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Indoor particulate matter in developing countries: a case study in Pakistan and potential intervention strategies

Zaheer Ahmad Nasir[1,2], **Ian Colbeck**[1], **Zulfiqar Ali**[3] **and Shakil Ahmad**[4]

[1] School of Biological Sciences, University of Essex, Colchester CO4 3SQ, UK
[2] Healthy Infrastructure Research Centre, Department of Civil, Environmental & Geomatic Engineering, University College London, London WC1E 6BT, UK
[3] Department of Zoology, University of the Punjab, Lahore, Pakistan
[4] Institute of Agricultural Sciences, University of the Punjab, Lahore, Pakistan

E-mail: colbi@essex.ac.uk

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Abstract

Around three billion people, largely in low and middle income countries, rely on biomass fuels for their household energy needs. The combustion of these fuels generates a range of hazardous indoor air pollutants and is an important cause of morbidity and mortality in developing countries. Worldwide, it is responsible for four million deaths. A reduction in indoor smoke can have a significant impact on lives and can help achieve many of the Millennium Developments Goals.

This letter presents details of a seasonal variation in particulate matter (PM) concentrations in kitchens using biomass fuels as a result of relocating the cooking space. During the summer, kitchens were moved outdoors and as a result the 24 h average PM_{10}, $PM_{2.5}$ and PM_1 fell by 35%, 22% and 24% respectively. However, background concentrations of PM_{10} within the village increased by 62%. In locations where natural gas was the dominant fuel, the PM concentrations within the kitchen as well as outdoors were considerably lower than those in locations using biomass. These results highlights the importance of ventilation and fuel type for PM levels and suggest that an improved design of cooking spaces would result in enhanced indoor air quality.

Keywords: indoor air pollution, intervention study, particulate matter, biomass, Pakistan

1. Introduction

Globally, 2.7 billion people rely on biomass energy (wood, charcoal, crop residues and dung) for cooking and this figure is projected to rise to 2.8 billion by 2030 (WHO 2009). The use of such fuels in open fires and rudimentary stoves results in a significant quantity of smoke being emitted. Exposure to the smoke has been associated with a number of diseases such as bronchitis and pneumonia. Generally it is women, their young children and elderly vulnerable family members who are at risk of exposure to high levels of indoor air pollution, as they spend the most time in the cooking areas. It has recently been estimated that the smoke produced from cooking with solid fuels kills 4 million people annually (Lim *et al* 2012). Globally 500 000 deaths are the result of cookstoves' contribution to outdoor air pollution (Lim *et al* 2012). Brauer *et al* (2012) have reported that 99% of the population in south and east Asia live in areas where the WHO Air Quality Guideline for $PM_{2.5}$ is exceeded.

A number of studies have been carried out on indoor air pollution in many low income countries (e.g. Fullerton *et al* 2008, Kaplan 2010 and Oluwole *et al* 2012). The majority of the studies reported mass concentrations in either the PM_{10} or $PM_{2.5}$ size fraction from kitchens using biomass fuels and revealed that levels were substantially higher than WHO guidelines. However, there are large differences in the usage of biomass fuel across the globe due to geography, climate and socio-economic conditions. Relatively few studies have considered the implications of poor indoor air quality on human health in Pakistan (Janjua *et al* 2012). The design, use and management of the cooking spaces in low income countries can vary considerably in different regions, even within the same country, largely depending on environmental and socio-economic factors. Hence there could be large differences in exposure due seasonal related shifts in kitchens from closed indoor to open outdoor locations. Knowledge of the variation in particulate matter due to such shifts is sparse. In addition, studies on the simultaneous measurement of PM_{10}, $PM_{2.5}$ and PM_1 are rare.

The present study reports the levels of particulate matter from rural and urban areas of Pakistan during summer and follows on from an investigation in winter (Colbeck *et al* 2010a).

