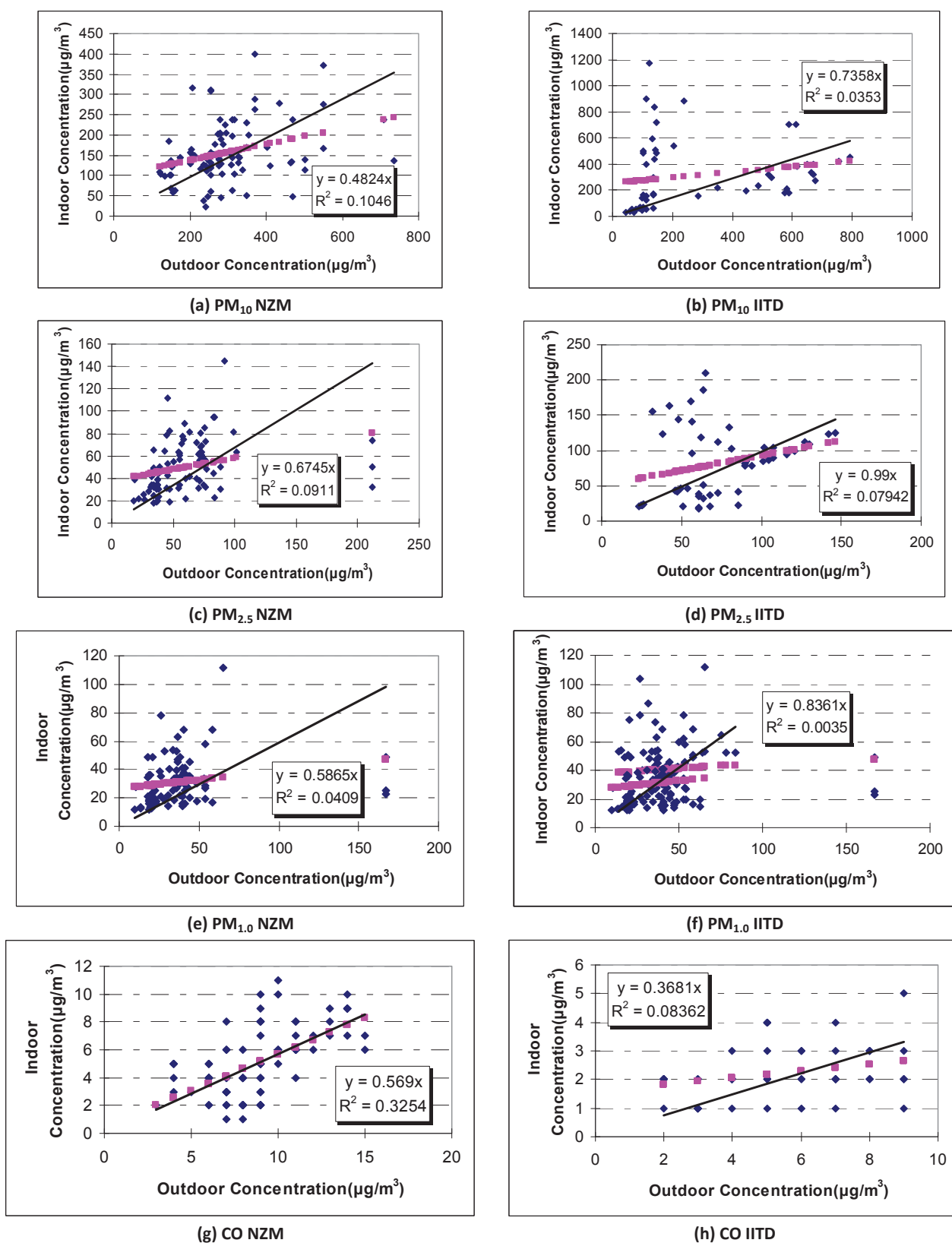


Figure 6. Indoor/outdoor comparison of pollutants during summer season by sites: (a) and (b) PM_{10} , (c) and (d) $PM_{2.5}$, (e) and (f) $PM_{1.0}$ and (g) and (h) CO.

