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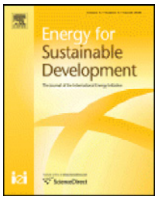

Assessment of effectiveness of improved cook stoves in reducing indoor air pollution and improving health in Nepal

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ABSTRACT

The mud improved cook stove (ICS) is a popular household energy intervention in rural Nepal. This research monitoring was designed to assess the impact of mud ICS, promoted by the Nepali national cook stove program, in reducing indoor air pollution (IAP).

This study employed a longitudinal, "Before and After" research design described previously by Edwards et al. (2007). Mean 24 h $PM_{2.5}$ (particulate matter less than 2.5 micrometers in aerodynamic diameter) and CO (carbon monoxide) concentrations were measured in the kitchen. A preliminary health survey was also conducted to evaluate the reported changes in key respiratory symptoms. The study was conducted at three geographically different sites with a sample size of 47 households. Household pollution monitoring was conducted in two phases — 3 months and 12 months post installation of the ICS.

After 1 year of ICS use, the mean values of $PM_{2.5}$ and CO were reduced 63.2% and 60.0% respectively. $PM_{2.5}$ concentration was significantly lowered from 2.07 mg/m^3 (95 % CI: 1.42–2.71) during traditional cook stove (TCS) use to 0.76 mg/m^3 (95 % CI 0.521–1.00) during ICS use. The mean CO concentration was reduced significantly from 21.5 ppm (95 % CI: 14.5–28.6) to 8.62 ppm (95% CI: 6.18–11.1). Comparison of 3-month and 12-month post-installation mean $PM_{2.5}$ and CO concentrations in homes with an ICS was not significantly different. The health survey preliminarily indicated changes in cough, phlegm, and eye irritation in ICS users. The study establishes that the mud ICS is an appropriate intervention to reduce $PM_{2.5}$ and CO in rural kitchens. This study recommends greater focus on proper operation and maintenance of ICS and ventilation to lower the smoke level even further.

Introduction

Indoor air pollution (IAP) represents a major environmental health burden. The problem is more severe in developing countries, where IAP ranks behind only malnutrition and unsafe water and sanitation (Smith, 2009) as a major contributor to morbidity and mortality. A number of research studies have shown strong associations between IAP and chronic obstructive pulmonary disease (COPD) and lung cancer in women and acute lower respiratory infections (ALRI) in young children (Bruce et al., 1998; Ezzati and Kammen, 2001; Smith et al., 2000).

In Nepal, over 76.9% of the population burns solid biomass fuels such as wood, dung, and agriculture residues in unvented, open-fire cookstoves for their daily cooking activities (Central Bureau of Statistics, 2008). Epidemiological studies evaluating the impact of IAP on health in Nepal have shown a positive association between key respiratory disorders and the use of solid fuel (Pandey, 1984; Shrestha and Shrestha, 2005). The World Health Organization (WHO) estimates that 2.7% of Nepal's national burden of disease is attributed to IAP. The total number of deaths attributed to IAP is 8700 per year, making exposure to indoor smoke the second largest environmental risk factor in Nepal after water, sanitation and hygiene (WHO 2007). High levels of indoor smoke have been reported in kitchens using traditional cook-stoves (TCS) in the rural parts of Nepal (Davidson et al., 1986; Nepal Health Research Council, 2004; Reid et al., 1986).

In order to address this problem, the government's energy unit, known as the Energy Sector Assistance Programme (ESAP) of the Alternative Energy Promotion Centre (AEPC) (www.aepc.gov.np) has been promoting improved cook stoves (ICS) in Nepal since 1999. Mud Improved cook stoves are a simple, cheap and popular intervention to reduce IAP in rural homes in Nepal. To date, over 250,000 stoves have been installed throughout the country (Alternative Energy Promotion Centre, 2006). Different models of ICS have been promoted by AEPC/ESAP (see Supplement B); however, the two

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pothole mud ICS (shown in Figs. 1a and b) is the most widely disseminated model. The recommended dimensions for this particular model are given in Table 1 (see Supplement A for pictures of TCS monitored during this study).

The two-pothole improved cook stove has two distinguishing features: improved efficiency in fuel wood consumption and the presence of a chimney to vent smoke outside the kitchen. The enclosed design of ICS compared to TCS allows for improved combustion, which could be related to the reported increase in efficiency (Centre for Rural Technology, 2005; Practical Action, 2007a).

Monitoring and evaluation data on the efficacy of the two pothole ICS promoted by AEPC/ESAP to reduce indoor air pollution and improve health are lacking. However, there exist a few comparative studies between TCS and ICS conducted in the past that provide an indication of an indoor air pollution reduction (Pandey et al., 1990; Reid et al., 1986). Previous studies evaluated a different model of ICS than the current study. These studies were also limited to measuring pollutants such as total suspended particles (TSP) and carbon monoxide (CO) over short durations. The scale of the AEPC/ESAP ICS intervention, coupled with the relative paucity of data on its effectiveness, indicated a strong need for more rigorous monitoring and evaluation of the program. Furthermore, the importance of monitoring may also help characterize ICS stove design and use best practices, in turn strengthening the program. Additionally, monitoring can provide a basis for creating awareness of the health risks associated with smoke emission during TCS use and would reinforce the need for ICS in rural populations. As such, the objective of this study was to quantify 24 h particulate matter ($PM_{2.5}$) and carbon monoxide levels in homes prior to ICS installation and at two time points after ICS installation. The study evaluated the factors associated with proper ICS functioning and conducted a preliminary health assessment of stove users, typically women, and children under age 5 in the study households.