2. Materials and methods

2.1. Sampling sites

Air samples were collected from two rural sites and an urban site. Rural site I (Village 35/2L) was 15 km away from District Okara (30.80°N 73.45°E). Rural site II (Bhaun) was located in District Chakwal (32.55°N 72.51°E), 12 km from the major town. Lahore (31.55°N 74.34°), the capital of Punjab province was the urban site. At rural site I the sampling was carried out in five different kitchens and two living rooms. All the kitchens used biomass fuel for cooking. The kitchens were detached from the living rooms. At rural site II sampling was conducted in three living rooms and six kitchens. All the kitchens bar one used natural gas as a fuel source. At the urban site sampling was conducted in four houses located at different places in the city. Measurements were undertaken in three living rooms and two kitchens. A general description of the sampling sites has been published elsewhere (Colbeck *et al* 2010a). In brief, the majority of houses at rural site I were made of mud and bricks and were roofed either with tiles or grass and bamboo. The courtyards of these were generally not tiled and devoid of any grass. Rural site II had a range of houses of different construction materials. As a result of canal irrigation systems rural site I was a region with extensive agriculture and domestic livestock. Natural gas was not available but biomass fuels were used as the household energy fuel due to crop residue and dung being readily accessible. Rural site II was in an area with little agriculture and natural gas was available. Vehicle emissions were very low at both rural sites however; suspension of dust was common especially during the summer. Lahore, the urban site, is one the mega-cities of Pakistan and the sampled houses were of masonry with a concrete roof. At this site the outdoor PM levels are very likely to be influenced by vehicle emissions and as well as resuspended dust.

2.2. Sampling design

Measurements of mass concentration were carried out in all three areas. All the kitchens at rural site I used biomass fuel while natural gas was used at both rural site II and the urban site. The stove designs and sampling position/location of the instruments has been described in detail by Colbeck *et al* (2010a). In outdoor kitchens at rural site I the stoves were built behind walls, generally on two sides, of 1–1.5 m high. The sampling was carried out at height 0.8 m above the floor and 30 cm away from the person cooking. In the kitchens using natural gas the sampling height varied from 0.8 to 1.5 m based on the location of stoves. In the living rooms sampling was conducted 1.5 m away from doors and windows at 1 m above the ground. Outdoors the sampling was carried out in the courtyards of the houses approximately 2 m away from any built structures at the height of 1 m. In all the cases kitchens were separated from the living rooms. During the winter campaign, the sampling was carried out simultaneously indoors and outdoors for PM_{10}, $PM_{2.5}$ and PM_1 for a period of one week in each setting. However during the summer campaign, due to the incorporation of more houses, the sampling duration was of 2–3 days in each setting. Furthermore the cooking at rural site I was carried out outdoors in either roofed or unroofed kitchens and so it was not possible to differentiate between indoors and outdoors.

2.3. Instrumentation and data analysis

The mass concentration of particles (PM_{10}, $PM_{2.5}$, PM_1) was monitored using two GRIMM aerosol spectrometers: (i) Model 1.108 and (ii) Model 1.101 (Grimm Aerosol Technik GmbH, Ainring, Germany). For the present study both of the spectrometers were used to report the mass fraction in the environmental mode (PM_{10}, $PM_{2.5}$, PM_1). A calibration factor was calculated gravimetrically for biomass cooking smoke. The concentration levels reported by the Grimm aerosol spectrometer were adjusted with a calibration factor (0.99). The activities of the occupants were logged during the sampling periods. The sampling interval was 1 min and data were further analysed hourly to investigate the effect of various activities on particulate levels. 24 h, hourly maximum and minimum mean concentrations of PM_{10}, $PM_{2.5}$, PM_1 and PM_{10}–$PM_{2.5}$ were calculated for each sampling space.

3. Results and discussion

3.1. Mass concentration of particulate matter at rural site I

Table 1 presents the summary statistics of concentration of particulate matter in living rooms, kitchens and outdoors. The windows and doors of the living rooms were open during the daytime due to the weather conditions and only the doors were closed during the night. The 24 h averages of PM_{10}, $PM_{2.5}$,

Table 1. Summary of mass concentration of particulate matter (μg m^{-3}) in living rooms, kitchens and outdoors at rural site I. (Ave (average), Max (maximum), Min (minimum), Std dev (standard deviation).)

