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CASE STUDY

Daily average exposures to carbon monoxide from combustion of biomass fuels in rural households of Haryana, India

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Abstract Exposure to harmful by-products of combustion arising from the use of biomass fuels for cooking and heating in rural areas of developing countries results in poor air quality and is responsible for millions of deaths yearly. Little formal quantification and measurement of carbon monoxide (CO), one of these harmful air pollutants, have been performed in rural areas of North India. In the current study, we measured exposure to CO from cooking and heating in seven households using biomass and liquid petroleum gas (LPG) in open and closed kitchens. Exposures to CO ranged from 4.81 to 7.01, 0.20 to 1.81, and 0.02 to 0.75 mg m^{-3} for households cooking with biomass, cooking with LPG, and for households in which no cooking occurred, respectively. It was observed that the CO concentration in biomass-only households is much higher (78%) than in LPG-only households (14%). We found exposures in closed kitchens approximately two times higher than in open kitchens. Location of the kitchen (i.e., open vs. closed) was the most important determinant of exposure of primary cooks to CO in this geography.

Keywords CO · Cooking · Biomass fuel · Rural India · Exposure · Kitchen · Health

1 Introduction

Approximately 2.4 billion people globally, primarily in low-income countries, rely on solid fuel (e.g., cow dung and wood) for household activities like cooking and heating (Gautam et al. 2016a, b; Gordon et al. 2014, Bonjour et al. 2013). It is estimated that household

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air pollution arising from the combustion of solid fuels is responsible for between 3 and 4 million deaths yearly (Cohen et al. 2017). In India, 90 and 32% of people use biomass for cooking and heating in rural and urban areas, respectively (Prasad et al. 2012). Cooking with biomass fuels in poorly ventilated kitchens leads to high levels of exposure to particulate matter (e.g., PM_{10}, $PM_{2.5}$, and PM_1) and gaseous pollutants like carbon monoxide (CO) and sulfur dioxide (SO_2) (Gautam et al. 2018; Wangchuk et al. 2016; Balakrishnan et al. 2002; Ezzati et al. 2000). Several recent studies have highlighted elevated exposures to CO of the primary cook (especially for women) and their children in developing countries (Njenga et al. 2016; Lu et al. 2016; Pant et al. 2016; Balakrishnan et al. 2002).

A number of assessments have been conducted quantifying exposure to biomass fuel combustion by-products, but few are conducted to represent actual exposure scenarios with consideration of different parameters (e.g., fuel type, food type, and kitchen location) in rural areas (Sun et al. 2016; Balakrishnan et al. 2015a, b; Chakraborty et al. 2014; Zhang et al. 1999; Smith 1993). These parameters are important to understand the relationship between exposure and response and to help make strategies to minimize exposure to pollution from cooking activities using biomass fuel.

Exposure to CO resulting from biomass combustion is well reported in the literature (Carter et al. 2017; Onodera et al. 2016; Balakrishnan et al. 2015a, b; Lu et al. 2016). However, limited information is available on exposure to CO in rural India, especially in different kitchen configurations (Carter et al. 2017; Mukhopadhyay et al. 2012a, b; Balakrishnan et al. 2004). CO is hazardous in nature and results from incomplete biomass fuel combustion during cooking and heating (Sinha et al. 2006; Balakrishnan et al. 2002; USEPA 1995). Fujisaki et al. (2014) reported that CO has greater than 250 times affinity for hemoglobin than oxygen and cause of the formation of COHb (carboxyhemoglobin). Exposure to CO has been observed to be associated with many health problems such as headache, dizziness, nausea (WHO 2010). High exposure to CO for long periods of time can cause death (Longo 1976).

The current study was conducted to assess the variation in 24-h exposure to CO during the winter in rural Haryana. In this paper, we describe an assessment of daily CO exposures in different kitchen configurations using low-cost, small, passive, lightweight electrochemical CO monitors. Our study is one of the few of its type undertaken in Northern India to date and is unique in that we measured periods of cooking and no cooking in the same households.

2 Methods

The current study is carried out in seven households of Bajada Pahari, a village (2802′45″N and 77017′31″E) with a population of approximately 600 (SOMAARTH DDESS Baseline Census 2012–2013). Bajada Pahari is in Palwal district of Haryana (Fig. 1), in the northern part of India.