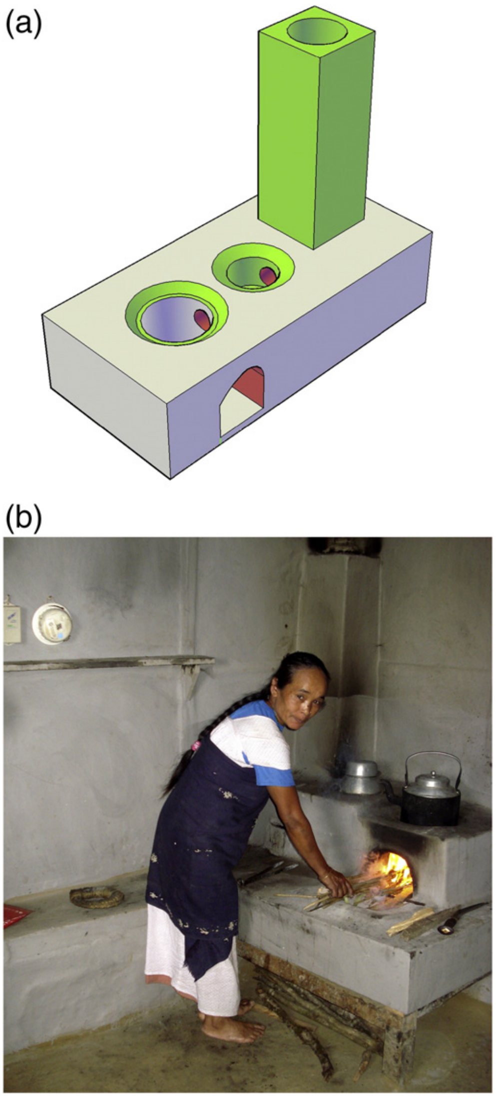

Fig. 1. a) Two pot hole mud ICS (Source: www.crtnepal.org), 1.b) Two pot hole mud ICS in use.

Table 1
Recommended dimensions of the two pot hole mud ICS (Source: www.aepc.gov.np).

Parts	Guideline dimensions
Combustion chamber	
1. Pothole 1	7.5 in. to 8 in. in diameter
2. Pothole 2	6 in. in diameter
Chimney height	48–60 in.
Chimney internal diameter	4–4.5 in.
Fire gate	36 sq. in.
Baffle height	5 in.
Baffle gap	2 in.

Materials and methods

The study design was chosen based on international best practices, a review of recent literature on study design for household energy studies, and optimum utilization of available resources in terms of time, funding and equipment. The study adopted the “Before-After” design described by the Household Energy and Health Project (Edwards et al., 2007; Smith et al., 2007). The design for this study also included consultation with the Centre for Entrepreneurship in International Health Development (CEIHD), University of California, Berkeley.

The study utilized a longitudinal research design that requires monitoring in the same household before and after the installation of ICS. The “before” monitoring was conducted once; the “after” monitoring of ICS was conducted in two phases, the first 3 months after installation of ICS *(Phase 1)* and the second 12 months after installation of ICS *(Phase 2)*. ICS were monitored twice to evaluate stove performance in terms of IAP reduction with consideration for potential changes over the lifespan of the stove. Indoor pollution monitoring was conducted for 24 h in the sample households during both periods. The monitoring intended to capture the normal daily stove use in the sample households. This includes 2 major meals in the morning and evening and a short meal during the afternoon. The sampling protocol for the proper placement of equipment in the kitchen was followed as per the standard developed by CEIHD (www.berkeleyair.com).

The required sample size for the study was based on statistical rules and sampling techniques designed by the CEIHD for the Household Energy and Health Project. According to Edwards et al. (2007), the sample size required to detect a statistically significant difference in the mean indoor air pollution levels before and after the installation of the ICS depends on the percent difference in mean value of IAP and in the coefficient of variation (COV). Thirty-one sample households were needed based on a conservative COV of 1.0 and assuming a detectable difference of 50% in the means. An additional 50% of the estimated 31 samples was added to account for any errors or loss to follow-up. 47 households were sampled.

Study sites

The promotion of the two-pothole mud ICS largely focuses on the mid-hill region of Nepal. However, AEPC/ESAP has also installed ICS in both the Terai (low-lying plains) and the high hill regions. Geographical variation is likely to influence the benefits of ICS. Further, variation in cultural practices may contribute to differing efficacies of ICS (Manibog, 1984; World Health Organization, 2005a, 2005b). This variation may have implications for pollution levels and their concomitant reduction with the adoption of ICS. Therefore, three study sites were selected to represent both the geographical distribution of the ICS program and the socio-cultural variation typical of different regions of Nepal. The sites included the following: (1) Dang, in the western development region and representing the Inner Terai (altitude: >500–1000 mts); (2) Dolakha, in the central development region and representing the high hills (altitude: 762 to 7134 m); and Ilam, in the eastern development region and representing the mid hills (altitude: 1300 m to 3636 m) (Fig. 2).

In Dolakha, the study was conducted in Boch village development committee (VDC). Boch VDC has a total of 741 households with a combined population of 4,192. The major ethnic groups are Tamang, Chhetri, and Sherpa. All of the households selected for this study had access to electricity for lighting.

In Dang, Laxmipur VDC was selected as the research site. Laxmipur is occupied by Chaudhary ethnic communities. The VDC has 10,729 households and the majority of the households do not have access to electricity; however, all of the sampled households had access to intermittent electricity and utilized kerosene lamps for lighting.

In Ilam, Mabu VDC was selected as the research site. The VDC has a total of 662 households, with a population of 3651. Ilam is comprised of Gurung, Rai, Limbu, Sherpa, and Magar ethnic groups (www.digitalhimalaya.com). The sampled households also had access to intermittent electricity and were found to use kerosene lamps occasionally during cooking periods. The duration and frequency of kerosene use was primarily limited to daily cooking sessions and was common across all the three sites.

Household selection

In each VDC, the Regional Renewable Energy Service Center (RRESC) was responsible for selecting study households. RRESCs support AEPC/ESAP in the stove dissemination effort and, as such, were ideal field assistants. Households were selected based on presence of a kitchen using wood, dung or agricultural residue; presence of children under the age of five; willingness to install an improved cook-stove; and willingness to follow through with all indoor air pollution monitoring phases. Households were selected based on similarity of kitchens; those with abnormally sized, shaped, or ventilated kitchens were ignored to minimize the impact of external factors on evaluation of improved cook stoves.

Timing of the monitoring

Field sampling for the traditional cook stove was conducted between October and November 2007, and the first round of monitoring in ICS was conducted between February and March 2008 (Phase 1). The second round of ICS evaluation was conducted between February and March 2009 (Phase 2). To eliminate the possible seasonal effects, the monitoring of TCS and ICS was conducted before and after the winter season (Table 2). Monitoring periods were selected to best minimize seasonal impacts on cooking; climate-related parameters tended to be similar across regions in the "before" and "after" study components.

