ORIGINAL ARTICLE

Cooking practices, air quality, and the acceptability of advanced cookstoves in Haryana, India: an exploratory study to inform large-scale interventions

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Background: In India, approximately 66% of households rely on dung or woody biomass as fuels for cooking. These fuels are burned under inefficient conditions, leading to household air pollution (HAP) and exposure to smoke containing toxic substances. Large-scale intervention efforts need to be informed by careful piloting to address multiple methodological and sociocultural issues. This exploratory study provides preliminary data for such an exercise from Palwal District, Haryana, India.

Methods: Traditional cooking practices were assessed through semi-structured interviews in participating households. Philips and Oorja, two brands of commercially available advanced cookstoves with small blowers to improve combustion, were deployed in these households. Concentrations of particulate matter (PM) with a diameter <2.5 μm ($PM_{2.5}$) and carbon monoxide (CO) related to traditional stove use were measured using real-time and integrated personal, microenvironmental samplers for optimizing protocols to evaluate exposure reduction. Qualitative data on acceptability of advanced stoves and objective measures of stove usage were also collected.

Results: Twenty-eight of the thirty-two participating households had outdoor primary cooking spaces. Twenty households had liquefied petroleum gas (LPG) but preferred traditional stoves as the cost of LPG was higher and because meals cooked on traditional stoves were perceived to taste better. Kitchen area concentrations and kitchen personal concentrations assessed during cooking events were very high, with respective mean $PM_{2.5}$ concentrations of 468 and 718 μg/m^3. Twenty-four hour outdoor concentrations averaged 400 μg/m^3. Twenty-four hour personal CO concentrations ranged between 0.82 and 5.27 ppm. The Philips stove was used more often and for more hours than the Oorja.

Conclusions: The high PM and CO concentrations reinforce the need for interventions that reduce HAP exposure in the aforementioned community. Of the two stoves tested, participants expressed satisfaction with the Philips brand as it met the local criteria for usability. Further understanding of how the introduction of an advanced stove influences patterns of household energy use is needed. The preliminary data provided here would be useful for designing feasibility and/or pilot studies aimed at intervention efforts locally and nationally.

Keywords: *household air pollution*; *dung fuel*; *solid fuel*; *stove usage*; *exposure assessment*

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Worldwide, nearly 3 billion people use solid fuels – including biomass (wood, dung, and crop residues) and coal – for their household energy needs (1). These fuels are typically burned in poorly ventilated indoor or near-household outdoor environments using inefficient 'traditional' stoves, resulting in exposure to smoke containing PM, carbon monoxide (CO), dioxins (2), and many other toxins (3, 4). The World Health Organization (WHO) estimated that household air pollution (HAP) from solid fuel use accounted for 2.7% of the global burden of disease in 2000, including approximately 1.6 million deaths (4, 5). This health hazard primarily impacts women and young children, as they spend much time in close proximity to the fire (4, 6–8).

According to the 2011 Indian census, approximately 66% of all households relied primarily on wood, crop residues, or cow dung for energy (9). This comprises 23% of urban households and 86% of rural households. Approximately 780 million Indians living in 160 million households relied primarily on these fuels for their cooking needs (9, 10). In the 2004 assessment by WHO, reliance on solid fuel was estimated to contribute 3.2% of the Indian national burden of disease (using 2000 as the base year), including approximately 400,000 deaths from acute lower respiratory infection in children and 34,000 deaths from chronic obstructive pulmonary disease in women (4).

In 2009, the Indian Ministry of New and Renewable Energy (MNRE) announced the National Biomass Cookstove Initiative, which seeks to 'achieve the quality of energy services from cookstoves comparable to that from other clean energy sources, such as LPG' (11). To identify different dissemination approaches for a national level advanced combustion stove program, an exploratory study to design a conceptual framework for a newborn stove (NBS) program was initiated. The initiative targets pregnant women who access the national public antenatal care system. The specific aim of the initiative would be to introduce advanced combustion biomass stoves through the antenatal care system for reducing the prevalence of adverse pregnancy outcomes, especially low birth weight, a serious problem in India today.

As approximately 75% of the nearly 27 million births in India each year include at least one antenatal care visit (12), a national program adding an advanced stove to the package of antenatal care benefits could cover a major portion of the country's most vulnerable households within a few years. Importantly, a stove intervention disseminated through the public antenatal care system could be highly effective in reaching poor, pregnant women, nearly all of whom use biomass fuels for cooking. Pregnant poor women are arguably the largest easily identified vulnerable group for HAP interventions. Middle- and high-income women, who commonly use LPG for cooking, would not be part of this proposed program.

A recent meta-analysis indicates that a truly advanced stove – one that brings HAP exposure close to those of clean fuels, particularly LPG – might be able to achieve an average increase of 93 g in birth weight (13). This would be a major improvement in India, where about 30% of babies are born underweight (<2,500 g) (14). To show the actual improvement in practice, however, will likely require a major cluster-randomized trial of the type historically required before public investment in large-scale national programs, such as for vaccines.

To obtain data needed to design such a large NBS trial, a study is underway in Palwal district, in the state of Haryana, India, to assess the feasibility of distributing advanced combustion cookstoves through the public antenatal care system. It intends to enroll 200 pregnant women to assess usage patterns of traditional and advanced combustion cookstoves and to measure HAP before and after introduction of the advanced stoves. The study is collecting data on user perceptions and acceptability of the advanced stoves and also assessing the feasibility of capturing gestational age and birth weight in rural Indian communities.