	24 h				Hourly maximum			
	PM_{10}	$PM_{2.5}$	PM_1	PM_{10}–$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_1	PM_{10}–$PM_{2.5}$
Living rooms ($n = 7$ days)								
Ave (μg m^{-3})	407	269	236	138	762	380	327	381
Max (μg m^{-3})	454	300	258	154	769	421	359	405
Min (μg m^{-3})	357	221	200	123	755	350	300	348
Std dev (μg m^{-3})	49	42	31	16	7	37	30	30
Kitchens (biomass fuel) ($n = 15$ days)								
Ave (μg m^{-3})	559	254	215	305	1507	622	525	885
Max (μg m^{-3})	656	294	250	395	1976	779	676	1422
Min (μg m^{-3})	406	170	138	236	1034	530	434	504
Std dev (μg m^{-3})	115	58	53	79	402	112	105	425
Outdoors ($n = 10$ days)								
Ave (μg m^{-3})	532	221	157	312	1469	370	266	1099
Max (μg m^{-3})	597	242	193	355	1827	455	353	1435
Min (μg m^{-3})	450	200	123	250	945	199	102	490
Std dev (μg m^{-3})	75	21	35	55	544	193	173	457

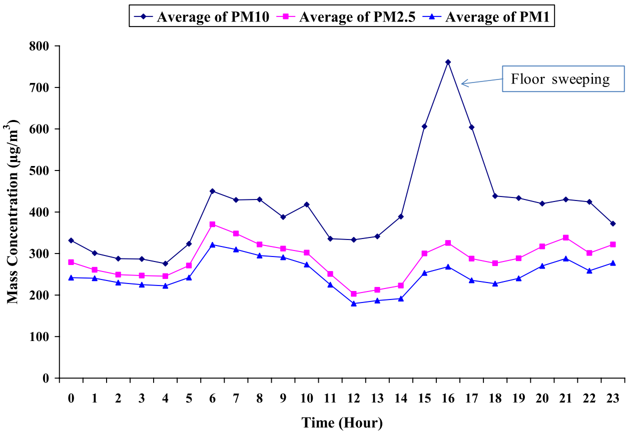

Figure 1. Representative hourly average mass concentration of PM_{10}, $PM_{2.5}$ and PM_1 in a living room at rural site I.

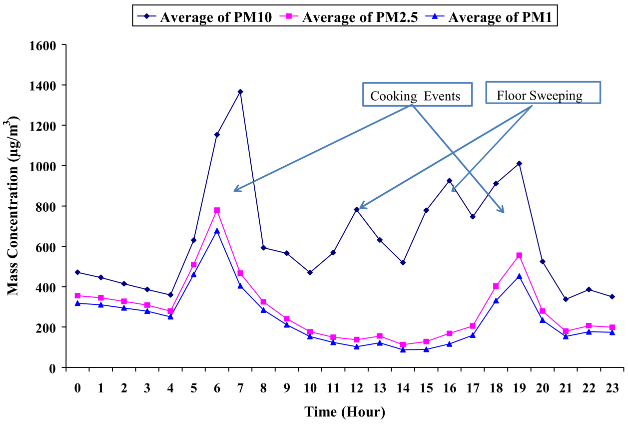

Figure 2. Representative hourly average mass concentrations of PM_{10}, $PM_{2.5}$ and PM_1 in an outdoor kitchen at rural site I.

PM_1 and PM_{10}–$PM_{2.5}$ were less than half those in winter (PM_{10} 953 μg m^{-3}, $PM_{2.5}$ 603 μg m^{-3}, PM_1 548 μg m^{-3} and PM_{10}–$PM_{2.5}$ 350 μg m^{-3}). This is most probably due to more ventilation in the living room spaces. The living rooms were occupied with smokers and the concentration of $PM_{2.5}$ and PM_1 showed less fluctuation as compared to the winter. The highest fluctuation was seen in PM_{10}, especially during indoor sweeping events (figure 1). However the measurements suggest that indoors there was some protection from outdoor dusts, while emissions of $PM_{2.5}$/PM_1 from domestic sources could have affected the wider environment.

