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Sustained usage of bioethanol cookstoves shown in an urban Nigerian city via new SUMs algorithm

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ABSTRACT

An unbiased assessment of cooking patterns during a cookstove intervention can provide strong evidence for sustained usage of a cookstove among the target population. A bioethanol cookstove was used as an intervention within a randomized controlled trial being conducted in Ibadan, Nigeria to assess the ability of a clean stove to improve birth outcomes. Sustained usage of the intervention was quantified using a newly developed method of analyzing cooking patterns based on time integrated temperature data from Stove Use Monitors (SUMs) installed on household cookstoves. The method accounts for household level variations in ambient temperatures. We report a significant decline of traditional kerosene stove usage, 84% of women in the Bioethanol arm giving away their kerosene stove before the conclusion of the study (56% within the first month of enrollment), suggesting the bioethanol stove replaced the kerosene stove. This is the first study to objectively evaluate a liquid-to-liquid fuel substitution.

Introduction

Household air pollution (HAP) is the number one environmental risk factor for death and disability worldwide (Lim et al., 2013), attributing to over 4 million deaths annually (Smith et al., 2014). HAP exposures vary greatly between rural and urban areas, especially in low- and middle-income countries (LMICs) (Martin et al., 2013). While residents of rural communities in LMIC continue to rely on biomass for their daily cooking needs, those living in urban areas in several developing countries of Africa, Asia, and Latin America use kerosene frequently as a substitute (Lam et al., 2012).

The use of kerosene fuel for cooking is a public health concern as kerosene cookstoves emit particulate matter (PM), carbon monoxide (CO), volatile organic compounds (VOC), nitric oxides (NO_x) and sulfur dioxide (SO_2) (Lam et al., 2012.). Studies have reported that households using kerosene cookstoves are exposed to kitchen PM concentrations ranging from 300 to 750 $\mu g/m^3$ (Habib et al., 2008; Zhang et al., 2000). While not as high as traditional biomass combustion, these PM concentrations greatly exceed current World Health Organization (WHO) guidelines.

Lam et al. (2012) summarized previous epidemiological studies of kerosene used for cooking or lighting, which provided evidence that kerosene emissions may impair lung function and increase risk of asthma. A hospital-based case–control study conducted among women in Nepal found that use of a kerosene fueled stove was significantly associated with 3.36 times the odds of developing tuberculosis (Pokhrel et al., 2010). Recently, WHO released new health-based air quality guidelines for household fuel combustion, which discourages the use of kerosene until further research into its health impacts is conducted.

Ethanol is a clean-burning fuel, comparable to liquefied petroleum gas (LPG). In one study, it was found to be cleaner-burning than kerosene under certain conditions and according to certain measures (Rajvanshi, 2006). It is similar to LPG in terms of combustion efficiency and particle emissions. Ethanol may be a viable option as a liquid

Abbreviations: HAP, household air pollution; SUMs, stove use monitors; RCT, randomized controlled trial; LMICs, low- and middle-income countries; PM, particulate matter; CO, carbon monoxide; NO_x, nitrous oxides; SO_2, sulfur dioxide; LPG, liquefied petroleum gas; PHCs, primary health centers; IHV, initial home visit; EM, expectation maximization; UCL, upper confidence limit; SD, standard deviation; IQR, inter quartile range; ICC, intraclass correlation coefficient; VOC, volatile organic compounds; WHO, World Health Organization.

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cooking fuel in Nigeria because it can be produced locally and in a renewable manner (Obueh, 2006). Given the health damaging nature of kerosene, a randomized controlled trial (RCT) aimed at quantifying improvements in pregnancy outcomes through reductions in exposures to HAP from cookstoves was conducted. An ethanol fueled stove named the CleanCook (Dometic Group, Durban South Africa) was chosen as the intervention stove in the trial. The CleanCook surpasses WHO benchmarks for $PM_{2.5}$ and International Organization for Standardization (ISO) International Workshop Agreement (IWA) Tier 4 standards for emissions (Berkeley Air Monitoring Group 2012). The CleanCook received the best rating possible, which is matched only by LPG stoves, induction stoves, electricity, biogas, and solar-powered stoves.

