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ULTRAFINE PARTICLES IN RURAL AND URBAN DWELLINGS WITH DIFFERENT HOUSEHOLD FUEL USE IN DEVELOPING COUNTRIES – AN EXAMPLE FROM PAKISTAN

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ABSTRACT

Exposure to indoor particulate matter (PM) is a major public health concern, in particular, in developing countries where solid fuels are typically used as a household energy source.Despite the fact that emission from these fuels can have a dominant fraction of ultrafine particles, exposure to PM is generally characterised in terms of mass concentration of PM_{10} and $PM_{2.5}$. The present study was carried out to examine the number concentration of ultrafine particles in rural and urban Pakistani households with different fuels. Air samples were collected from kitchens, living rooms and courtyards of two rural sites (Site I - Solid fuel; Site II - Natural gas) and an urban site (Natural gas) by using condensation particle counters.At rural site –I the 24 hour mean concentration of particles in the kitchen, living room and outdoors was 40,991#/cm^3 (± 7472), 30,291#/cm^3 (± 13774) and 34,534#/cm^3 (± 4947), respectively. During cooking the number concentration can increase significantly with an average hourly maximum value of 169,455#/cm^3. Higher outdoors levels than in living rooms highlight the effect of cooking in open kitchens on ambient levels. At the rural site II the daily average number concentration in living rooms was in the range of 10,745 – 16,126 #/cm^3 with a mean of 13,542 #/cm^3.These values were more than half those in living rooms at rural site I. Whereas in the kitchen the 24hour mean was 27,446#/cm^3 (± 4487). At the urban site the mean 24 hour average in the living rooms and kitchens was 45,466 #/cm^3 (± 5919)and 65,904 #/cm^3 (± 11490), respectively. The 24 hour mean concentration was more than double in the urban kitchens than in rural kitchens at site II. The 24 hour average outdoors was 33,424 #/cm^3 (± 6037)– slightly lower than outdoors at rural site I. Overall, the number concentration was higher in kitchens using natural gas fuel at the urban site than in those with solid fuels and natural gas at rural sites. While between rural sites the households with solid fuel had higher concentrations than those with natural gas. Furthermore, outdoors at rural site-I households had higher concentrations as compared to urban household outdoors.

Key words: Ultrafine particles, number concentration, household fuel, Pakistan

INTRODUCTION

Indoor air pollution (IAP) resulting from household energy use for range of purposes (e.g. cooking, heating, lighting) is a significant public health risk.The risk of exposure to IAP vary considerably from low to high income countries due to differences in the types and strength of air pollution sources. Globally, 2.8 billion people rely on solid fuels and the use of these as household cooking fuel in low efficiency stoves is one of the biggest sources of IAP (WHO, 2014). Women, young children and elderly are at increased risk of exposure to IAP due to amount of time spent in cooking areas. IAP is responsible for 4 million premature deaths and 5% of the global disease burden (Smith *et al*. 2014; Lim *et al*. 2013). It also significantly contributes to ambient air pollution (AAP) and 12% of deaths from AAP (0.4 million) are due to emissions from IAP (Smith *et al*. 2014). The reliance on solid fuels is concentrated in low to middle income countries mainly in Asia, Africa and Latin America (WHO, 2014). Hence the vast proportions of population in these countries are exposed to high levels of indoor air pollutants and have significant implications in terms of public health.

Like other developing countries the vast proportion of households in Pakistan use solid fuels (62%). The use of solid fuels is pervasive in rural areas where 87% of households rely on solid fuel in comparison to 13% in urban areas. Additionally, 94% of households do not have a separate space for cooking and cook inside the house and this trend is slightly higher in urban areas (95%) than rural (93%) (NIPS and ICF, 2013). Household members in these settings, in particular, women, children and elderly, are exposed to excessive levels of air pollutants. Hence a significant burden of disease is associated with indoor air pollution.