Cooking was carried out in outdoor kitchens and, as a result, levels of particulate matter show a substantial reduction in comparison to the winter when 24 h averages of PM_{10}, $PM_{2.5}$, PM_1 and PM_{10}–$PM_{2.5}$ were 1581 μg m^{-3}, 1169 μg m^{-3}, 913 μg m^{-3} and 311 μg m^{-3}, respectively. Figure 2 depicts that a significant amount of particulate matter was in the coarse fraction during the various periods of cooking as indicated by the average hourly maximum value of PM_{10}–$PM_{2.5}$ equal to 885 μg m^{-3}. Compared to the winter the PM_{10} concentration was more variable and remained higher during most of the day; this being likely due to a contribution from outdoors. The 24 h average PM_{10}–$PM_{2.5}$ in the kitchen (305 μg m^{-3}) was close to the outdoor coarse fraction (312 μg m^{-3}). In addition peaks in $PM_{2.5}$ indoors were associated with outdoor cooking events and this suggests a contribution from outdoors.

During the night time the levels outdoors were relatively stable, but with the onset of the morning the signature of the outdoor kitchens can be seen in fine fraction (figure 3). In addition other outdoor activities, for example courtyard sweeping can lead to the suspension of coarse size particles.

By moving the kitchens outdoors during the summer the 24 h average PM_{10} concentrations were 35% lower than those observed during the winter. However background concentrations of PM_{10} within the village had increased by 62%.

Table 2. Summary of mass concentration of particulate matter (μg m^{-3}) in living rooms, kitchens and outdoors at rural site II. (Ave (average), Max (maximum), Min (minimum), Std dev (standard deviation).)

	24 h				Hourly maximum			
	PM_{10}	$PM_{2.5}$	PM_1	PM_{10}–$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_1	PM_{10}–$PM_{2.5}$
Living rooms ($n = 7$ days)								
Ave (μg m^{-3})	190	82	67	108	417	167	145	250
Max (μg m^{-3})	285	94	81	197	637	221	202	455
Min (μg m^{-3})	116	51	38	31	223	111	85	98
Std dev (μg m^{-3})	62	17	17	64	176	48	48	180
Kitchens (natural gas) ($n = 15$ days)								
Ave (μg m^{-3})	300	174	117	126	2240	1448	829	792
Max (μg m^{-3})	441	254	181	186	5015	3352	1521	1712
Min (μg m^{-3})	193	89	54	76	570	369	310	202
Std dev (μg m^{-3})	99	69	53	39	1467	977	394	643
Outdoors ($n = 10$ days)								
Ave (μg m^{-3})	162	26	15	136	937	71	30	866
Max (μg m^{-3})	209	40	30	187	1809	96	55	1713
Min (μg m^{-3})	131	18	7	97	191	38	18	153
Std dev (μg m^{-3})	31	8	9	36	837	25	17	815

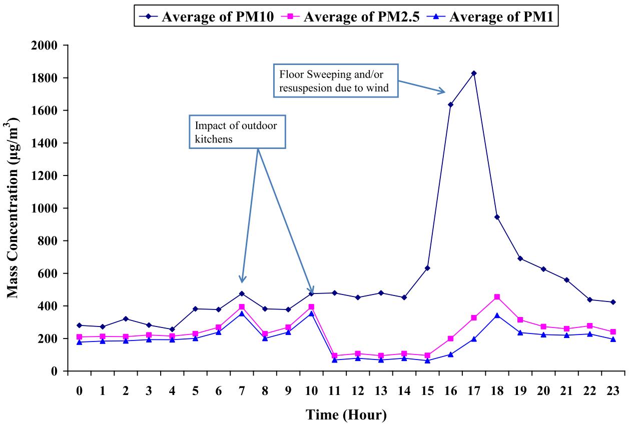

Figure 3. Representative hourly average mass concentration of PM_{10}, $PM_{2.5}$ and PM_1 outdoors at rural site I.