The study is conducted in SOMAARTH DDESS (Demographic Development and Environment Surveillance Site) established by INCLEN (International Clinical Epidemiological Network). SOMAARTH DDESS covers 51 villages with a total population of 200,000. The study village was selected on the following criteria: (1) It is 10–12 km away from the Mathura National Highway, reducing pollution from vehicles; (2) there are no industrial areas within 10 km, to minimize the impact of industrial pollution; and (3) villagers use solid fuels (specifically cow dung, wood, and crop residues) for cooking and heating. Households were a

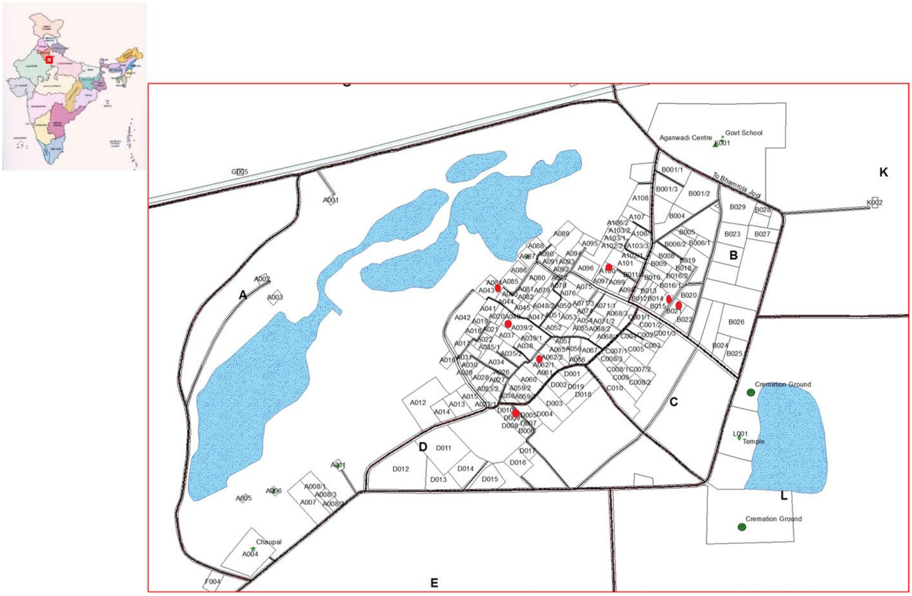

Fig. 1 Study site and selected locations: Bajada Pahari village of Palwal district of Haryana

convenience sample selected based on stove type, fuel use, quantity of fuel used, kitchen location, and cooking timings.

The present study was conducted over 21 days between January 1, 2016, and February 25, 2016, during a period in which equipment was available. CO was monitored using the EL-USB-CO carbon monoxide data logger (MicroDAQ, USA) which can store up to 32,510 CO readings over a 0 to 1000 ppm measurement range. In each household, we logged 24-h exposures during distinct periods of biomass-only cooking, LPG-only cooking, and no cooking (in which exposure is presumed to result from exposures from other sources). This study presents a limited dataset comparing different cooking modes—cooking with biomass only, cooking with LPG only, and no-cooking periods—in the same households over time, controlling to some extent for variable behavior and other factors that may influence exposure. A schematic diagram of methodology is presented in Fig. 2. CO exposures were measured beginning in the morning at 09:00 for 24 h. Data were collected from CO monitors placed on primary cook (women) near the breathing zone.

A total of 39 sampling events were conducted, including 15 monitoring events during cooking with biomass fuel; 12 monitoring events during cooking with LPG; and another 12 when no cooking was done. All monitoring events were conducted in the same seven households, controlling for cook behavior, indoor setting, etc. One-way ANOVA, Tukey's honestly significant difference, and *t* tests were utilized to compare average exposures between groups at a significance level of $p < 0.05$.