The information on the levels of indoor air pollution in Pakistani households is limited. Studies carried out recently have demonstrated that levels of different indoor air pollutants (CO, PM_{10}, $PM_{2.5}$, PM_1 and NO_2) were many times higher than WHO guidelines (Nasir *et al*. 2013; Colbeck *et al*. 2010a,b; Siddiqui *et al*., 2009). Likewise, studies on the health impacts of poor indoor air quality are rare (Janjua *et al*. 2012). With reference to interventions, scattered efforts have been made by government and nongovernmental organisations over the last three decades but still lacks serious consideration by policy makers (Colbeck*et al*. 2010c).

Among the cocktail of pollutants emitted from household fuels, particulate matter (PM) is of great concern due to its association with cardiopulmonary ailments.However, there is still considerable uncertainty about which physical and/or chemical characteristics of particles are the most important regarding health effects. A number of studies carried out to assess indoor air pollution in many low income countries have monitored mass concentration of PM (PM_{10} and $PM_{2.5}$) and revealed that levels of PM in kitchens using solid fuels were significantly higher than WHO guidelines (Helen *et al*. 2015;Oluwole *et al*. 2012;Fullerton *et al*. 2008). Historically the exposure to PM is characterised in terms of mass concentration of PM_{10} and $PM_{2.5}$, although emission from combustion sources will have a dominant fraction of ultrafine particles. Various studies advocate the importance of ultrafine particles due to their high number relative to their mass and because they may penetrate into the bloodstream leading to systemic effects (He *et al*. 2004). Nevertheless, most of the studies on exposure to PM due to solid fuels have focused on evaluating mass concentration of PM_{10} or $PM_{2.5}$ and knowledge on number concentration of ultrafine particles is relatively limited.

This study was part of a large scale investigation on indoor air quality in Pakistan and aims to report number concentration of ultrafine particles in rural and urban households with different fuel types. To the best of our knowledge no other study has reported the number concentration of ultrafine particles from households using solid fuels.

MATERIALS AND METHODS

Sampling Sites: Sampling sites were selected to reflect different households and fuels. Air sampling was carried out at two rural sites (Rural Site I - Chak NO.35/2.L and Rural Site II - Bhaun) and an urban site (Lahore) (Fig. 1). Rural site I uses predominantly solid fuels as household energy fuel while rural site II and urban site uses natural gas as household energy fuel.

Fig. 1. Location of sampling sites in Pakistan (Source: http://www.passportsrus.com/countries/pakistan.php)

A detailed description of the sampling sites along with monitoring spaces and other relevant variables is shown in Table 1.

Table 1. General description of sampling sites in Pakistan

Site	Area	Monitoring space	Number of occupants	Ventilation	Fuel used/ activity
Rural Site-I (Chak NO. 35/2.L.)	Rural, residential, lots of agricultural land, low traffic density, mud buildings, large number of livestock in most houses. No paved streets. Lighting with electricity.	Living room I,II	combined, used by 3-7 persons)	Window opening (one)	None/ normal household activities, smoking
		Kitchen –I, II, III, 1V, V Floor: mud plaster Courtyard: untilled, no grass	Varied (3 – 10 people) Mostly women and children from 2 – 8 years old	Door/ window opening	Dung and crop residues/ cooking, cleaning
Rural Site-II (Bhaun)	Semi urban, near road, low traffic density, paved streets, mud, concrete and iron shed buildings. Lighting with electricity.	Living rooms I, II, III Floor: concrete Courtyard: tiled	1 – 4 people	Window/ door opening	None/ I (Smoking). II &III (Non-smoking)
		Kitchen – I, II, III, IV, V, VI	Varied (3 – 6 people) Mostly women and children from 2 – 8 years old	Window/ door opening	I (Wood) II, III, IV, V, VI (Natural gas) /cooking cleaning
Urban Site (Lahore) H(I)	Residential, densely populated, close to road, no greenery, wooden roofs and brick walls	Living room(carpet) Courtyard: concrete floor	2 – 5 people sharing the room,	Window (two)	None/ student life, smoking, cleaning
H (II)	Residential, densely populated, close to main road, heavy traffic. Concrete roof and bricked walls	Living room , carpeted,	Shared by 2 adults and 4 children	Window (One)	None/ house hold activities.
		Kitchen	1 women and up to 3 children	Window/ door opening	Gas/ cooking, cleaning
H(III)	University Hostel, densely populated, close to main road. Less vegetation.	Living room	2 people	Window (one)	None/ student life, smoking, cleaning
H(IV)	Residential, densely populated, close to main road, heavy traffic. Concrete roof and bricked walls.	Kitchen	One couple with 4 children aged 11 – 4 years	Window (one)	Natural Gas/Cooking and cleaning