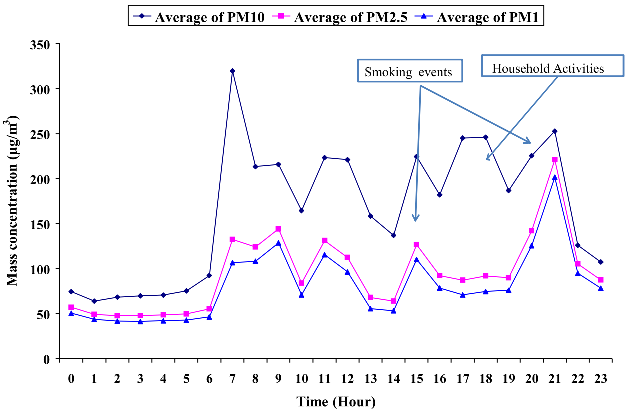

Figure 4. Representative hourly average mass concentration of PM_{10}, $PM_{2.5}$ and PM_1 in a living room at rural site II.

3.2. Mass concentration of particulate matter at rural site II

At rural site II the 24 h average values were almost half than those in the living rooms at site I (table 2). This might be due to differences in the indoor and outdoor micro-environments of the sites. At rural site II, the outdoors was tiled and the room floors were cemented while at site I outdoors was bare and devoid of any vegetation. However due to the weather conditions the windows remained open all the times and living rooms were occupied most of the day due to the heat. The resuspension of settled dust by ceiling fans along with the activities of the occupants (cleaning, smoking) had a considerable effect of levels of particulate matter (figure 4). During winter the sampling at this site was carried out in a non-smoking living room and the mass concentration of PM_{10} did not exceed 110 μg m^{-3} and background values were as low as 40 μg m^{-3}.

At rural site II most of the homes use natural gas. However in the outskirts of the village a few houses use biomass fuels. Measurements were made in both types of kitchens. A direct comparison, in terms of particulate matter, cannot be made as biomass fuels were used in the outdoor stoves while natural gas kitchens were within enclosed spaces. PM levels in this biomass fuel using kitchen were far lower than those at rural site I. The likely reason could be the design of the kitchen as it was unroofed. In some of the natural gas kitchens the average values were highly variable depending upon the number of meals cooked. Figure 5 shows the hourly average mass concentration of PM_{10}, $PM_{2.5}$ and PM_1 in a kitchen (natural gas) at rural site II.

The outdoor concentration of particulate matter in all the size fractions was lower at this site than those outdoors at site I. This was due to differences in the micro-environments as already discussed in the case of living rooms. Another

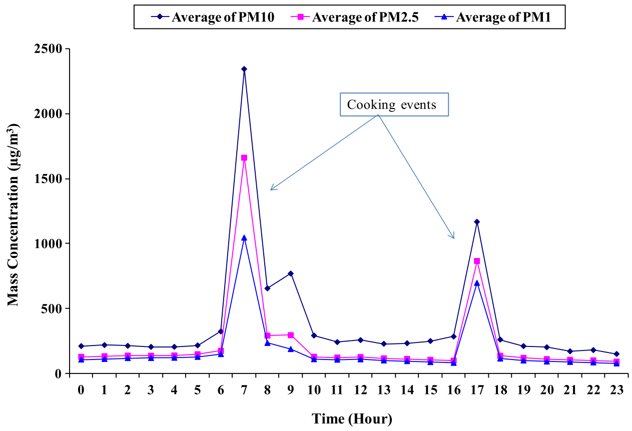

Figure 5. Representative hourly average mass concentration of PM_{10}, $PM_{2.5}$ and PM_1 in a kitchen (natural gas) at rural site II.

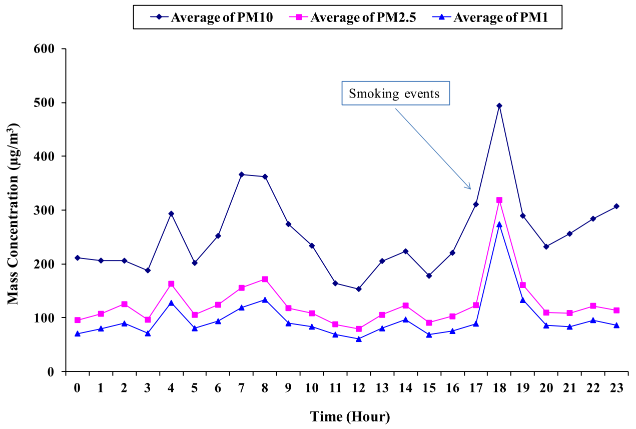

Figure 6. Representative hourly average of indoor concentration of PM_{10}, $PM_{2.5}$ and PM_1 in a living room at the urban site.

striking difference from site I was the considerably lower background levels of $PM_{2.5}$ and PM_1 (26 and 15 μg m^{-3}). This was most probably due little external biomass cooking. The outdoor levels were generally stable except during courtyard sweeping.