Monitoring parameters

Indoor air pollutants

Particulate matter less than 2.5 microns in diameter ($PM_{2.5}$) and carbon monoxide (CO) were the key indoor pollutants evaluated during this study. Sampling of these two pollutants was conducted in the kitchen only. Epidemiologically, these two pollutants are important indicators of IAP (WHO, 2002, 2005b). $PM_{2.5}$ was measured using the UCB, a portable particle monitor developed by University of California, Berkeley (Chowdhury et al., 2007). CO concentrations were measured using commercial HOBO CO loggers (Onset Computer Corporation USA). Both monitors were calibrated at the Indoor Air Pollution Laboratory, University of California, Berkeley. The monitors contain data loggers,

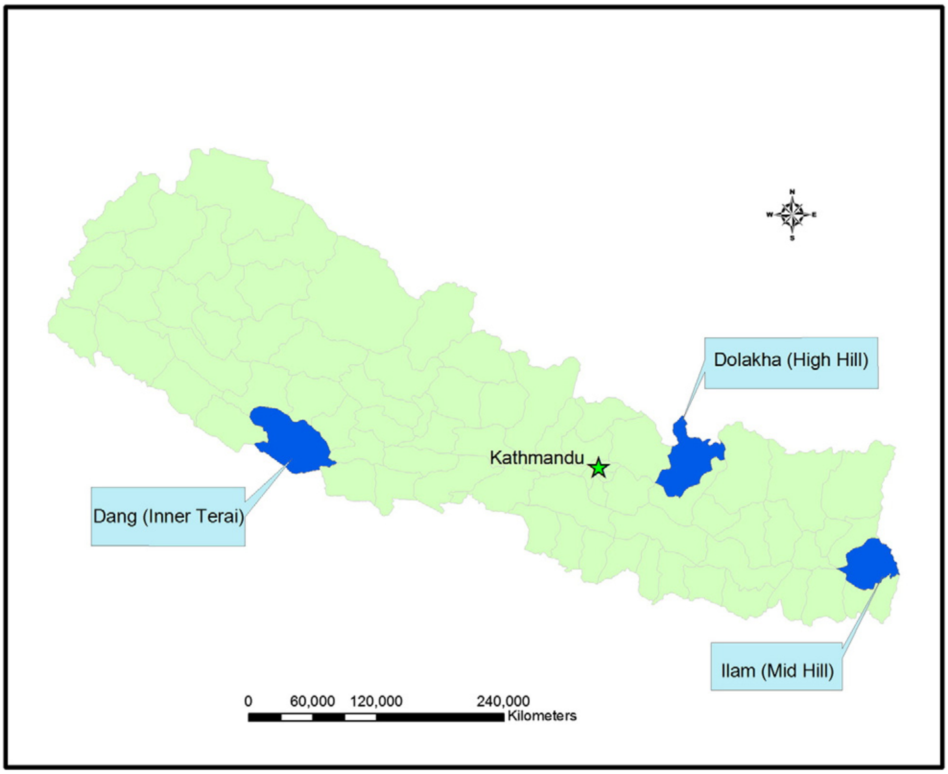

Fig. 2. Study site.

Table 2
Timing of monitoring and monitored parameters.

Monitoring round	TCS ("Before" Monitoring)	ICS After 3 months (Phase 1)	ICS After 1 year (Phase −2)
Months	October–November 2007	February-March 2008	February–March 2009
Monitoring parameters	IAP monitoring, Health Survey	IAP monitoring, Health Survey	IAP monitoring, Health Survey, Technical Evaluation of ICS

which store the minute-by-minute data over the measurement period. After sampling in each household, data were downloaded onto a personal computer and analyzed. UCB particle monitors and HOBO CO loggers were bought from the Berkeley Air Monitoring Group at the inception of the study. Monitors were factory-calibrated for wood smoke. Regular cleaning of the photoelectric chamber of the UCB particle monitor was conducted weekly. As a part of standard operating procedures, the UCB particle monitor was zeroed for at least 30 minutes prior to each monitoring session in a clean zip-lock bag.

IAP pre- and post-sampling questionnaire

An IAP survey was used to account for factors influencing levels of indoor air pollution in the kitchens. The factors evaluated included the following: type of fuel, condition of fuel used, stove type, family size, duration of cooking, other indoor air pollution sources, ventilation features (windows, doors, and eaves), and kitchen characteristics, including roof type, floor and wall type. The questionnaire was administered twice, once before and once after sampling. Pre-sampling surveys were administered during the installation of indoor air samplers. The post-sampling survey was administered after the completion of 24 h of sampling. This survey collected information on cooking activities and factors affecting smoke levels in the kitchen during cooking.

Technical evaluation of stove

Stove age can alter key stove dimensions. To explore the possible implication of changes in stove dimensions, Phase 2 monitoring also included a technical evaluation of ICS. This evaluation measured key stove dimensions such as the size of the combustion chamber, potholes, fire gate, baffle, and chimney (see Supplement B (S6) for the simple picture showing key dimension of ICS). Changes are anticipated due to the long duration of operation and variable maintenance of the ICS. Existing standard evaluation formats developed by AEPC/ESAP and RRESC were the primary source of reference material for this evaluation.

Health survey

A simple questionnaire-based health impact assessment was also administered for the study. The questionnaire utilized similar surveys from Nepal Health Research Council and Practical Action Nepal (Nepal Health Research Council, 2004, Practical Action, 2007b). The questionnaires included questions about respiratory health symptoms of the mother (usually the cook) and her children (under age 5). From the selected households, the respondents were chosen based on their involvement in cooking. Emphasis was placed on questioning mothers of children under the age of five. The individuals who were not involved in cooking at least once per week were excluded from the interview.

Data analysis

Both the qualitative and quantitative data obtained from field measurements were compiled and analyzed in MS Excel and SPSS Version 13 (SPSS Inc.) After organizing the data into different subsets, central tendencies were calculated. Inferential statistics including non-parametric tests were performed to show the statistical significance of the differences between the 24 h mean value of TCS and ICS in $PM_{2.5}$ and CO. The analysis is presented in aggregate for the total sample size and separately for the three study sites.