Here, we describe exploratory work for the design of this ongoing feasibility study that (1) characterized traditional cooking practices in the study communities, (2) compared different methods for monitoring air pollution levels associated with traditional cooking practices and establish baseline air pollution levels associated with these practices, (3) evaluated the cultural acceptability of two commercially available advanced combustion cookstoves through semi-structured interviews, (4) tested methods to objectively monitor advanced stove usage, and (5) evaluated the feasibility of assessing personal exposures to combustion byproducts among pregnant women.

Methods

Study location

Current work is being undertaken at the INCLEN (International Clinical Epidemiological Network) SOMAARTH demographic and environmental surveillance site, located in Palwal District, Haryana, approximately 80 km south of Delhi (also the location of the ongoing feasibility study described in this article). Palwal district has an area of 1,367 km^2 and a population of approximately 1 million (9). The surveillance site has a population of approximately 200,000 from 51 villages across three administrative blocks of Palwal encompassing 308 km^2. The villages selected for this preliminary assessment use predominantly wood and cow dung for cooking and have periodic access to electricity. From the

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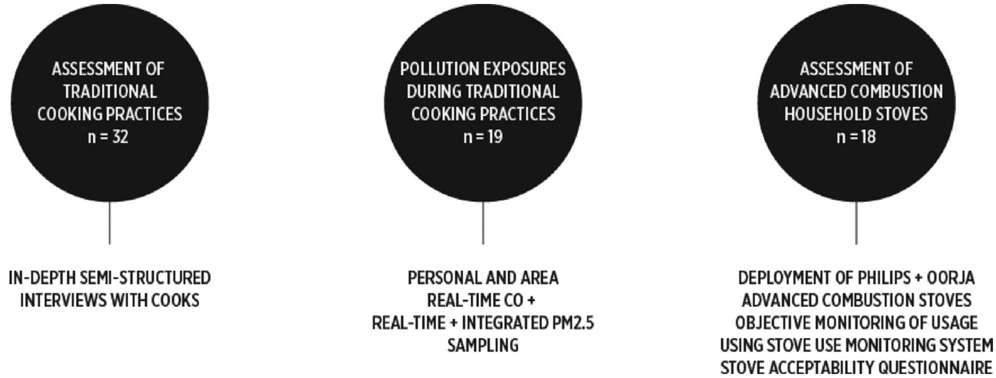

Fig. 1. Graphical representation of the three primary study components.

villages in the SOMAARTH site, convenience samples were drawn for each of the following three distinct components of the current study (Fig. 1).

Assessment of traditional cooking patterns

In-depth, semi-structured interviews with primary cooks in 32 households in 23 SOMAARTH villages were conducted and analysed by a trained anthropologist from INCLEN. Primary cooks were those who prepared 50% or more of the meals in a household. The interviews began with a consent process and an explanation of the study purpose. Questions were derived from a literature review and tailored to meet specific research aims. Interviews were conducted in Hindi and digitally recorded.

All interviews were transcribed verbatim. Transcriptions were reviewed against recordings and translated into English. Data were processed through free-listing domain analysis (15, 16).

Assessment of pollution exposures during traditional cooking practices

In a separate activity, personal exposures and area concentrations of CO and $PM_{2.5}$ resulting from traditional stove use were assessed in 10 households in two villages by a collaborating team from the Environmental Health Engineering Department at Sri Ramchandra University, Chennai, India. A combination of monitoring durations and techniques was used to determine the feasibility of multiple methods of assessing the primary cook's exposure to combustion-related byproducts. Area sampling of CO and PM occurred continuously for either 24 or 48 hours. Personal sampling of PM occurred during cooking periods of approximately 2 hours, during which personal continuous CO sampling also occurred.

Real-time measurements of $PM_{2.5}$ were taken using the UCB Particle and Temperature Sensors (UCB-PATS™, Berkeley Air Monitoring Group, Berkeley, CA). The UCB-PATS is a passive, portable, data logging optical particle monitor that has been validated on-site in India (17, 18). Data were recorded every minute. Instruments were placed 1.5 meters above the ground in all locations; in the primary cooking location, the monitor was placed 1 meter from the primary stove. UCB-PATS were deployed in each home for 3 days in the kitchen, primary living area, and outside, in the main courtyard.

Integrated $PM_{2.5}$ measurements were collected using an SKC Air Sampling Pump (SKC Inc., Eighty Four, PA) at a flow rate of 1.5 liters per minute. $PM_{2.5}$ was collected on 2.0 μm pore Teflon™ filters (Pall Corporation, Port Washington, NY), backed with cellulose support pads placed in a filter cassette connected to a BGI cyclone (BGI Inc., Waltham, MA). Using a laboratory calibrated rotameter, flow rates were measured before and after initiation of the sampling in the field. Separate integrated measurements were collected in the living area for 24 hours ($n = 4$), the kitchen for 24 hours ($n = 5$), and in the vicinity of the primary cook during two cooking events (total duration $= 125 \pm 53$ min, $n = 10$).

Filters were weighed pre- and post-sampling, using a Mettler balance (Mettler of Toledo, Inc., Toledo, OH) in a temperature- and humidity-controlled room at Sri Ramachandra University. Filters were conditioned for 24 hours prior to weighing.