3.3. Mass concentration of particulate matter at the urban site

In the living rooms at the urban site PM_{10} concentrations fluctuated (figure 6) and this could be due to resuspension of settled dust by household activities and by the ceiling fan. The concentrations of $PM_{2.5}$ and PM_1 were higher than in the living room at rural site II. This increase is very likely due to higher background levels of $PM_{2.5}$ and PM_1 at the urban site (table 3). However, these levels were almost half those of winter in a living room with smokers at the urban site (winter PM_{10} 533 μg m^{-3}, $PM_{2.5}$ 402 μg m^{-3}, PM_1 362 μg m^{-3} and PM_{10}–$PM_{2.5}$ 128 μg m^{-3}), highlighting the impact of enhanced ventilation during the summer.

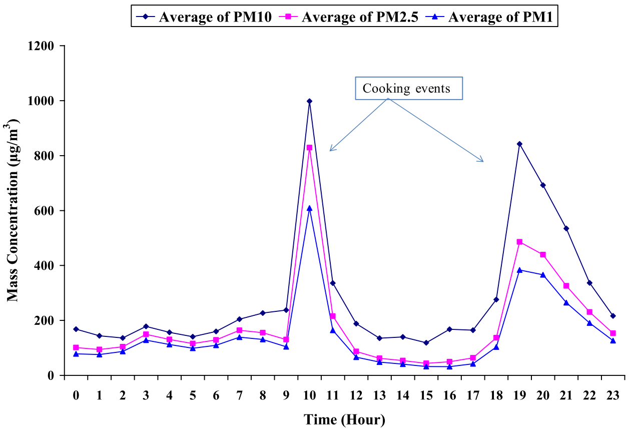

Figure 7. Representative hourly average mass concentration of PM_{10}, $PM_{2.5}$ and PM_1 in kitchen (natural gas) at the urban site.

Cooking resulted in substantially high levels of particulate matter. A characteristic peak was found in most of the kitchens at the rural (figure 5) and urban sites (figure 7). This might be due to the process of bread making on a pan, which involves frying with a resultant increase in PM. The suspension of finely ground flour might have also contributed to coarse size fraction.

Outdoors most of the particulate matter was in the coarse size fraction and fluctuated throughout the day; $PM_{2.5}$ and PM_1 were more stable. The concentrations are similar to those reported elsewhere for Lahore (e.g. Colbeck *et al* 2010c) and significantly above the WHO guidelines (25 μg m^{-3} for $PM_{2.5}$ and 50 μg m^{-3} per 24 h (WHO 2006)).

4. Discussion

Overall, the concentration of PM_{10}–$PM_{2.5}$ was comparable in living rooms at rural site II and the urban site, although levels of $PM_{2.5}$ and PM_1 were considerably higher in urban living rooms. At rural site I the concentration of both the coarse and fine fraction in the living room and outdoors was higher than that at either rural site II or the urban site. This could be due to the use of biomass as a cooking fuel outdoors and other agricultural activities during the measurement period. The concentrations in kitchens with biomass fuel usage were still higher than in kitchens with natural gas. It is of note that cooking with natural gas was carried out indoors although under enhanced ventilation conditions (e.g. open doors and windows). While the levels of particulate matter in kitchens and living rooms were lower in the summer as compared to winter they are still significantly higher than the WHO guidelines.