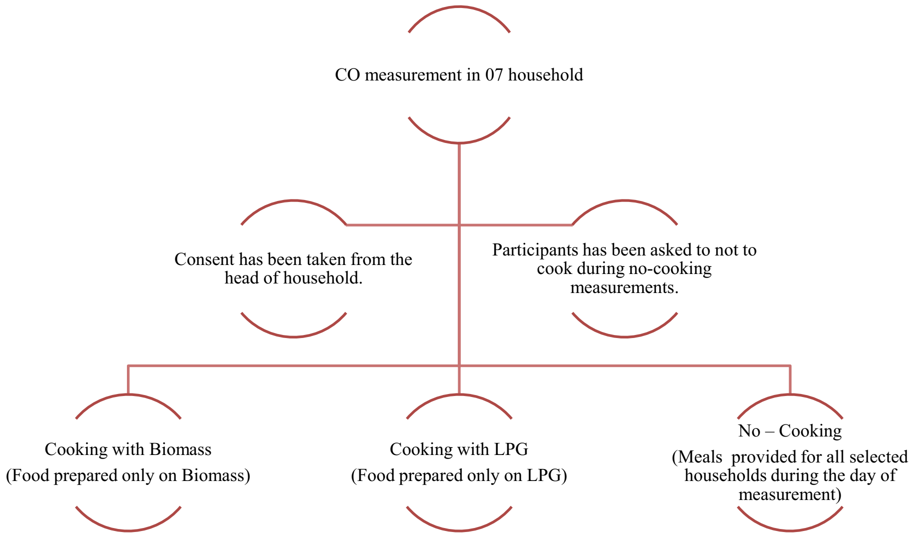

Fig. 2 Conceptual sampling schematic. Note that seven households were selected and, in each of the three households, three types of samples were taken

3 Results and discussion

3.1 Kitchen configurations and fuel use practices in study households

Two types of kitchens, similar to those found across rural Northern India, were found in Bajada Pahari (Fig. 3). Traditional stoves in study households were simple, mud-brick *chulas,* with a single pothole. Fuel was loaded into the front of the stove. Stoves in this

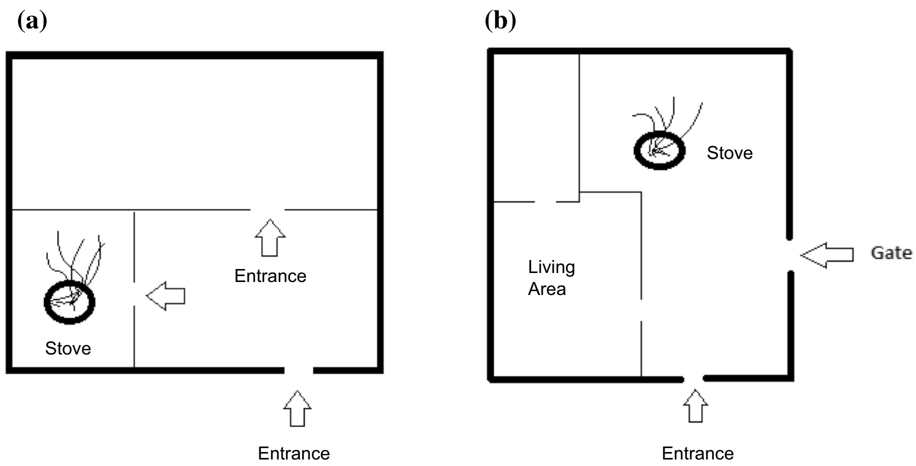

Fig. 3 Location of kitchen area in study village: **a** unventilated kitchen location and **b** ventilated kitchen location. The entrance is the main entry point to the courtyard; the gate is a secondary entrance

area have been described elsewhere (Pillarisetti et al. 2014; Mukhopadhyay et al. 2012a, b).

On a daily basis, approximately 70, 24, and 6% of household of the study village use biomass only, mixed fuels [biomass + liquid petroleum gas (LPG)], and LPG only for household activities. No kerosene use was observed in study village area. In the case of biomass fuels, 80–90% of people cook in a courtyard (a highly ventilated open outdoor space with walls surrounding the housing compound and typically without roof). In the case of LPG, 100% of people used the fuel in a separate indoor kitchen (a less-ventilated indoor room with four walls and a roof).