Real-time CO concentrations were assessed using the Draeger Pac 7000™, a portable, electrochemical CO sensor. The Pac 7000 recorded the CO concentration every minute during the monitoring period. Personal CO was assessed for 24 hours on nine primary cooks. Correlations between logged data from the Pac 7000 and corresponding integrated $PM_{2.5}$ samples during the same cooking events were investigated.

Exploratory assessment of advanced combustion stoves

Among 17 households, two advanced combustion stoves (Fig. 2), both relying on two-stage combustion with forced air, were assessed. The stoves were chosen based on their availability on the Indian market (19) and their laboratory and field-confirmed efficiency and emission performance (20, 21). Kar et al. (21) found that the

Fig. 2. Advanced stoves evaluated in Palwal, Haryana. (A) The Philips Woodstove Model HD4012. (B) The Oorja (photo courtesy First Energy, India). Both are manufactured in India.

Philips stove reduced black carbon emissions in the field by approximately 77% when compared to a traditional, mud cookstove and reduced concentrations in the breathing zone by approximately 70%, though the latter reduction was not statistically significant due to intra-test and device variation. Jetter et al. found that a prototype Philips blower stove reduced CO and PM emissions in the laboratory by ~90% relative to a traditional three-stone open fire (20).

The Philips stove burns biomass and requires minimal fuel processing – fuel must be chopped into pieces less than approximately 2.5 cm in diameter and 5 cm long. The Oorja™ uses manufactured biomass pellets. Both stoves have a controllable electric fan powered by a rechargeable battery and thus require at least intermittent access to power. Manufacturers of both stoves claim that a single charge can provide power to the fan for 7–8 hours of cooking. To the best of our knowledge, there is no peer-reviewed published literature examining the acceptability of either stove amongst rural communities in north India.

Nine and eight households received Philips and Oorja stoves, respectively, in convenience samples of villages. Primary cooks were trained in stove use by field workers. Stoves were given to the households in their original packaging with instruction manuals in both Hindi and English. Philips users were instructed on proper processing of biomass prior to adding it to the combustion chamber. Oorja users received an allotment of fuel pellets and were given contact details of the field staff, from whom they could receive additional allotments as needed. The assessment had the following two parts:

Assessment of advanced cookstove usage

Objective usage of stoves was assessed using the Stove Use Monitoring System (SUMS™, University of California, Berkeley, CA). The SUMS (22–24) consists of a small, unobtrusive, battery-powered, temperature data-logger (Maxim Integrated Products, Sunnyvale, CA) and related signal-processing software (University of California, Berkeley, CA). Each SUMS was affixed to a household combustion device and recorded its temperature profile over time.

Prior to the field work, multiple SUMS were attached to both stove types using heat-resistant tape and sampled every 10 sec during three independent cooking events. Optimal positions were determined by investigating temperature traces and choosing a location on the stove that captured temperature variations not exceeding 85°C, the maximum tolerable temperature for the SUMS. Locations that were minimally obtrusive to the cooks were chosen.

After determining the optimal sensor location, SUMS were programmed to record temperature readings every 10 min. Data were downloaded every 2 weeks across a 12-week period by research staff from INCLEN.

Assessment of advanced cookstove acceptability

After distribution of the advanced stoves, research staff from INCLEN collected data on stove acceptability amongst primary cooks using a simple questionnaire. The questionnaire was administered at regular 7-day intervals during the 12-week follow-up period. Final analysis on stove acceptability was carried out at INCLEN. Questions fell into the following broad categories: convenience of use, problems experienced, perceptions, and comparisons with the traditional hearth.

Data analysis

Data were summarized and analyzed using R64 (R version 2.13.2, R Foundation for Statistical Computing, Vienna, Austria) and Microsoft Excel™ (Microsoft, Redmond, WA). Preliminary analyses in Excel included measures of central tendency and event counts. Box plots, confidence intervals, and plots of device signals were created in R64 using built-in packages.

Ethical considerations

The study was approved by INCLEN Independent Ethics Committee (Protocol ID IIEC 002; Ref: IEO-Delhi/Gen Corres 2011/IIEC-19); University of California, Berkeley Committee for the Protection of Human Subjects (Protocol ID 2010-11-2567); the Columbia University Human Research Protection Program (Protocol Number IRB-AAAI0866); and the Indian Health Ministry's Screening Committee (Ref. 5/8/4-1/Env/Indo-foreign/09-NCD-I).

All participants provided informed consent and were given information about the purpose of the study and potential study outcomes. During air pollution monitoring sessions, field staff received permission from participants to place air pollution monitoring devices in their homes. Devices chosen for pollution and stove usage monitoring have minimal risk for participants. Stove training sessions were organized by SOMAARTH technical teams to teach study participants about stove operations and safety protocols and included dissemination of an instruction manual in Hindi. SOMAARTH technicians, during regular field visits, emphasized on critical safety measures related to stove usage with study participants and helped troubleshoot any stove problems. Advanced stoves were evaluated based on their safety, reliability, and user-friendliness prior to dissemination.

Results

Assessment of traditional cooking patterns

The median age of the 32 primary cooks was 32 years (range 18–65 years). Fifty nine percent of the participants were illiterate. The average number of household members was eight, but half of the households had less than six members. All primary cooks were women; men only cook in unusual circumstances. The majority of households did not purchase their solid cooking fuel and all used wood and/or cow dung for household cooking. Out of 32 households, 20 had LPG stoves in addition to traditional hearths and purchased an LPG cylinder every 1–3 months. Twenty eight of the thirty two primary cooking spaces were located in a courtyard outside the main house. Courtyards shared many attributes – they were typically large, open spaces bounded on two sides by mud-brick walls. The remaining two sides contained storage and living areas. The courtyard served as a place for household members to congregate and work.