Results

A total of 47 households were sampled from the three study sites during the "before" monitoring. The number of sample households in each site was fairly equal (13 in Dolakha, 15 in Dang, and 19 in Ilam). The first phase of ICS monitoring considered only 36 households. The second round of monitoring of the same ICS included 34 households. Dropout from 47 to 36 homes in Phase 1 was attributed mainly to instrument errors. Other reasons include no ICS installation and unusually lengthened cooking events. The dropout in Phase 2 monitoring (after 1 year) was mainly related to cases of unused ICS (primarily due to unsuitability for use) and instrument errors.

The analysis is reported into two portions. The first analysis compares $PM_{2.5}$ and CO between TCS and ICS post 3 months installation (Phase 1). The second analysis compares the TCS values with the ICS values post 12 months installation (Phase 2). The health results include a comparative tabulation that shows prevalence of health symptom in users during TCS and ICS use after 1 year only. The health survey was also done during the 3 month period. Comparison between the 3 month and 12 month surveying sessions showed no significant difference among key respiratory symptoms like coughing, phlegm, etc. Therefore, the results from the initial 3 months period were excluded.

IAP monitoring

Summary of the results from TCS and ICS monitoring after 3 months (Phase 1)

The percent reduction in the mean IAP concentration between the TCS and ICS was 65.7% for $PM_{2.5}$ and 62.3% for CO (Table 3a). The $PM_{2.5}$ mean concentration of 2.13 mg/m^3 reduced significantly ($P = 0.000$) to 0.73 mg/m^3 after ICS installation. Similarly, the CO mean concentration was reduced significantly ($p = 0.000$) from 22.2 ppm to 8.35 ppm after ICS installation.

ICS in each of the study sites achieved significant reductions ($p < 0.05$) in mean $PM_{2.5}$ and CO (Table 3b–d). Households in Dang had the highest percent reductions — 68.3 % and 71.7% for $PM_{2.5}$ and CO respectively (Table 3c). This was followed by Ilam and Dolakha. Between study sites, the mean values of $PM_{2.5}$ and CO during TCS and ICS were highest in Dolakha, (TCS: 3.37 mg/m^3, 38.7 ppm and ICS: 1.43 mg/m^3, 17.2 ppm). In contrast to Dolakha, mean $PM_{2.5}$ and CO values were lowest in Ilam (0.89 mg/m^3 and 8.66 ppm with the TCS; and 0.31 mg/m^3 and 3.34 ppm-ICS).

Summary of the result from ICS monitoring after 1 year

Only 34 valid households were considered during this phase of monitoring. Among the households monitored during this study, 9 were from Dolakha, 14 were from Ilam, and 11 were from Dang.

After 1 year, mean $PM_{2.5}$ concentrations were significantly lowered ($p = 0.000$) to 0.76-mg/m^3, a 63.2% drop from 2.07 mg/m^3 in TCS in the same households (Table 4a). The mean CO concentration was 8.62 ppm in ICS households after 1 year, significantly lower ($p = 0.000$) than the measured 21.5 ppm during TCS use. The percentage reduction in mean value for CO was 60%.

Similar to the Phase 1 results, the highest percent reduction (70.6%, 67.4% for $PM_{2.5}$ and CO, respectively) was noted in Dang, with lesser reductions in Dolakha and Ilam. Likewise, mean $PM_{2.5}$ and CO values of ICS were lowest mean concentration of 0.37 mg/m^3 and 3.85 ppm (Table 4d) in Ilam. In contrast, stoves in Dolakha had the highest mean value for IAP level with ICS (Table 4b). Absolute value reductions in Dolakha and Dang for mean $PM_{2.5}$ were 1.91 and

Table 3
Traditional cook stove and Improved cook stove (3 months post installation).
(Table 3a: Aggregate of 3 sites Table 3b: Dolakha , Table 3c : Dang, Table 3d: Ilam).

a

Aggregate		Before						After 3 months						*p*-Value (Wilco. sig-rank)	Aggregate % change (95 % Cl)
	N	Mean	Median	SD	Max.	Min.	95 % Cl	Mean	Median	SD	Max.	Min.	95 % Cl		
$PM_{2.5}$ (mg/m^3)	36	2.13	1.61	1.80	7.13	0.21	1.59–2.85	0.73	0.45	0.65	2.90	0.09	0.53–1.00	0.000	65.7(46.9–65.5)
CO (ppm)	36	22.2	18.6	19.7	102.6	4.25	16.2–30.0	8.35	5.30	7.25	27.6	0.20	6.22–11.3	0.000	62.3(44.1–66.2)

b

Dolakha		Before						After 3 months						p-Value (Wilcox. sig-rank)	Aggregate % change
	N	Mean	Median	SD	Max.	Min.	95 % Cl	Mean	Median	SD	Max.	Min.	95 % Cl		
$PM_{2.5}$ (mg/m^3)	8	3.37	3.06	1.65	5.65	1.51	1.99–4.75	1.43	1.09	0.81	2.90	0.42	0.752–2.11	0.008	57.6
CO (ppm)	8	38.7	36.4	13.7	55.9	20.0	27.20–50.10	17.2	17.2	7.70	27.6	5.55	16.7–23.6	0.012	55.6

c

Dang		Before						After 3 months						*p*-Value (Wilcox. sig-rank)	Aggregate % change
	N	Mean	Median	SD	Max.	Min.	95 % Cl	Mean	Median	SD	Max.	Min.	95 % Cl		
$PM_{2.5}$ (mg/m^3)	14	2.65	2.21	1.95	7.13	0.56	1.53–3.8	0.75	0.60	0.51	1.86	0.14	0.453–1.04	0.001	71.7
CO (ppm)	14	26.3	20.5	23.2	102.6	4.25	12.9–39.6	8.32	6.97	5.53	22.18	2.50	5.12–11.5	0.002	68.3

d

Ilam		Before						After 3 months						*p*-Value (Wilco. sig-rank)	Aggregate % change
	N	Mean	Median	SD	Max.	Min.	95 % Cl	Mean	Median	SD	Max.	Min.	95 % Cl		
$PM_{2.5}$ (mg/m^3)	14	0.89	0.66	0.72	2.75	0.21	.475–1.304	0.31	0.28	0.19	0.77	0.09	0.20–0.42	0.002	65.4
CO (ppm)	14	8.66	7.41	4.74	23.2	4.44	5.92–11.4	3.34	3.33	1.95	8.12	0.20	2.21–4.46	0.002	61.5

1.97 mg/m^3. The value dropped by 21.5 ppm and 17.7 ppm for CO in these two respective sites.