During the present investigation a substantial fall in mass concentration of particulate matter was seen in all indoor settings in comparison to winter time concentrations. Indoor concentrations were close to those outdoors. In the kitchens with biomass fuel and living rooms with smokers the concentrations were less than half the winter values. This is very likely due to the increased ventilation in the living rooms and cooking in outdoor kitchens. However, a rise in outdoor concentrations was seen in the summer which was most probably due the shift of the kitchens from indoors

Table 3. Summary of mass concentration of particulate matter (μg m^{-3}) in living rooms, kitchens and outdoors at the urban site. (Ave (average), Max (maximum), Min (minimum), Std dev (standard deviation).)

	24 h				Hourly maximum			
	PM_{10}	$PM_{2.5}$	PM_1	PM_{10}–$PM_{2.5}$	PM_{10}	$PM_{2.5}$	PM_1	PM_{10}–$PM_{2.5}$
Living room ($n = 9$ days)								
Ave (μg m^{-3})	273	156	127	117	670	344	294	326
Max (μg m^{-3})	409	293	251	171	2132	730	660	1859
Min (μg m^{-3})	200	113	91	72	403	221	175	123
Std dev (μg m^{-3})	64	53	48	28	482	164	152	484
Kitchen (natural gas) ($n = 7$ days)								
Ave (μg m^{-3})	359	237	194	122	766	569	454	197
Max (μg m^{-3})	474	314	260	159	998	829	609	238
Min (μg m^{-3})	287	185	147	102	640	424	368	169
Std dev (μg m^{-3})	100	68	59	32	201	226	134	36
Outdoor ($n = 10$ days)								
Ave (μg m^{-3})	258	81	58	177	605	168	131	438
Max (μg m^{-3})	309	108	83	234	925	317	271	789
Min (μg m^{-3})	180	50	33	130	404	91	68	264
Std dev (μg m^{-3})	54	19	17	45	190	73	66	188

to outdoors along with dry weather accompanied with high temperatures and wind speeds. A considerable rise was seen in the outdoor coarse fraction and the 24 h average PM_{10}–$PM_{2.5}$ in the kitchens (305 μg m^{-3}) was close to outdoor coarse fraction (312 μg m^{-3}). In the summer outdoor cooking was carried out either in an open space or with a roof over it. When a roof was present the levels were far higher than without one. The outdoor levels at rural site II were lower than those at I; differences in the outdoor environment are the likely reason. Rural site I was an agricultural site with most of surfaces bare and biomass fuel usage while site II utilized natural gas and the streets were paved. A large variation was seen in the mass concentration of particulate matter in kitchens. Among the natural gas users the levels in urban kitchens were higher than in rural ones. The number of meals cooked played a role in determining these levels along with ventilation parameters. Rural kitchens were more ventilated than urban ones.

5. Potential interventions

Interventions to mitigate indoor air pollution exposure due to biomass fuel use can be grouped into three categories: the source of pollution, the environment of the cooking space and user behaviour. Switching to cleaner fuels is the main route of intervention relating to the source of pollution and can result in a substantial reduction in exposure to a range of air pollutants. However, choice of household energy is influenced by the level of infrastructure, environmental, cultural and socio-economic factors. Another cost effective way to reduce emissions from biomass fuel is the use of improved cook stoves. Since the early 1980s various programmes have been operating in developing countries and these have shown mixed results in terms of their effectiveness (Smith *et al* 2013). This is often due to either complex subsidy procedures or technical or cultural inappropriateness. With reference to the environment of the cooking space, the design of the kitchen, the location of the cooking stove and ventilation efficiency of the cooking space have been reported to reduce the exposure to indoor air pollutants (Mobarak *et al* 2012, Fullerton *et al* 2008).

In Pakistan few interventions to combat indoor air pollution due to solid mass fuels have been carried out. Colbeck *et al* (2010b) conclude that interventions involving simple technologies, local materials and participation of local women were more successful. This lends supports to the notion that local participation, community involvement and people's empowerment can play a pivotal role in the development and implementation of interventions. During the current investigation the variable levels of PM in different kitchens and, in particular, the substantial reduction in PM due to shifts in cooking spaces during the summer highlights the role of stove type/design, kitchen design and ventilation in influencing indoor air pollution. At rural site I relocating the kitchen outdoors resulted in halving PM_{10} concentrations. For natural gas there is less seasonal variation. This provides support to environmental interventions that focus on the design of cooking spaces along with improved stoves would greatly enhance indoor environmental quality.