Primary meal preparation occurred twice daily in 27 households. The morning meal was cooked between 5:00 and 9:00 AM; the evening meal was prepared between 5:00 and 9:00 PM. Cooks reported that cooking one meal took, on average, 1.5 hours (range: 0.5–2.5 hours). In addition to primary meals, 22 respondents reported primary traditional stove use for tea preparation, 1–3 times daily. Ten households reported no further use of the primary traditional stove other than the two primary meals.

Twenty five households reported two or more cooking locations. Among the 32 households, fieldworkers identified a total of 68 cooking locations, 71% of which were outdoors and 29% were indoors. Of the outdoor cooking locations, 18% were partially covered, whereas the others were completely in the open. Of the respondents who had an indoor cooking location, nearly half reported that the indoor space was used only during inclement weather, including rain or extreme heat or cold. Almost all of these indoor cooking locations had LPG stoves along with traditional mobile hearths.

A total of 90 traditional hearths were identified across the 32 respondent households. Larger households (with a family size of greater than five) had on average three hearths, whereas smaller households (five or fewer family members) had on average two hearths.

Two primary types of traditional hearths were identified (Fig. 3). The stationary hearth, or *chullah*, (Fig. 3A) is made of bricks that are covered on three sides with mud plaster. Fuel is loaded into the front of these hearths. Twenty nine of thirty two households had a *chullah* outside. A portable hearth, or *uthaao chullah* (Fig. 3B), is also made of brick and mud plaster. These hearths are not fixed to the ground and can be moved indoors during cold or inclement weather. All 32 households used the *chullah* or *uthaao chullah* as their primary hearth.

Two additional stove types were identified. The *angithi* (Fig. 3C) is a top-loading, mobile hearth made entirely of mud. Fuel is loaded into the top of the hearth. Respondents noted that the *angithi* was used primarily for simmering items for long periods of time, including preparation of animal fodder and heating water or milk. In all houses, the *angithi* was located in a corner of the courtyard. The *haroo* (Fig. 3D) is a fixed, top-loading, mud and brick hearth. The observed *haroo* were pits lined with bricks and coated with a mud layer. Usage is similar to an *angithi.* Twenty households prepared animal fodder outdoors daily using either the *angithi* or the *haroo*.

User perceptions: LPG vs traditional hearths

As noted, 20 households had LPG stoves with two burners. However, none of the respondent households used LPG exclusively. Most respondents stated that the cost of LPG was the major reason for using traditional stoves. Biomass is free and readily available. Almost all stated that chapatis (traditional Indian flat breads) made on the traditional hearth tasted better, remained soft, and did not become stale as quickly as those made on the LPG stove. A smaller proportion of respondents indicated that other foods, including deep-fried breads and green vegetables, cook and taste better when prepared on a traditional hearth. Finally, respondents stated that milk simmered on a traditional hearth produced more cream.

Respondents stated that while they preferred the traditional hearth, they recognized that LPG cooked food faster, did not produce smoke, was convenient to light and turn off, and allowed use of a pressure cooker.

Fig. 3. Common traditional stoves found in homes in Palwal District, Haryana. (A) The traditional stationary hearth or *chullah*. (B) The portable hearth, or *uthaao chullah*, used during inclement weather under a covering or indoors. Both (A) and (B) are made of mud and plaster. (C) A top-loading, fixed hearth made of brick and mud or *haroo*. (D) A portable top-loading hearth or *angithi*. (C) and (D) are used for simmering items for long periods of time. (D) is used during inclement weather under a covering or indoors.

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Respondents ranked fuel efficiency as their primary criterion for a ‘good’ hearth, followed by decreased smoke emission. Others mentioned the taste of the food. In addition, a small number mentioned design and durability of the stove, convenience of ignition, safety, and mobility as important factors when choosing a hearth.

Air pollution assessment

As aforementioned, all air pollution measurements were performed in households while using traditional cookstoves. The distribution of gravimetric measurements across locations and monitoring durations is shown in Fig. 4. Figure 5 shows one day’s worth of real-time PM and CO data. Pollution peaks are consistent with usage peaks. Area measurements of the kitchen and kitchen personal concentrations assessed during cooking events were highest, with respective mean $PM_{2.5}$ concentrations of 468 and 718 $\mu g/m^3$. Living area concentrations were lowest (315 $\mu g/m^3$), due in part to the location of kitchens outside of the homes and away from primary living spaces. Outdoor measurements were noticeably elevated, with a mean concentration of 400 $\mu g/m^3$. Concentrations measured were consistent with other studies across India and other countries where biomass fuel was burned in traditional hearths (18, 25, 26). Twenty-four hour personal measurements of PM were not possible because of participant refusal to wear sampling pumps with adjoined tubing and cyclones. Although such equipment has been used in other studies in India and elsewhere, participants in this study stated that the equipment was loud, bulky, conspicuous, and uncomfortable to wear.