3.2 Carbon monoxide exposures: descriptive summary

Mean CO exposures (averaged over 24-h periods) were higher during cooking with biomass as compared to LPG or no cooking. Exposures varied from 4.81–7.01, 0.20–1.81, and 0.02–0.75 mg m^{-3} for cooking with biomass, cooking with LPG, and no cooking, respectively (Fig. 4).

Figure 5 shows the average exposures by kitchen location. The exposures ranged from 4.81 to 7.01 mg m^{-3} and from 3.75 to 4.93 mg m^{-3} for closed kitchen areas and open kitchen areas, respectively. We observed a difference in means between closed and open kitchen areas. Exposure to CO in a closed kitchen area is approximately two times higher than in an open kitchen area.

3.3 CO exposures by fuel–stove combinations

A total of seven biomass-only, seven LPG-only, and seven no-cooking periods were monitored (as summarized in Table 1). One-way ANOVA (Table 2) of CO exposures by cooking type shows a significant difference ($p < 0.05$) between fuel types. The exposures of participants during no-cooking periods or during periods of cooking with LPG were lower than those in households cooking with biomass, despite the fact that biomass cooking occurred predominantly outdoors, in more ventilated areas.

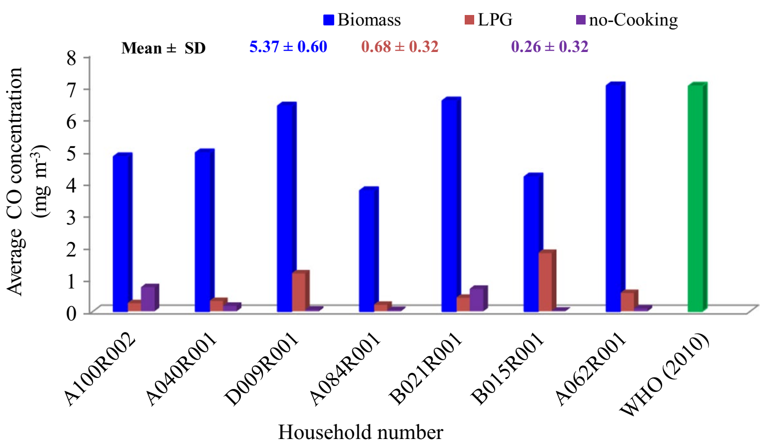

Fig. 4 Average 24-h CO exposure with WHO guidelines (2010) at Bajada Pahari village

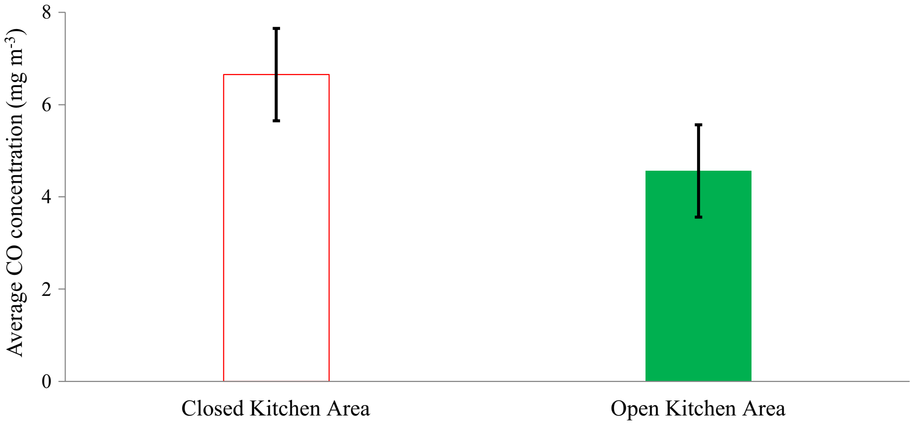

Fig. 5 Average 24-h CO data profile among two different kitchen locations based on mean exposure at Bajada Pahari village

Table 1 Summary of collected CO exposure values from study village

Group	Count	Sum	Average	Variance
No cooking	10,371	3119	0.301	1.14
LPG	10,371	5274	0.509	4.87
Biomass	10,371	30,473.5	2.934	60.02

Table 2 Results of one-way ANOVA for 24-hr average exposure to CO in study village