Sampling Design: The sampling campaign was carried out during August – November, 2007. The number concentration of ultrafine particles was monitored in kitchens, living rooms and outdoors at each site for the duration of 2 – 3 days each. At rural site I the kitchens were outdoors (roofed or unroofed) due to the summer season while at rural site II and the urban site cooking was performed indoors. The details on design of outdoor kitchens at rural site I and sampling position/location of the instruments at all the sites has been described in detail in Nasir *et al.* (2013). The different activities of the occupants were also documented during the period of sampling.

Instrumentation and Data Analysis: To measure the particle number concentration, two different condensation particle counters (CPC) were used: TSI model 3781 and 3010 (TSI Incorporated, St. Paul, MN, USA). The Model 3781, a water-based CPC, is a continuous laminar flow instrument that uses water as its working fluid. It provides rapid measurement of ultrafine particles in air and detects airborne particles down to 6 nm in diameter. Model 3010 (TSI Incorporated, St. Paul, MN, USA) measures the total number concentration of ultrafine particles down to 10 nm. It was found that concentration of particles in kitchens and some outdoor environments were far above the detection limit of CPC. Hence a dilution system was assembled following Knibbs *et al*. (2007) with some modification. Two different dilution systems were made for the CPC 3010 and 3781.Temperature and relative humidity were recorded at each sampling space by Gasprobe IAQ 4 (BW Technologies Ltd, Canada). The data logging interval was one minute. It was further computed into hourly concentration to investigate the impact of various activities and 24 hour, hourly maximum and minimum concentrations of ultrafine particles were calculated for each sampling area.

RESULTS AND DISCUSSION

During the measurement period the daily mean temperature and humidity in the rural living rooms ranged from 19 – 20°C and 59 – 64%, while in kitchens the daily mean temperature and humidity were between 16 – 22°C and 61 – 74%, respectively. At the urban site, the daily mean indoor temperature and humidity were in the range of 25 – 31°C and 52 – 75 %, respectively. Table 2 presents the number concentration in living rooms, kitchens and outdoors at rural site I. The 24 hour mean concentrations in living rooms were in the range of 20,551 to 40,031 #/cm^3 with an average of 30,291#/cm^3. The living rooms were with smokers and average hourly maximum values were in the range of 58,005 to 93,983#/cm^3. These values depict the considerable effect of indoor smoking. In the kitchens with biomass fuel the 24 hour average number concentration was 40,991#/cm^3 with a range 29,983 to 45,959#/cm^3. During the events of cooking the number concentration can jump significantly and the average hourly maximum values ranged from 76,916#/cm^3 to 169,455#/cm^3. The 24 hour mean concentrations outdoors were in the range of 29,487 to 39,374 #/cm^3 with an average of 34,534 #/cm3. The 24 hour average was higher outdoors than in indoor living rooms. This might be due to the effect of cooking in open kitchens during the measurement periods. Furthermore, the indoor living rooms had intermittent events of smoking, while the outdoors levels were influenced by cooking for longer times. The average background levels (hourly minimum) were almost double outdoors as compared to indoors. The sampling site was a rural agricultural site and burning of garbage and crop straws for expelling flies from domestic animals was a common practice. These practices and outdoor cooking might be likely reasons of the high background values.

Table 2. Summary of number concentration (#/cm³) at rural site I.