The average personal CO exposure (summarized in Table 1) during daily cooking was 7.4 ppm, with a range between 0.82 and 18.5 ppm. Non-cooking period concentrations ranged from 0.37 to 5 ppm, with an average of 2.4 ppm. Twenty-four hour personal CO exposures, averaged over both cooking and non-cooking periods, ranged between 0.82 and 5.27 ppm. Concentrations measured were consistent with studies in Guatemala (27–29) and The Gambia (30, 31).

Exploratory assessment of advanced combustion stoves

Usage

To determine acceptability of the two advanced stoves amongst primary cooks, we assessed the total time each stove was used and the number of stove events over the 12-week monitoring period. Stove usage data from the SUMS were grouped into three periods (periods 1–3),

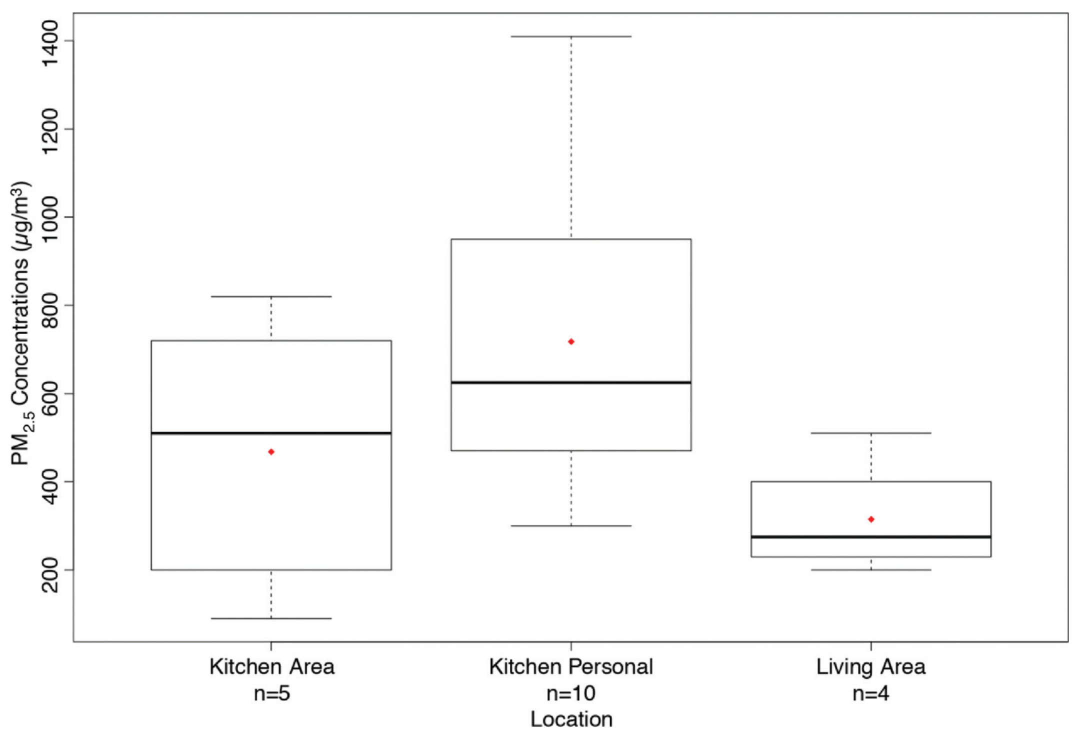

Fig. 4. $PM_{2.5}$ concentrations across all study households, during a period of use of traditional stove (i.e. no use of advanced combustion stoves). Each box represents a separate subsample by location and monitoring approach. The height of each box is the interquartile range. The median concentration is marked with a solid black line. The mean concentration is marked by a diamond. The box whiskers extend to 1.5 times the interquartile range. Kitchen area and living area concentrations were measured for at least 1,440 min; personal concentration measurements were during cooking periods and lasted between 90 and 225 mins. Outdoor concentrations have been not depicted because of small sample size ($n = 3$).