Source of variation	SS	*df*	MS	*F*-stat.	*p* value	*F*-crit.
Between groups	44,609.25	2	22,304.62	1013.41	0	2.99
Within groups	684,709.79	31,110	22.01			

Table 3 Comparison between groups with Tukey–Kramer rules

Comparison	Abs. Diff. mean	Critical range	Results
No cooking–LPG	0.21	0.12	Mean is significantly different
No cooking–biomass	2.64	0.12	Mean is significantly different
LPG–biomass	2.43	0.12	Mean is significantly different

Average differences between comparison groups are described in Table 3. All comparisons between no-cooking, LPG-only cooking, and biomass-only cooking exposures were statistically significant using Tukey–Kramer rules ($p < 0.05$).

In Table 4, we have shown the pairwise comparison for average effect of CO between no cooking–LPG cooking, no cooking–biomass cooking, and LPG cooking–biomass cooking, respectively, by using paired *t* comparison test. Similarly, *t* tests indicated significantly

Table 4 Comparison between no cooking–LPG cooking–biomass cooking

	No cooking–LPG cooking	No cooking–biomass cooking	LPG cooking–biomass cooking
Absolute mean difference	0.21	2.64	2.43
Absolute variance difference	3.75	58.88	55.15
Pooled variance	3.01	30.58	32.44
t-Stat. values	− 8.65	− 34.34	− 30.71
p values	2.61e−18	8.53e−252	5.68e−203
t-Critical values	1.64	1.64	1.64

significant differences between exposures during no-cooking, LPG-only, and biomass-only periods (Table 4).

4 Conclusion

We build upon existing research in India quantifying the exposures arising from combustion of solid fuels for heating and cooking. Our study presents a limited dataset comparing different cooking modes—cooking with biomass only, cooking with LPG only, and no-cooking periods—in the same households over time, controlling to some extent for variable behavior and other factors that may influence exposure. Our findings unsurprisingly find that exposure to CO is higher on primary cooks using biomass. We note that, however, on average, cooking outdoors—whether with biomass or not—leads to lower average exposures that cooking indoors. This is not surprising, given the higher ventilation and dilution potential in outdoor settings.

Our findings are consistent with other CO measurements related to the use of solid fuels for cooking. A recent review by Carter et al. investigating the relationship between particulate matter (PM) and CO (Carter et al. 2017) identified nine global studies that had personal measurements for both pollutants. For those nine studies, the average exposure is 2.0 ppm (95% CI 1.9–2.2; 2.47 mg m^{-3}, 2.34–2.71); ranges were comparable to those reported here. During previous work in Palwal district (Balakrishnan et al. 2015a, b), we found slightly higher CO exposures among pregnant women; this may have been an impact of behavioral changes during pregnancy.

Our study has limitations. First, the number of households was relatively small. More households may have enabled more rigorous statistical analysis and more conclusive results. Second, the reported exposures of CO were from a single winter season in a single location. Longer-term measurements may provide more reliable estimates of annual exposures and allow us to contextualize our findings relative to that annual mean and compare them with findings from other seasons. Third, we collected CO data on the primary cook only—further assessments of exposures of no-cooking adults and children may also be needed to better characterize population-scale exposures. Finally, measurement of PM and CO would have provided valuable context on the relationship between the two pollutants in this season and for these fuel–stove combinations, but was not possible with available equipment. While PM is the most dominantly studied biomass-combustion-related pollutant, CO is easier and cheaper to measure and has health effects that may warrant further examination.

We conclude that the CO exposure level in biomass-only households is much higher (78%) than in LPG-only households (14%). On the other hand, the exposure to CO in closed kitchen area was reported ~2 times higher than open kitchen area, indicating the importance of the kitchen location and the potential influence of ventilation on exposures. The higher exposure to CO during cooking and heating can increase the potential for adverse health effects, suggesting need for guidance in rural area of northern India on ways to ensure that the most household or people are able to avoid exposure to harmful by-products of biomass fuel combustion. Possible measures to reduce the exposure to CO from cooking and heating by using biomass fuel include the following: (1) use of cleaner fuels, such as electricity for cooking and heating and LPG for cooking and (2) trying to promote cooking in areas with good air exchange rates and proper ventilation.

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