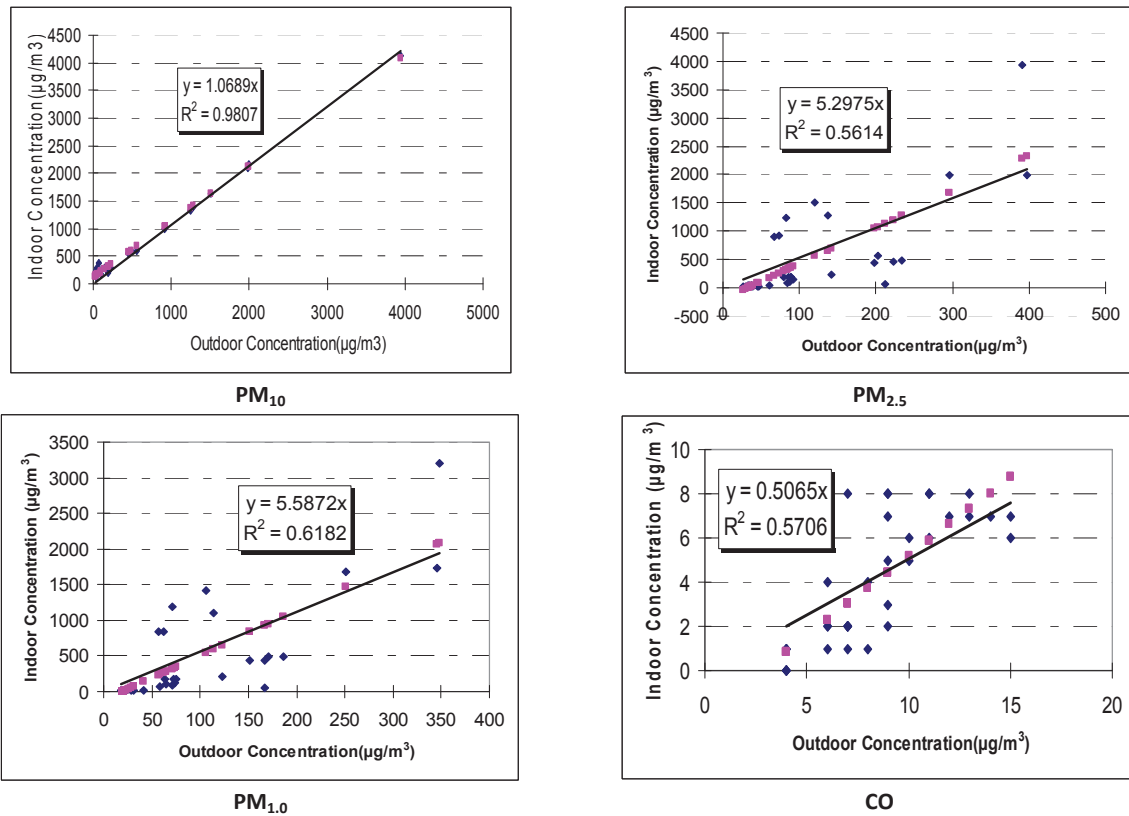


Figure 7. Concentrations of PM₁₀, PM_{2.5} and PM_{1.0} in LIG using biomass fuel for cooking at Site I.