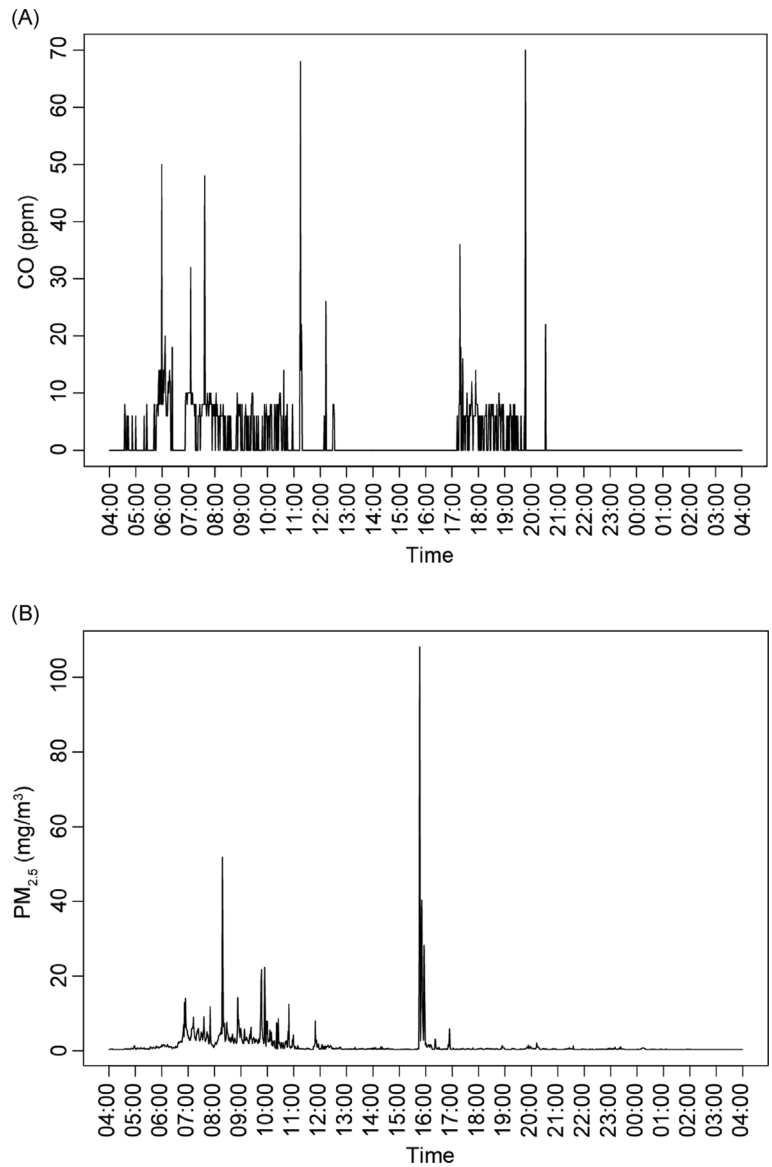

Fig. 5. Sample plots from (A) the Drager Pac7000 real-time carbon monoxide (CO) monitor and (B) the University of California Berkeley Particle and Temperature Sensor (UCB-PATS) logging data during cooking with a traditional stove. Note that peaks roughly correspond with cooking times from Fig. 6.

each consisting of 4 weeks of data. Counts of usage events were determined using an algorithm[1] and confirmed by manual counting of peaks on printed, weekly traces from each household. No significant difference was found between manual counts and the utilized algorithm.

Figure 6A and 6B display one day's worth of raw data from the SUMS. Elevated temperatures indicate stove usage. A distinct morning and evening stove usage event is visible for each stove type.

Overall, the Philips stove was used more often and for more hours than the Oorja stove across the entire monitoring period (Table 2 and Fig. 7). For both stoves, the number of events and the total duration of use were highest during period 1 and dropped during period 2. Usage of the Oorja stove during period 3 was elevated relative to period 2; usage of the Philips stove dropped during period 3. Even during its periods of lowest use, Philips was used more often than Oorja. In one household, the Oorja stove was used only during the preliminary monitoring period; in two other households, the the Oorja stove was unused during the final monitoring period. The Philips stove was used consistently by all households.

[1]We applied a six-point moving average to smooth the temperature data from the SUMS. We identified usage events by evaluating the changes in temperature from point n to point $n+5$. Any positive change greater than 2 degrees was denoted as the beginning of an event.

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Table 1. Descriptive summary of 24-hour pollutant area concentrations by monitoring approach

	n	Mean ± SD
$PM_{2.5}$ (μg/m^3) gravimetric	10	718 ± 369
$PM_{2.5}$ (μg/m^3) UCB	7	686 ± 753
CO (ppm) during cooking	9	7.46 ± 5.75
CO (ppm) non-cooking	9	2.36 ± 1.43
CO (ppm) average	10	2.58 ± 1.52

n = the number of samples; SD = the standard deviation of the pooled household concentrations.

Acceptability

Findings from the acceptability survey confirm objective usage data. All of the Oorja users reported mechanical or operational issues, including the stove consistently going out and requiring relighting and the fan being 'weak'. One stove failed completely in the trial. Others (12.5%) reported smoke as a significant problem with the stove. Seventy five percent of Oorja stove users stated at least once during the 12-week follow-up period that the Oorja stove offered 'no convenience'. Of those reporting a benefit, 50% reported reduced smoke as the major convenience of the Oorja stove. Furthermore, 37.5% reported that the portability and speed of cooking were advantageous. When considering the overall utility of the stove, only 12.5% of respondents cited the Oorja stove to be beneficial when compared to their traditional stove.

In contrast, consistently throughout the follow-up period, all of the Philips users attributed some benefit to their stove. All users reported that the stove reduced smoke, increased cooking speed and fuel efficiency, and stated that the stove's portability was a benefit. All users also reported significant benefits of the Philips stove over the traditional cookstove.

For both stoves, 16 out of the 17 respondents were of the opinion that the combustion chambers were too small and required constant refueling. However, they also stated that when functioning properly, both stoves used less fuel than their traditional hearths.

Discussion and conclusions

As has been known previously, the concentrations of PM and CO measured during traditional cookstove use (both in the cooking area and outdoors) confirm the imminent need for exposure reductions in the household environment. Of the two potential interventions we evaluated, only the forced draft stove using minimally processed biomass (the Philips) was found to be acceptable to participant households in this community. From the outset, the Philips stove was used more frequently and for more hours per day than the pellet stove, the Oorja. The Oorja stove users noted the inconvenience of the pelletized fuel and numerous mechanical and operational difficulties. As a result of these findings, only the Philips stove is being used in the feasibility study presently underway at the site. Although the Philips stove requires fuel be broken into small pieces, cooks had no difficulty doing so because the local fuel consists mainly of cow dung and fine woody debris (twigs). Our results may not generalize to settings where fuels include coarser wood or where any type of fuel is scarce. As the Oorja stove requires a steady supply of pellets, its use may be reduced in poor populations. Stove manufactures strive to improvise their designs over time, so the conclusions herein refer only to the particular models used in this study.