While a high performing stove is crucial for HAP reduction, its usage is just as important for improving health outcomes (Johnson and Chiang, 2015). Efforts to implement improved cooking technologies (ICTs) have been met with significant challenges. The translation of high energy efficiency and smoke removal standards from cookstoves in laboratory testing has not led to consistent, reproducible performance in the household. Frequently, when ICTs are used within a home, 'stove stacking' results. Stove stacking occurs when individuals continue to utilize their traditional stove in conjunction with the new cooking technology they have received. Thus, the potential health benefits of the ICT are hampered because individuals are still exposed to levels of HAP above WHO guidelines from continued use of their traditional cookstove (Johnson and Chiang, 2015).

In order to effectively reduce exposure to HAP and achieve the greatest health benefit, complete displacement of traditional stoves with clean cooking technologies must be achieved (Johnson and Chiang, 2015). Cooking patterns must be closely monitored within the target population to systematically evaluate if use of a newly introduced cookstove is consistently maintained, resulting in significant disuse of the traditional cookstove.

This paper presents an analysis of cooking patterns via stove use monitor (SUM) data from the CleanCook stoves disseminated in the RCT in Nigeria. It is quantitatively demonstrated that, in an urban setting, the transition from a kerosene cookstove to an ethanol cookstove can be achieved with minimal occurrence of stove stacking.

Methods

Study overview

The RCT was conducted in Ibadan, Nigeria, a metropolis of over 3 million people located in Southwest Nigeria. Pregnant women less than 18 weeks gestational age, who cooked primarily with kerosene and/or biomass, were recruited from one of five local, primary health centers (PHCs). Participants were randomized into control and intervention groups. Participants in the control group continued to cook with their traditional stove. The intervention group participants were given a bioethanol cookstove called the CleanCook, valued at $60, and free bioethanol fuel until the delivery of the baby. SUMs were placed on all cookstoves used in participant homes. Cooking patterns and stove preferences were monitored throughout their pregnancy using a combination of the SUMs and interview-administered questionnaires data regarding cooking habits and daily activities. The data were collected every two to three weeks during subsequent home visits. At the conclusion of their participation in the study, participants are given the option to purchase bioethanol fuel subsidized to match the current cost of kerosene.

Temperature readings via SUMs

Thermochron iButtons 1921G (Maxim Integrated Products, Sunnyvale, CA) were used to monitor the temperature of each stove and are described in detail elsewhere as SUMs (Ruiz-Mercado et al., 2012). The SUMs record temperatures to the nearest 0.5 °C and were programmed to monitor either every 3, 10 or 13 min based on the length of time between field visits. The SUMs were placed 10 cm from the center of the kerosene cookstove burner and 14 cm directly in between the double burner of the CleanCook stove. These distances were determined pre-trial by defining an optimum length away from the stove burner that provides sufficient resolution of temperature fluctuation while not causing the SUMs to overheat and rupture.

Inclusion criteria

While SUMs remained on each cookstove for the entire study duration, each cookstove did not have SUMs data available for the complete study duration (detail on SUMs field performance is provided in SI). A reliability analysis was conducted to determine how many days of SUMs cookstove monitoring were necessary to be representative of cookstove use during the entire period of the intervention (Ruiz-Mercado, 2012). The analysis took into consideration both overall and monthly days of SUMs data during a participant's enrollment in the intervention to account for potential variations in cooking occurring at different months during the pregnancy.