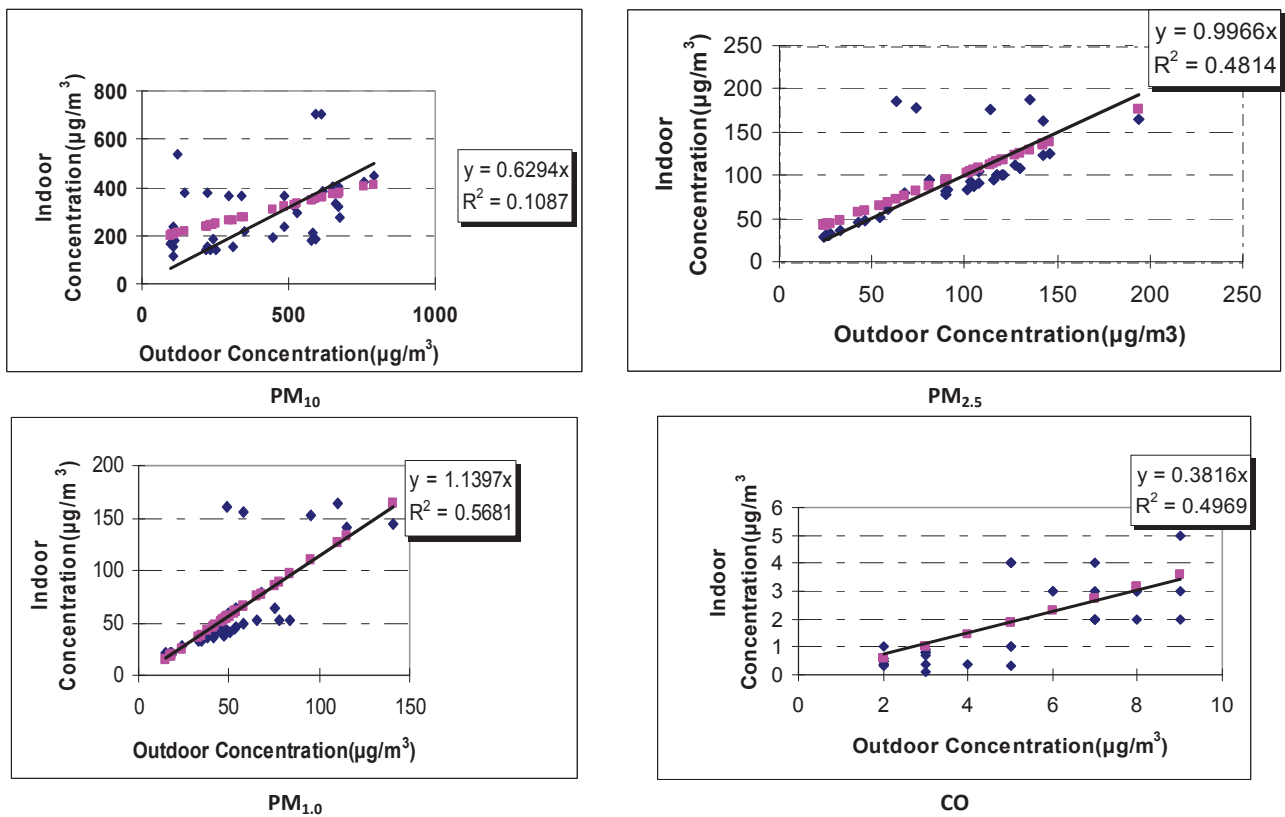


Figure 8. Concentrations of PM₁₀, PM_{2.5} and PM_{1.0} at LIG-IIT using LPG for cooking (Site II).

Table 6. Winter/Summer concentration ratios of PM_{10} , $PM_{2.5}$, $PM_{1.0}$ and CO