Fig. 3 depicts a graphical representation of the median values of the $PM_{2.5}$ and CO for traditional and improved cook stoves. The plot indicates a significant drop in IAP levels from TCS to ICS. When using ICS, there is a slight increase in IAP from Phase 1 to 2.

Fig. 4 depicts the correlation between 24 h mean $PM_{2.5}$ and CO. The correlation was found significant, ($p<0.000$) and the Pearson's coefficient was estimated $r = 0.847$ ($n = 34$).

Table 4
Traditional cook stove and Improved cook stove (12 months post installation).
(Table 4a: Aggregate of 3 sites, Table 4b :Dolakha, Table 4c : Dang, Table 4d: Ilam).

a

Aggregate		Before						After 1 year						*p*-Value (Wilco. sig-rank)	Aggregate % change (95 % Cl)
	N	Mean	Median	SD	Min	Max	95 % Cl	Mean	Median	SD	Min	Max	95 % Cl		
$PM_{2.5}$(mg/m^3)	34	2.07	1.52	1.86	0.21	7.13	1.42–2.71	0.76	0.54	0.69	0.12	2.89	0.521–1.00	0.000	63.2 (48.0–63.1)
CO (ppm)	34	21.5	18.2	20.1	4.25	102.6	14.52–28.58	8.62	7.32	6.98	1.41	28.0	6.18–11.1	0.000	60.0 (45.9–63.1)

b

Dolakha		Before						After 1 year						*p*-Value (Wilco. sig-rank)	Aggregate % change
	N	Mean	Median	SD	Min	Max	95 % Cl	Mean	Median	SD	Min	Max	95 % Cl		
$PM_{2.5}$(mg/m^3)	9	3.22	2.42	1.61	1.51	5.65	1.98–4.46	1.31	1.14	0.73	0.36	2.51	0.74–1.87	0.000	59.3
CO (ppm)	9	36.5	34.4	14.7	16.9	55.9	24.9–47.5	15.2	14.1	7.10	8.55	28.0	10.3–21.2	0.000	58.3

c

Dang		Before						After 1 year						*p*-Value (Wilco. sig-rank)	Aggregate % change
	N	Mean	Median	SD	Min	Max	95 % Cl	Mean	Median	SD	Min	Max	95 % Cl		
$PM_{2.5}$(mg/m^3)	11	2.79	2.37	2.20	0.56	7.13	1.30–4.26	0.82	0.57	0.73	0.26	2.89	0.33–1.31	0.000	70.6
CO (ppm)	11	26.3	19.6	26.0	4.25	102.6	8.84–43.8	8.57	7.25	5.73	4.08	25.2	4.72–12.4	0.000	67.4

d

Ilam		Before						After 1 year						*p*-Value (Wilco. sig-rank)	Aggregate % change
	N	Mean	Median	SD	Min	Max	95 % Cl	Mean	Median	SD	Min	Max	95 % Cl		
$PM_{2.5}$(mg/m^3)	14	0.76	0.73	0.48	0.21	1.59	0.49–1.03	0.37	0.23	0.29	0.12	1.17	0.20–0.54	0.000	51.6
CO (ppm)	14	8.66	7.41	4.67	4.44	23.2	5.68–11.1	3.85	2.95	3.11	1.41	10.9	2.30–5.85	0.000	55.5

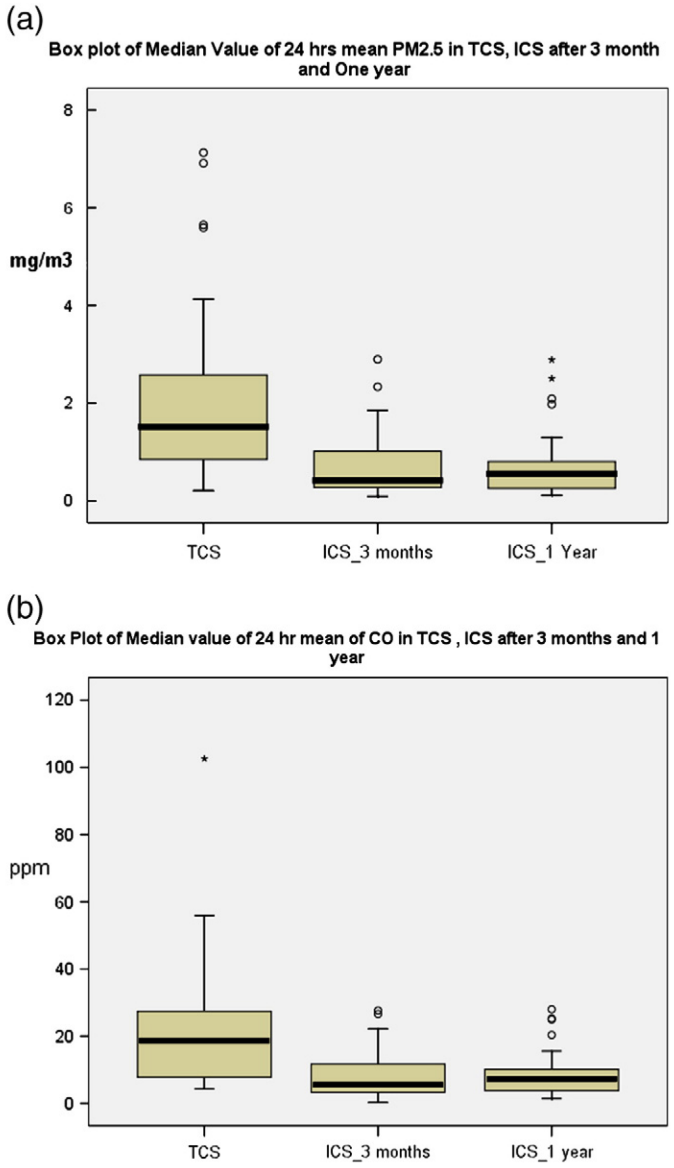

Fig. 3. Box plot of the Median $PM_{2.5}$ (a) and CO (b) in TCS and ICS (aggregate of all the three sites, $N=34$).