In the reliability analysis, 'study months' were defined as 30-day periods, beginning with a participant's entry into the study (established as the day a participant received her initial home visit), and ending with the birth of her baby. Because study participants were recruited and randomized at no later than 18 weeks of gestational age, approximately five study months of SUMs data was collected from the cookstove(s) of each participant. Participants with at least eight days of stove monitoring with SUMs in study months one through four, on at least a kerosene or CleanCook stove, prior to October 1, 2014, were included. Higher variability (also reported in an Indian intervention (Pillarisetti et al., 2014)) coupled with less days of data due to the delivery of the child resulted in the exclusion of study month five from the analysis presented. More details about how sufficiency was assessed are provided in SI.

Converting temperature readings to stove usage

All data management and statistical analysis was conducted in RStudio, version 0.98.507 (R Core Team, 2014). A stove was determined as in-use when the SUMS temperature was above a threshold temperature. A unique threshold was determined for each home to account for ambient temperature variations among the households.

The temperature distribution from each SUM followed a bimodal distribution with the two peaks occurring at the mean ambient temperature and the mean cooking temperature (Fig. 1).

The ambient temperature curve was assumed to be normally distributed due to large number of data points (average per stove = 10,070 data points) for each cookstove. Using the Expectation Maximization (EM) algorithm via the Mixtools package, version 1.0.2 (Benaglia et al., 2009), in RStudio, the average and standard deviation of the ambient temperature was obtained. The 99.9% upper confidence limit (UCL) of the mean ambient temperature was estimated as the cutoff between a stove being in and out of use for a particular SUM, creating a unique threshold temperature for each cookstove (Fig. 1).

The mixed EM algorithm requires a minimum number of data points with-in both modes of the expected bi-modal distribution. Secondary stoves (kerosene stoves in the intervention arm) were not used enough by study participants for the mixed EM algorithm to converge and identify two modes. For this reason, only the primary cookstove (CleanCook stove in intervention arm and kerosene cookstove in control arm) were used to define a temperature threshold for 'stove in-use' versus 'stove nonuse'. This cutoff was applied to all SUMs in the home, regardless of the type of stove. Additionally, the mixed EM algorithm is only effective on stove types that heat and cool rapidly such that a distinct dichotomy of ambient and cooking temperatures is present.

For participants that owned and used more than one kerosene stove, the kerosene cookstove with the higher usage was deemed the primary cookstove for that household and only one threshold temperature was used. Higher usage was quantitatively determined by the cookstove that had a higher cooking temperature mixing proportion as determined by the EM algorithm. This was the kerosene cookstove that had a higher proportion of temperature data corresponding to the curve of cooking temperatures as compared with ambient temperatures. The variability of threshold temperatures of all kerosene stoves in the control arm was modeled using random effects (accounting for multiple kerosene stoves within a control arm home) to confirm that the main source of variance in ambient temperatures was between homes and not within homes.

Metrics of cookstove usage

Stove usage was evaluated by length of a cooking event, duration of cooking per day and number of cooking events per day. Cooking event lengths were calculated as the number of consecutive temperature readings above the threshold temperature multiplied by the SUMs logging interval. Cooking events were calculated as the number of discrete times that a SUM recorded at least one temperature above the temperature cutoff during each 24-h monitoring day. Each event is separated by a minimum of 10 min from a previous cooking event. SUMs data from two kerosene stoves belonging to the same participant were aggregated to effectively evaluate each participant's total daily stove usage.

Quantification of sustained cookstove usage

A ‘stove-day’ is defined as a particular day with any amount of stove usage (Ruiz-Mercado, 2012). Any amount of stove usage on a SUMs monitoring-day is defined as having at least one cooking event registered to a SUM, regardless of the length of that single cooking event. The number of stove-days per study month was counted for each participant to assess the prevalence of stove stacking within the intervention arm.

Pre-stove dissemination SUMs

Kerosene stove usage among intervention arm participants prior to stove-dissemination was compared to their CleanCook stove usage during the intervention to observe potential changes in cooking patterns furnished by introduction of the bioethanol stove. SUMs data from the same time period for control arm participants was leveraged to assess the reliability of cooking patterns during this time as a reflection of cooking patterns during the intervention (Pillarisetti et al., 2014).