	Ave (#/cm³)	Max (#/cm³)	Min (#/cm³)	Stddev (#/cm³)
Living room				
24 Hour	30291	40031	20551	13774
Hourly Maximum	75994	93983	58005	25440
Hourly Minimum	9111	11775	6448	3767
Kitchen				
24 Hour	40991	45959	29983	7472
Hourly Maximum	139868	169455	76916	42412
Hourly Minimum	10908	14480	8201	2722
Outdoors				
24 Hour	34534	39374	29487	4947
Hourly Maximum	72983	112520	10042	55103
Hourly Minimum	17297	20443	15102	2794

Ave (Average), Max (Maximum), Min (Minimum), Stddev (Standard Deviation)

At the rural site II the number concentration was only monitored from living rooms and kitchens. In the living rooms the daily average number concentration was in the range of 10,745 to 16,126 #/cm^3 with a mean of 13,542 #/cm^3 (Table 3). These values were more than half those in living rooms at rural site I. Although the living rooms were with smokers, the outdoor micro-environment was completely different from that at rural site I. The streets and house floors were tiled, no livestock was present indoors and natural gas was used as cooking fuel. The very low background values also suggest that indoor smoking was the only source of fine particles. However, the considerable difference in hourly maximum values between living rooms at rural site I and II could be due to the number of smokers, volume of rooms and ventilation. In the kitchen the 24 hour mean was 27,446#/cm^3. A substantial rise was observed during the various events of cooking and the mean hourly maximum was 136,151#/cm^3. The average background values were almost the same as those in the living room. However, the hourly minimum values in the kitchen were more stable than those in the living room and showed a smaller standard deviation. This reflects a longer time of source operation in the kitchen (cooking) than in the living rooms (smoking). The number concentration in the kitchen is similar to that reported by Dennekamp*et al*. (2001) for gas cookers.

Table 3. Summary of number concentration (#/cm³) at rural site II.

	Ave (#/cm³)	Max (#/cm³)	Min (#/cm³)	Stddev (#/cm³)
Living room				
24 Hour	13542	16126	10745	1910
Hourly Maximum	43187	49103	37468	4324
Hourly Minimum	3224	4679	126	1780
Kitchen (Natural gas)				
24 Hour	27446	32973	24586	4787
Hourly Maximum	136151	154106	108328	24432
Hourly Minimum	3052	3866	2214	827

Ave (Average), Max (Maximum), Min (Minimum), Stddev (Standard Deviation).

At the urban site the mean 24 hour average in the living rooms and kitchens was 45,466 #/cm^3 and 65,904 #/cm^3 respectively (Table 4). Cooking resulted in substantially higher levels. The 24 hour mean concentration was more than double in the urban kitchens than in rural kitchens at site II. Although the cooking frequency and number/ duration of meals was higher in rural kitchens, the higher levels in urban kitchen were probably due to higher background levels and less ventilation. The 24 hour average in outdoors was 33,424 #/cm^3 – slightly lower than outdoors at rural site I.

Table 4. Summary of number concentration (#/cm³) at urban site

	Ave (#/cm³)	Max (#/cm³)	Min (#/cm³)	Stddev (#/cm³)
Living rooms				
24 Hour	45466	53668	40051	5919
Hourly Maximum	91103	115290	68661	21251
Hourly Minimum	23563	25006	20424	2162
Kitchens				
24 Hour	65904	78611	56245	11490
Hourly Maximum	189931	222543	168602	28686
Hourly Minimum	21219	33335	14663	10504
Outdoors				
24 Hour	33427	37696	29159	6037
Hourly Maximum	57242	57871	56613	889
Hourly Minimum	17133	19697	14569	3626

Ave (Average), Max (Maximum), Min (Minimum), Stddev. (Standard Deviation).