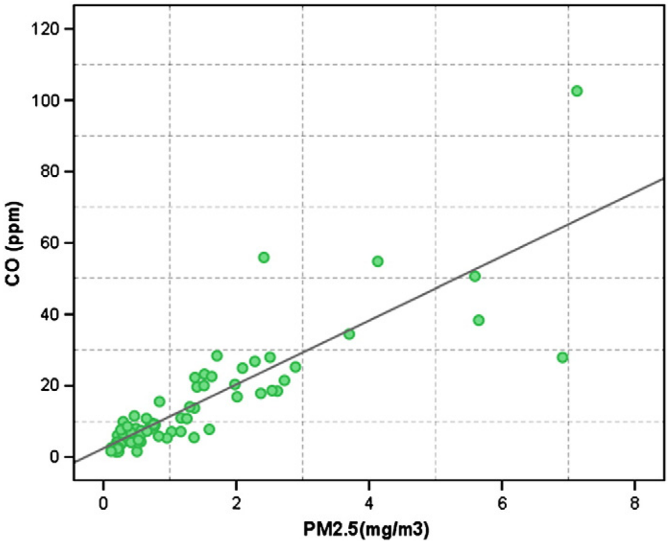

Fig. 4. Correlation between 24 h average $PM_{2.5}$ and CO here (Aggregate data from all the three sites, $N=34$).

Distribution of PM $_{2.5}$ and CO after 1 year

$PM_{2.5}$ and CO values from individual households with ICS shows the majority of stoves ($n=23$ for $PM_{2.5}$ and $n=21$ for CO) are lower than the population mean. Similarly, analysis of the distribution of percent reductions in households switching from TCS to ICS indicates that fifty percent ($n=17$) of improved stoves had a reduction of CO in the range of 60–80%, followed by 32% of stoves ($n=11$) in the 40–60% range. For $PM_{2.5}$, the majority of stoves led to reductions in the range of 40–60% and 60–80% ($n=9$, $n=10$ respectively). The amount of reduction in the absolute value ranges from 0.03 to 6.14 mg/m^3 for $PM_{2.5}$ and 3.44 to 77.3 ppm for CO.

Technical evaluation of the stoves

Changes in the dimensions of the stoves were evaluated relative to the guideline values recommended by AEPC/ESAP. Notable changes were seen in the baffle gap (an inclined structure below the second pot hole region of the stove) and the total area of the fire gate (Table 5 below). No significant change was found in any of the measured dimensions in comparison with the guideline value. Correlation between the stove parameters resulted in a weak, non-significant relation with the IAP level resulting from ICS use. The technical evaluation also included the frequency of chimney cleaning (in days) by users. It showed that users were cleaning the chimney every 20 days on average, longer than the suggested guideline of 7–10 days.

The overall technical evaluation did not reveal any relationship between IAP levels and stove dimensions. Because the technical evaluation was limited to households in which IAP was measured, the sample size was not sufficient to show any relationship between changes in stove dimension and smoke levels. Stove dimensions did not change from the guideline values statistically; however, it still remains a pertinent issue requiring further investigation. Dimensional changes in stove structure would need to be re-evaluated at more time points during the stove's lifespan — for example, in 2 years and 5 years — to understand stove durability over time and its concomitant impact on stove performance.

Kitchen structure, stove use and maintenance

The kitchens in all the households were enclosed. However, there were variations in kitchen designs, which include separate indoor kitchens inside the main house ($n=12$, 36%, kitchen type a), indoor kitchens with or without partitions inside the main house ($n=12$, 36%, kitchen type b), and separate kitchens outside the main house or in a separate house ($n=10$, 28% kitchen type c) (Fig. 5 below).

Table 5
Change in key dimensions in ICS after 1 year (Aggregate of all the three sites).

Dimension	*N*	Min.	Max.	Mean	Std. Dev.	Ref. Dimension
POT1_Outer Diameter (in.)	34	8	12	10.2	0.9	10 (9.8)
POT1_Internal. Diameter (in.)	34	5.3	8.5	6.9	0.7	7
POT2_ Outer Diameter (in.)	34	7	10.5	8.6	0.8	8
POT2_ Internal. Diameter (in.)	34	5	7	5.7	0.5	6
Chimney_Height (in.)	34	29	51	42.0	6.2	48
Baffle_Height (in.)	34	5	12	7.9	2.6	5.5
Baffle Gap (in.)	34	1	2.5	1.7	0.5	2
Chamber_Height (in.)	34	6.5	9	7.3	0.6	7
Area_Fire gate (sq. in.)	34	33	76.5	48.0	11.8	36
Chimney Clean (days)	34	7.5	60	19.8	14.6	7–10 days