NZM site	W/S ^a Indoor \pm SD	W/S ^a Outdoor \pm SD	W/S ^b P value Indoor	W/S ^b P value Outdoor
LIG 1				
PM ₁₀	5.31 \pm 4.39	1.21 \pm 0.71	0.002 ^c	0.150
PM _{2.5}	22.13 \pm 16.95	3.18 \pm 1.49	0.001 ^c	0.000 ^c
PM _{1.0}	30.85 \pm 23.46	4.25 \pm 1.83	0.000 ^c	0.65
CO	0.22 \pm 0.56	0.59 \pm 0.21	0.015 ^c	0.000 ^c
LIG 2				
PM ₁₀	2.84 \pm 1.69	2.77 \pm 0.71	0.000 ^c	0.09
PM _{2.5}	4.08 \pm 3.24	3.51 \pm 1.49	0.000 ^c	0.16
PM _{1.0}	5.94 \pm 4.76	5.16 \pm 2.22	0.000 ^c	0.18
CO	0.14 \pm 0.37	0.50 \pm 0.23	0.810	0.009 ^c
LIG 3				
PM ₁₀	5.23 \pm 4.76	2.34 \pm 1.11	0.005 ^c	0.000 ^c
PM _{2.5}	15.26 \pm 16.11	4.52 \pm 3.33	0.007 ^c	0.002 ^c
PM _{1.0}	23.65 \pm 24.65	7.13 \pm 6.13	0.004 ^c	0.001 ^c
CO	0.14 \pm 0.19	0.83 \pm 0.53	0.36	0.08
MIG				
PM ₁₀	2.88 \pm 1.34	2.06 \pm 1.25	0.000 ^c	0.008 ^c
PM _{2.5}	4.19 \pm 2.06	3.71 \pm 1.46	0.12	0.59
PM _{1.0}	6.17 \pm 3.74	5.72 \pm 2.44	0.09	0.85
CO	0.20 \pm 0.17	0.50 \pm 0.26	0.07	0.000 ^c
HIG				
PM ₁₀	9.40 \pm 6.94	1.18 \pm 0.50	0.24	0.44
PM _{2.5}	7.33 \pm 4.37	1.57 \pm 1.69	0.70	0.55
PM _{1.0}	9.57 \pm 5.69	1.83 \pm 2.61	0.059	0.59
CO	0.02 \pm 0.86	0.49 \pm 0.17	0.31	0.11
IITD site				
LIG IITD				
PM ₁₀	0.81 \pm 0.54	0.37 \pm 0.24	0.01	0.06
PM _{2.5}	0.93 \pm 0.68	0.61 \pm 0.43	0.59	0.001 ^c
PM _{1.0}	1.54 \pm 1.13	0.93 \pm 0.58	0.05	0.808
CO	0.01 \pm 0.29	0.63 \pm 0.41	0.43	0.001 ^c
MIG IITD				
PM ₁₀	0.81 \pm 0.68	1.54 \pm 0.45	0.161	0.000 ^c
PM _{2.5}	1.29 \pm 0.61	1.25 \pm 0.66	0.145	0.217
PM _{1.0}	2.48 \pm 1.35	1.82 \pm 1.26	0.003	0.059
CO	0.20 \pm 0.55	0.42 \pm 0.34	0.001 ^c	0.81
HIG IITD				
PM ₁₀	8.51 \pm 4.59	2.87 \pm 1.39	0.18	0.000 ^c
PM _{2.5}	6.72 \pm 2.90	2.34 \pm 1.53	0.023	0.000 ^c
PM _{1.0}	8.15 \pm 3.42	2.98 \pm 3.17	0.003 ^c	0.000 ^c
CO	0.15 \pm 0.09	0.34 \pm 0.21	0.08	0.008

^a Winter/summer concentration ratios^b P values were calculated from paired t test, for comparing summer and winter concentrations^c P < 0.05**Table 7.** Regression analysis between individual residential indoor and their respective ambient-outdoor PM_{10} , $PM_{2.5}$ and $PM_{1.0}$ and CO at both monitoring sites

Households	PM_{10} (n=36)		$PM_{2.5}$ (n=36)		$PM_{1.0}$ (n=36)		CO (n=36)	
	R ²	β	R ²	β	R ²	β	R ²	β
LIG 1	0.98	1.06	0.56	5.29	0.61	5.58	0.57	0.51
LIG 2	0.78	0.65	0.42	1.06	0.4	1.08	0.70	0.50
LIG 3	0.33	1.23	0.76	2.61	0.76	2.52	0.42	0.65
MIG	0.65	0.56	0.93	0.86	0.93	0.85	0.47	0.27
HIG	0.05	1.16	0.02	1.56	0.02	1.68	0.40	0.31
LIG-IITD	0.10	0.62	0.48	0.99	0.56	1.13	0.42	0.34
MIG-IITD	0.07	2.34	0.02	1.53	0.01	1.34	0.49	0.38
HIG-IITD	0.23	1.49	0.42	1.63	0.49	1.79	0.33	0.26

outdoor $PM_{2.5}$ are significantly higher than the summer concentrations.