This exploratory study – despite the relatively small sample sizes in each of its three components – indicates that full piloting of advanced cookstoves prior to large disseminations will be necessary to ensure choice of proper interventions for each area of use, taking into account local fuel availability and cultural practices. Objective monitoring with the SUMS and assessment of stove performance by questionnaire can help program designers understand why a particular intervention is adopted or abandoned by primary cooks. This has been illustrated here as both stoves performed admirably in the laboratory, but only one was well received by the study group.

Certain tasks – including simmering of milk and preparation of animal fodder – were not accomplished by either advanced stove, but left to one of the many traditional stoves used regularly at the households. Future studies should investigate the contribution of the persistent use of traditional stoves to personal exposures and to ambient outdoor pollution. Exposure reductions because of the implementation of an advanced cookstove may be inconsequential if the HAP concentrations remain elevated owing to other household combustion sources or external sources of exposure. That cooking tends to takes place simultaneously across households in a community may exacerbate this problem. Work in Mexico has shown that adoption and sustained usage of stoves is a complex, multi-stage process, in which more than one device is routinely used, a practice sometimes called 'stacking' (32, 33). Further investigation – combining qualitative and quantitative data – of how the advanced stoves integrate into daily routines may help elaborate best practices for exposure reductions and inform future stove designs.

Monitoring of the primary traditional hearths before and after the household receives the advanced stove is one method to understand changes in stove use patterns. A challenge moving forward will be what we now realize is a requirement for two related behavioral changes. Users must not only adopt the advanced stove as their primary hearth, but also must decrease (or stop) use of the traditional stoves. Motivating this transition will remain

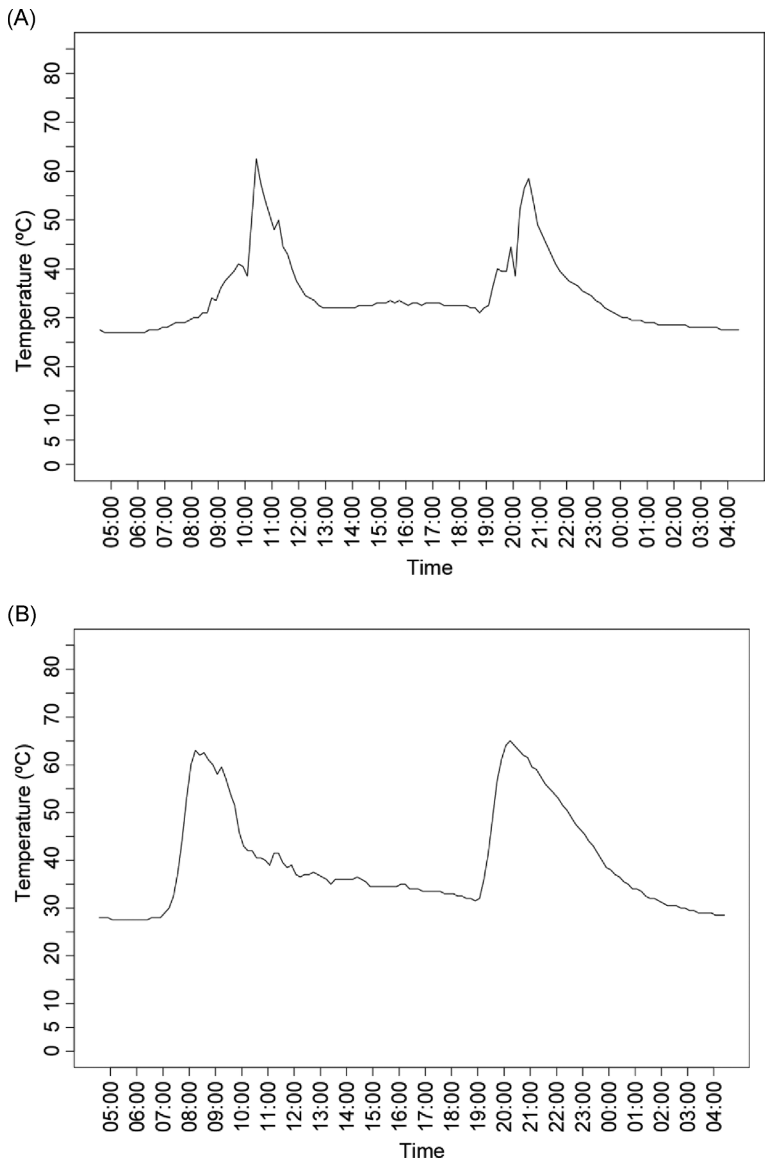

Fig. 6. Typical daily use pattern for a stove use monitor in a house with the Philips Stove (A) and the Oorja stove (B). Peaks in the graphs represent cooking events.

a challenge and may require development of specialized stoves for particular tasks. Our ongoing study tracks changes in traditional stove use before and after introduction of the advanced stove, allowing better understanding of shifts in usage and how they relate to personal exposures to hazardous air pollutants.