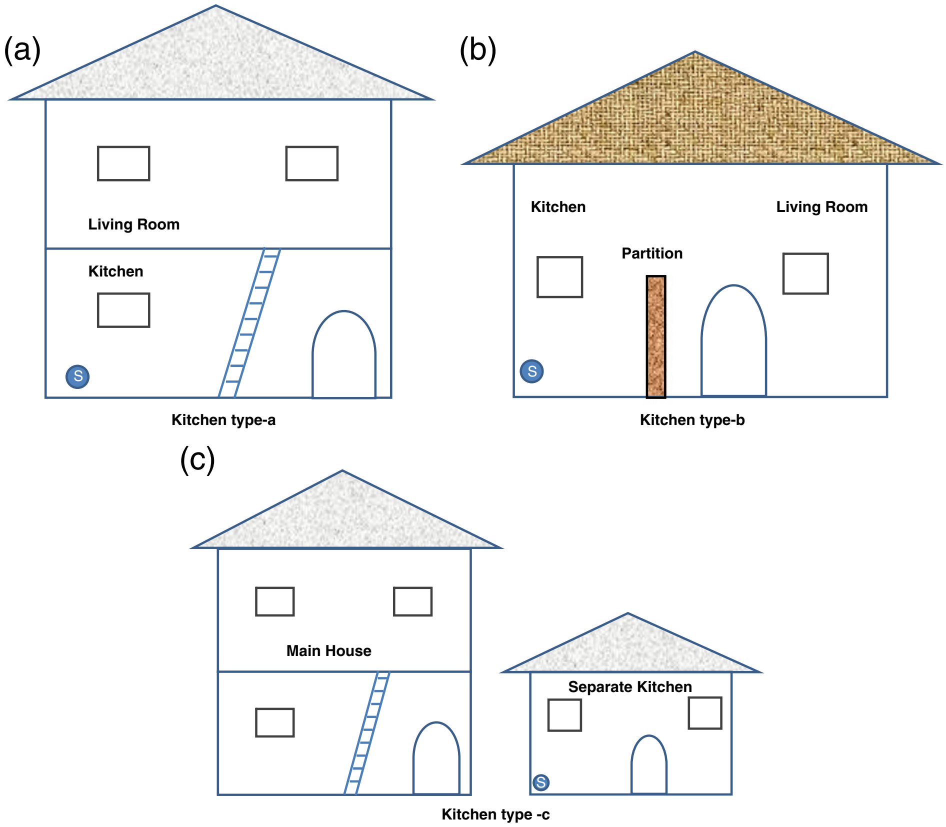

Fig. 5. Kitchen type in unique to each study site. **a: Dolakha** (separate indoor kitchen inside the main house), **b: Dang** (indoor kitchen with or without partition inside the main house), **c: Ilam** (separate kitchen outside the main house or in a separate house).

Kitchens in Dolakha were in a separate room and on a different floor from the living room (kitchen type a), in contrast to Dang where the kitchen and the living room were on the same floor and separated by a partition (kitchen type b). All the kitchens in Ilam were separate from the main house (kitchen type c). The kitchens varied in the presence and number of windows, flue structures, eaves, building materials, and size. Most kitchens had either one or two doors and one to five windows, excluding a few households ($n=2$) with no windows.

a: Dolakha (separate indoor kitchen inside the main house)**, b: Dang** (indoor kitchen with or without partition inside the main house)**, c: Ilam** (separate kitchen outside the main house or in a separate house).

The majority of households had roofs of wood planks (55.9%), corrugated metal (35.3%), or thatched straw (8.8%). All kitchens had earthen floors. The majority of households had mud or mud and brick walls (94.1%). 5.9% of households had walls made of bamboo, woven sticks or other materials. The average family size across all study sites was 5.

Among all households, 75.7% intermittently reported the problem of smoke accumulating in the kitchen during ICS use, rather than being exhausted out of the chimney. Improper orientation of the stove inside the kitchen, with placement of the chimney towards the direction of the wind, is believed to be one of the main reasons for the backflow of polluted air into the kitchen.

With TCS, the average cooking time was 5.2 h; with ICS, that time reduced to 3.5 h daily. Major fuel types were wood logs (41.2 %), and a mixture of wood logs, wood twigs, and dung (44.1 %). In Ilam and Dolakha, the predominant fuel types were wood logs and twigs. In Dang, households reported use of dung, wood twigs and logs, and infrequent use of agriculture residues.

User perceptions of improved cook stoves were also assessed in the survey. Users recognized a high reduction of IAP levels in the kitchen (85.3%), less time spent cooking (50%), reduced wood consumption (59%), improved cleanliness of the kitchen and utensils (56%) as the major changes.

Health survey

The survey compares the prevalence of health symptoms during TCS use and post ICS installation (assessed at phase 2). A total of 36 principal cooks or users were interviewed (mean age 34.3 ± 12 years, range: 17–71) and 26 children under age five were surveyed during monitoring. Coughing, phlegm, chest wheezing or whistling, eye irritation, and headache were the key health symptoms evaluated via self-reporting during the survey.

Prevalence of key respiratory health symptoms in both the mothers and young children was reported lower in ICS than TCS. Fifty-five percent (55%) of users reported episodes of cough during TCS use compared to 36.1 % in ICS. Likewise, episodes of phlegm were seen in 69.4% TCS users, but 44.4% ICS users reported phlegm episodes during ICS use. Among the users reporting phlegm, one notable indicator was the reduction in the color of phlegm from yellow or brown/black color (72%) to white phlegm (17%). Likewise, a lower prevalence of headaches from (25.5% to 8.0%) and chest wheezing or whistling (83.1 to 61.0%) was reported for mothers. Eye irritation was observed to decrease from 75% to 22.2% in mothers.

Among 26 children surveyed, 27% percent were found with their mother during cooking events. 46% of the children reported coming in and out of the kitchen; 27% of the children generally did not stay in the kitchen. Coughing events were reported to decrease from 96.2% to 65.4% after ICS use. The prevalence of headaches, chest wheezing, or fast breathing among children does not show a difference between TCS and ICS use. Similarly, in children, eye irritation decreased from 50% to 15.4% after ICS installation.

In Nepal, comparative health surveys similar in nature to the current assessment have also reported reduction in cough, phlegm, headache, and eye irritation (Nepal Health Research Council, 2004, Practical Action, 2007b).

A relatively higher reduction in prevalence was seen in both of these studies after the post intervention period, especially in cough and presence of phlegm.

Discussion

Comparison of IAP levels between (Phase 1) and (Phase 2)

After 1 year of ICS use, there is a slight, statistically insignificant absolute increase in the $PM_{2.5}$ and CO concentrations. The mean concentration of $PM_{2.5}$ and CO reported three months after stove installation was 0.73 mg/m^3 and 8.35 ppm. After 1 year, these values did not change significantly ($p = 0.822$ for $PM_{2.5}$, $p = 0.814$ for CO). This indicates that the ageing of the stoves after 1 year may not have any impact on the IAP levels. The technical evaluation of the stoves also supports the claims that most of the key dimensions of the stove did not change during the first year of use. However, it is difficult to predict the effectiveness of the stoves after 1 year; the rates of deterioration of the stove may differ among different regions and cultural practices. Thus, further monitoring at additional time points would be beneficial to clarify the effectiveness of these stoves over longer periods of time.

Comparison of IAP with WHO guidelines

Despite a noticeable improvement in the smoke level, the mean values of pollutants are still higher than the guideline value. The mean $PM_{2.5}$ concentration of ICS in Phase 1 and 2 still exceeds the WHO Interim Target-1 of 0.075 mg/m^3 (World Health Organization, 2005a, 2005b) by at least a factor of 10 and by a factor of above 30 from the WHO Air Quality Guideline (AQG) of 0.025 mg/m^3. The CO concentration during ICS use (9.91 mg/m^3) is slightly below the WHO guideline of 10 mg/m^3 set for the 8-h average. However, it should be noted that the WHO guideline value for CO is an 8-h mean. The study reported a 24-h mean, which includes a long period during the night when the stove is not used and the CO is very low. These values indicate that while the ICS effectively reduces indoor air pollution, it does in most instances achieve levels that are safe.