During the current study users' awareness and use of different methods to reduce the smoke exposure due to biomass fuels was observed (e.g. different layouts of the traditional three stone stove) and this lends support to the idea that traditional entho-environmental knowledge can be used as tool to design and implement sustainable environmental interventions to reduce indoor air pollution in low income countries. These interventions should be more viable and widely accepted in the local communities as they recognize the existing limits in economic resources, social norms, and human behaviour. Figure 8 shows the proposed

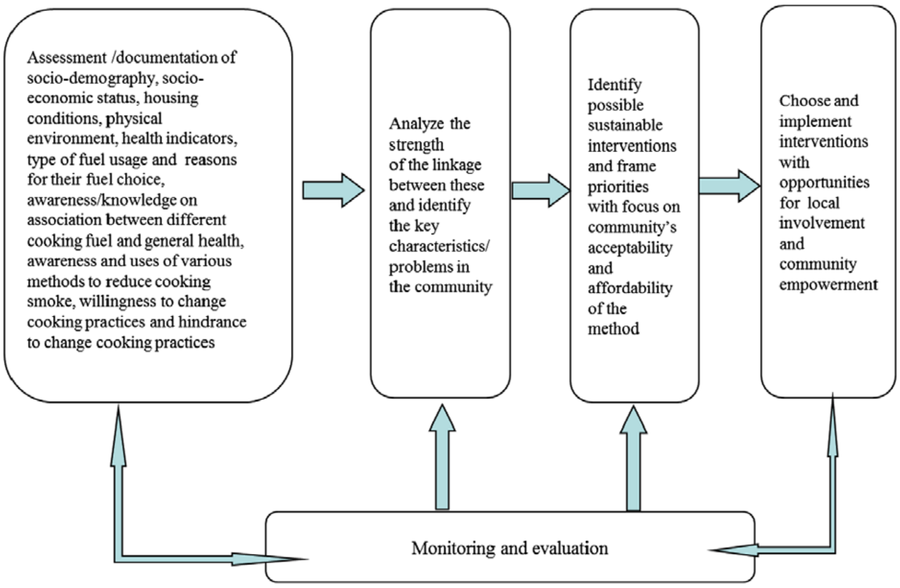

Figure 8. Methodological approach to identify and implement sustainable environmental interventions at community level.

methodological approach to develop a framework in order to identify and implement the sustainable environmental interventions at community level.

To date community based interventions have not considered utilizing the indigenous knowledge as a tool to design and implement strategies to mitigate the risk of exposure to indoor air pollution. Studies will be needed to assess the effectiveness of the above proposed framework.

6. Conclusions

The present work was an extension of a previous study to gather quantitative information on the concentration of PM_{10}, $PM_{2.5}$, PM_1 and PM_{10}–$PM_{2.5}$ in rural and urban residential environments in Pakistan during summer time. A number of key conclusions can be drawn:

(i) A seasonal variation in particulate matter concentration was observed in the kitchens using biomass fuels. Higher levels were found during the winter than the summer. This change resulted from the kitchens being moved outdoors during the summer. Kitchens using natural gas at the rural site had lower concentrations of particulate matter than urban kitchens. Similarly the living rooms at both rural and urban sites had lower concentrations in summer than winter and enhanced ventilation could be the most probable reason for the observed fall.

(ii) Fuel selection had a significant effect on particulate pollution levels. The concentration of particulate matter was less than half that in kitchens using natural gas than biomass fuel, even in outdoor cooking spaces.

(iii) During the present study, a significant fall in particulate matter concentration at the rural sites, during the summer, highlights the importance of ventilation and provides further evidence that a better design of cooking spaces along with improved stoves would result in enhanced indoor air quality.

(iv) The current study was limited to a number of houses in one province of the country with clear summer and winter seasons and a resultant shift in kitchen spaces. Given the variation in climatic conditions and other socio-economic differences the fuel use pattern and seasonal variations in indoor air pollutants may not be the same across all the country.

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