The presence of LPG stoves in many of the households in this study indicates that the traditional stove is preferred over the 'ideal' device for some tasks, primarily because of fuel cost, although better taste was also cited as a reason. Further investigation over longer timeframes will be needed to understand how the introduction of an

Table 2. Advanced stove usage over time by 4-week periods. Means with standard deviations of usage per day in hours and events per day are reported for 19 households

	Period 1		Period 2		Period 3	
	Use/day (hours)	Events/day	Use/day (hours)	Events/day	Use/day (hours)	Events/day
Philips	2.14 ± 0.50	2.13 ± 0.58	1.92 ± 0.84	1.92 ± 0.90	1.84 ± 1.06	1.68 ± 0.99
Oorja	1.24 ± 0.82	0.96 ± 0.61	0.47 ± 0.61	0.56 ± 0.61	0.79 ± 0.90	0.67 ± 0.76

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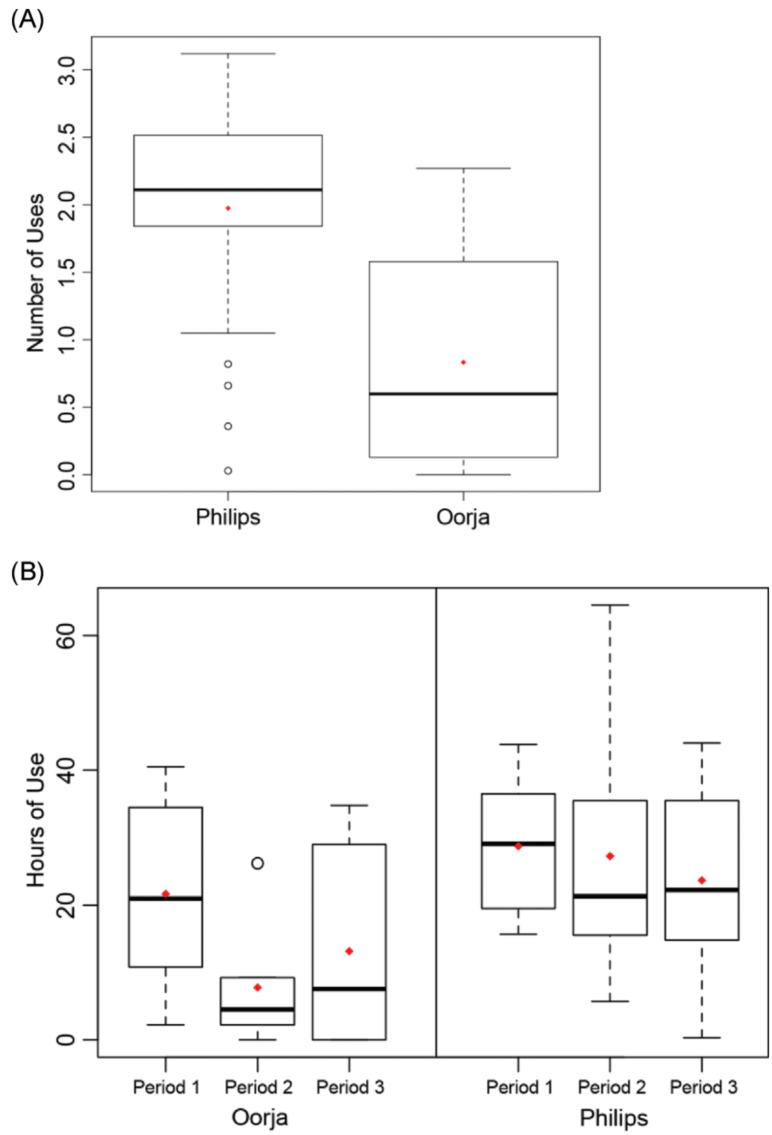

Fig. 7. Average use per day and hours of use over time by stove type. (A) shows the average number of uses per day of the Philips Stove versus the Oorja stove. (B) shows the changes in cumulative hours of use over each period. Note that both stoves start with high usage but then diverge, with both stoves being used, though at different levels. For both A and B, the length of the box is the interquartile range. The median concentration is marked with a solid black line. The mean concentration is marked by a diamond. The box whiskers extend to 1.5 times the interquartile range.

advanced stove alters usage patterns and user perceptions, and in turn how the device is used within the overall household cooking device profile.

Outdoor air pollution levels were higher than expected. Possible explanations for this include (1) preliminary monitoring during the early winter, when inversions are common in northern India; (2) outdoor cooking by many households at the same time, leading to large increases in neighborhood level pollution; and (3) other sources of ambient pollution, including brick kilns and trash burning. Further ongoing evaluation will better characterize the role of outdoor air pollution in driving daily exposure. High background rates of pollution in this community indicate that achieving significant personal exposure reductions may require interventions focused at the village or regional level. Targeting individual households may fail to control exposures resulting from the use of traditional stoves in the neighborhood.

Understanding exposures in this context, especially amongst the pregnant women we propose to monitor in the larger NBS feasibility study, is challenging. Initial attempts at 24-hour personal monitoring failed because of participant unwillingness to wear larger devices, including pumps, cyclones, and UCBs. Less intrusive or demanding approaches – using a minimally invasive set of equipment, such as the small CO sensors, gas diffusion tubes, or prototype personal PM samplers that are now being tested by researchers in the US and Ghana – may offer the best compromise of participant compliance and data quality.

The global resurgence in clean cookstoves projects highlights a need for accurate estimation of personal exposure to validate potential health effects. This study draws attention to the need for further development of valid techniques for investigation of the shifts in household energy usage patterns upon new device introduction. It also highlights the necessity of vetting multiple interventions in small, exploratory studies to find ones best suited to cultural habits and cooking practices.

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Conflict of interest and funding

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