Stoves in Ilam are relatively closer to the guideline value for $PM_{2.5}$ during ICS use than the other two districts evaluated. This may be an indicator of geographical and cultural differences, in addition to differences in stove use and maintenance. Specifically, we noted differences across regions in factors such as kitchen type (structure and volume); the number of ventilating structures, such as windows and flues; and fuel types. Interestingly, the cooking hours reported in the three sites differed, with Ilam reporting 6–7 cooking hours, compared to 4 h in Dang and 5 h in Dolakha. Further investigations in Ilam may help illuminate best practices that could help decrease indoor air pollution in other districts.

Mean $PM_{2.5}$ and CO levels for TCS and ICS in Ilam were lower than Dang and Dolakha. Interestingly, the TCS smoke levels in Ilam were close to the ICS levels of Dang and even lower than the ICS levels of Dolakha. This shows that in terms of pollution levels, many houses with TCS in Ilam were better off than some households with ICS in Dang and the majority of households in Dolakha. The IAP data correlates well with the improved ventilation conditions and well-maintained stoves observed in the kitchens of Ilam. Almost all the kitchens in Ilam had separate kitchens outside the house, whereas kitchens in other study sites were indoors and in the same house. Good ventilation in Ilam is attributable to 3–4 windows, bigger kitchens *(in volume)*, eaves, pseudo-hood structures and flue structures observed in the kitchen. In contrast, all the kitchens in Dolakha were poorly vented, with one or no windows, hindering optimum air movement in the kitchen. However, it is out of the scope of this study to evaluate the major factors THAT affect the IAP level in the kitchen besides the stove.

IAP levels higher than WHO guideline values also indicate the need for intervening in other relevant areas that influences the IAP level in the kitchen. This study also observes the possible role of ventilation influencing smoke levels in the kitchen. The importance of ventilation is also supported or indicated by recent studies (Balkrishnan et al., 2004; Dasgupta et al., 2006; Still and MacCarty, 2006). Additionally, newer stoves represent technological breakthroughs in reducing the amount of pollution released and fuel consumed. These new stoves, however, come at a high capital cost and may require additional training and fuel processing, and as such require new deployment mechanisms that enhance community uptake.

Comparison of indoor air level with similar studies

Studies similar in design and employing the same IAP equipment in India have comparable results in percent reduction and correlation between PM2.5 and CO with the current study. The unadjusted Pearson's coefficient is similar to the reported values in recent literature from India and Mexico (Chengappa et al., 2007; Dutta et al., 2007; Masera et al., 2007). The Appropriate Rural Technology Institute (ARTI) in India reports reductions of 24 % and 39 % in mean $PM_{2.5}$ and CO levels with the Laxmi stove and 49 % and 38 % reduction in mean $PM_{2.5}$ and CO levels with the Bhagyalaxmi stove (Dutta et al., 2007) . In the Bundelkhand region of India, Development Alternatives (DA) evaluated improvements in IAP after ICS installation in 60 households. One year after installation of the stoves, 48 h $PM_{2.5}$ and CO levels were reduced by 44% and 70% (Chengappa et al., 2007).

Mean $PM_{2.5}$ and CO levels reported by the ARTI's Laxmi stove of 0.99 mg/m^3 and 8.37 ppm and the Bhagyalaxmi stove of 0.48 mg/m^3 and 6.91 ppm are comparable to the values reported by ICS in the current study. Similarly, the Sukhad stove of DA resulted in reported mean $PM_{2.5}$ and CO concentrations of 0.36 mg/m^3 and 2.8 ppm, which is close to values reported for ICS in Ilam during this study. Direct comparisons between the Nepali study and the Indian studies are difficult due to different monitoring durations (24 h and 48 h, respectively) and variation in the stoves and kitchen types. However, it is important to note that reductions noted in Nepal during the current study are consistent with changes in IAP from recent studies using the same study design in similar regions throughout the world.

Conclusion and recommendations

Overall, the study found very high levels of indoor air pollutants from the burning of biomass fuels, particularly in houses with poor ventilation. The reduction in indoor air pollutants ($PM_{2.5}$ and CO concentration) after 1 year of ICS use is over 60% and only slightly less than the percent reduction recorded after three months of use. This indicates that the improved stoves are reducing indoor concentrations even after 1 year of use. The study has also indicated alteration in ICS stove dimensions after 1 year of use. However, no relation could be confirmed between changes in stove dimensions and IAP levels. Future research should focus more on baffle gap, chimney height, chimney cleaning interval, and diameter of the pothole to strengthen the relation between stove dimension and IAP. Further, smoke reentering the kitchen, though periodic in nature, is an important concern when the IAP level is expected to be higher. Proper stove placement with respect to wind direction is one possible solution to this problem. Additionally, further research in specific meteorological and geographic features may help explain variability between study sites. The preliminary health assessment reported here indicates low prevalence of key respiratory symptoms, especially for mothers, during ICS use. Users also reported improved hygiene and cleanliness in the kitchen. This could be also an indicator of reduced smoke levels in the kitchen. However, lack of personal monitoring and objective measures of health status limits the strength of the health survey conducted in the study.

Based on these findings, this study concludes that there are benefits from using two pothole mud ICS. The stoves are cheap, easy to build with local materials and technicians, and are a suitable intervention to reduce exposure of women and children to pollutants. However, to realize the full benefits of a smoke-free kitchen and scale up this technology, the need for good ventilation, proper operation and maintenance of stoves, and behavioral change should also be highlighted. Additionally, we believe that additional stove testing — including standard tests, like the Water Boiling Test and controlled cooking tests, and detailed emissions testing — could help establish the relative effectiveness of this intervention in the light of similar and more advanced interventions available globally. Contextualizing this ICS within the broader available market of stoves would allow easy comparison with recent proposed guidelines for global stove interventions. Finally, while the stoves perform admirably, additional interventions — including advanced cookstoves — should be evaluated to decrease the amount of pollutant released during combustion and best protect human health.

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Appendix A. Supplementary data

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