There are a growing number of studies on indoor number concentration of ultrafine particles in different micro environments in the developed world (Reche*et al*. 2014; Diapouli *et al*. 2007; Matson, 2005, Morawska*et al*. 2003) however, the studies from households in developing countries are very limited. During a study on number concentration in urban Indian households Mönkkönen*et al*. (2005) found that the 24 hour mean concentration in living rooms were 23,000#/cm^3, 41,000 #/cm^3, 25,600#/cm^3, 30,400#/cm^3 and 22,200 #/cm^3 during March, April, August and October, respectively. The 24 hour mean outdoor number concentration during these months was 32,300 #/cm^3, 29,200 #/cm^3, 26,200 #/cm^3, 25,300#/cm^3, and 26,100#/cm^3, respectively. These levels were considerably lower than those in the present study except for April. It is of note that results from different studies are not comparable due to differences in instruments used to monitor ultrafine particles and their corresponding lower detection limits.

Overall, the number concentration was higher in kitchens using biomass fuel (rural site I) than those using natural gas (rural site II). However, the levels in biomass kitchens were lower than in urban natural gas kitchens. It is very likely that the number concentration at the rural site, with biomass fuel, would be considerably higher during winter time (enclosed kitchens). The rural kitchen with natural gas had a lower number concentration than urban kitchens. This was probably due to more ventilation and lower background levels. Similarly the urban living rooms had higher concentrations than rural living rooms. The daily mean outdoor number concentrations were slightly higher at rural site I than those at the urban site reflecting the contribution of open space cooking and burning of agricultural waste. Apart from these indoor smoking was also identified as a major source of ultrafine particles indoors. Recent estimates (NIPS and ICF, 2013) have shown that 39 percent of Pakistani households are exposed to second hand smoke daily and this proportion is higher in rural households (43%) than urban one (32%).

Conclusion: The present study reports the number concentration of ultrafine particles in rural and urban residential environments in Pakistan during the summer time. A number of key conclusions can be drawn:

i) The number concentration of ultrafine particles differs considerably in rural and urban households using different fuels. Despite cooking in outdoor kitchens higher concentrations were recorded in households using solid fuels than cleaner fuels (natural gas) at rural sites. While urban households using natural gas had higher concentrations than rural households with the same cooking fuel.

ii) The indoor levels of ultrafine particles are greatly influenced by outdoor sources, in particular, at rural sites with high infiltration/ventilation housing types.

iii) Type, location, frequency and degree of use of household fuels and other indoor and outdoor activities can lead to considerable variation in exposure to ultrafine particles.

iv) Lower concentrations of ultrafine particles in rural households using natural gas than urban households clearly highlights the role of ventilation and background levels and offers support to the use of better design of cooking areas to reduce the risk of exposure to indoor air pollutants.

One of the Millennium Development Goals is to decrease the percentage of the population that relies on solid fuels and the progress of Pakistan to achieve it is very slow. There has been only 5% decrease in population using solid fuels over the period of 2006-07 to 2012-13 (NIPS and ICF 2013). Different interventions to reduce indoor air pollution from solid fuels in Pakistan have been reviewed in detail by Colbeck *et al*. (2010c). Recently Nasir *etal*. (2013) has reported that better design of cooking spaces can reduce indoor air pollution and proposed the use of ethno environmental knowledge of the communities to design and implement such environmental interventions. A study by Nasir *et al*. (2014) provided evidence that communities have knowledge and methods to reduce exposure to smoke from household solid fuel use and this can used to identify and implement sustainable environmental interventions to reduce the risk of exposure to indoor air pollution. There are many factors informing the choice of household fuel. A holistic system approach informed by the contextual understanding of determinants of household fuel choice and use is required to speed the transition towards cleaner and greener household fuels. While poverty is the biggest contributor to household fuel choice, household location and area, household size, low level of human capital, asset ownership structure and access to basic utilities are also important correlates (Nasir *et al*. 2015). Although the current study offers insights to dynamics of risk of exposure to ultrafine particles in developing world households it reports the findings from a limited number of households from Pakistan and may not truly reflect the actual level of exposure to ultrafine particles in other developing countries due to differences in climatic conditions, architectural types, household energy practices and other socio-economic differences.

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