3.5. Regression analysis

Table 7 shows the values of R^2 at both sites including both seasons. The finer particles ($PM_{2.5}$ and $PM_{1.0}$) show a strong

correlation ($R^2=0.56-0.93$) between indoor and outdoor data in LIG 1, LIG 3 and MIG homes at Nizamuddin site which indicate that outdoor concentrations can explain 56%–93% of variations in indoor concentrations thereby suggesting penetration of particulate matter from outdoors. CO shows a moderately strong correlation in the range of 40% to 70% variations in indoor concentrations due to outdoor concentrations at Site I.

4. Conclusions

The maximum exposure due to health-damaging indoor pollution probably occurs in developing world, where the exposure studies and development of database is still at a preliminary stage. India being a tropical country faces extremes of climate especially in the northern region and predominant usage of biomass fuels for cooking and heating further deteriorates the problem of IAQ. This study investigates the relationships between indoor and outdoor air quality using I/O ratios and linear regression analysis in eight residences in Delhi, the capital of India during the summer and winter period. The mean I/O ratios of RSPM and CO are found to be more than unity ($PM_{10}=1.43\pm0.84$, $PM_{2.5}=2.72\pm1.94$, $PM_{1.0}=3.21\pm2.39$ and $CO=2.99\pm2.19$) in the five households at Site I during winters indicating a presence of an indoor source. According to the time activity results, the reasons for such high concentrations were cooking with biomass fuels and closure of doors and windows for most time during the day. I/O ratios for CO at Site II during winters are found to be $0.16(\pm0.04)$ which is much lower than Site I due to lower traffic density and cooking with cleaner fuels. The linear regression results of RSPM also show a weak correlation between indoor and outdoor concentrations (PM_{10} $R^2=0.03$, $PM_{2.5}$ $R^2=0.34$ and $PM_{1.0}$ $R^2=0.32$, respectively) indicating an indoor source. The W/S ratios of RSPM at Site I ranged between $2.84-30.85(\pm8.65)$ further supporting our findings that the finer particles contributed a major fraction to the particulate matter concentration especially during winters. The trend of increased indoor pollution during the winter months when compared with the summer months implies that several factors influence indoor air quality during winters, including the indoor activities like cooking and cleaning, meteorological factors, ventilation and human occupancy. As there are no standards available for indoor air quality in India, the findings were compared with available WHO guidelines (WHO, 2005). Ignorance about the benefits of proper ventilation and use of cleaner fuels along with weak financial stability were found to be the important factors contributing to exposure to indoor air pollutants. A lesser amount of attention has focused on improved fuels, possibly because it is deemed more feasible to change the design of stoves than fuels. The use of hoods and modifying house design to increase ventilation are also possible interventions for reducing IAP. Improved stoves are the most obvious and popular technical response to reducing IAP. Improving housing design also increases cross ventilation within the households, thereby results in dispersion of indoor smoke. The kitchen or cooking area can also be designed to reduce IAP. If a stove is close to doors or windows, emissions will be dispersed. The stove at waist height will reduce the emissions inhaled by the user. Education about the impacts of smoke on health is an essential component of IAP interventions, as often people are unaware or have lay beliefs about the risks. Keeping children away from the fire and smoke is a practical way to reduce children's exposure. Drying wood prior to burning, cutting wood into smaller pieces, and extinguishing the fire immediately after use can also reduce emissions. Cooking time can be reduced by pre-soaking food, preparing food before lighting the fire and using lids. A major intervention that should be adopted in developing countries by the governmental agencies is provision of incentives for shifting to efficient and high-energy fuels.

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