Statistical analysis

Mixed effects linear regression was conducted to account for variations both between household and within a participant's household to determine differences in average cooking length between the primary cookstoves. Mixed effects Poisson regression was used to compare the rates of cooking events/day between primary cookstoves. Mixed effects logistic regression was used to assess differences in the proportion of days during the intervention that the primary cookstoves were used at least once daily by study participants. The same analyses were conducted to compare traditional kerosene stove usage pre-stove dissemination to ethanol stove usage during the intervention, among intervention arm participants. In all regression models involving cooking length estimation, only similar SUMs sampling intervals (three, ten, thirteen) were compared, and unless otherwise noted, all cooking length regression was done with 13 min monitoring, as this was the most prevalent sampling interval during our intervention (see SI for more information). In analyses of cooking events per day, all SUMs data was aggregated. Study month was controlled for (when applicable).

Results

Study population

The study population included in the analysis consists of 50 participants (25 intervention; 25 control) with an average of 71 SUMs monitoring-days (SD = 8, range = 47–88) during enrollment months one through four. The 50 participants had a total of 3564 SUMs monitoring-days from their study entry through either the last day of their fourth enrollment month or through October 1, 2014, whichever came first. These 50 pregnant Nigerian women used kerosene cookstoves exclusively prior to randomization. Descriptive statistics are provided in Table 1. Table 1 shows that there were no significant differences in measured baseline characteristics, including participant-estimated average monthly amount of money spent on kerosene fuel and estimated monthly amount of kerosene fuel used.

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Variation in ambient temperatures

The individual household threshold temperature used to determine if a stove was in use ranged by nine degrees Celsius (range = 30.6–39.1, IQR = 33.4–35.0, mean = 34.2, SD = 1.5) across the entire study population. Within a home very little variation in temperature was observed. An intraclass correlation coefficient (ICC) of 80% was found in the random effects model of temperature thresholds from all kerosene cookstoves within a home.

Consistency of stove usage among participants

Fig. 2 illustrates that the percent of ‘stove days’ of the CleanCook stove consistently remained at approximately 90% throughout months 1–4 of participants' duration in the intervention, similar to the percent of stove days for kerosene stoves among control arm participants. Based on logistic regression analysis, there was no significant difference (p = 0.9) between the percentage of stove days with kerosene stove use among control arm participants and the percentage of stove days with CleanCook stove use, controlling for each study month. Using two

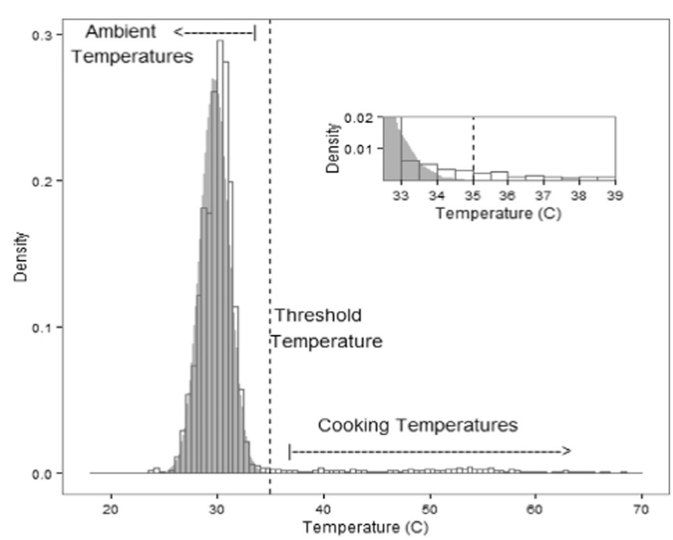

Fig. 1. Distribution of temperatures recorded to SUM placed on CleanCook stove from participant HAP12-184). Reflective of 106 SUMs monitoring-days and 12,238 temperatures collected over the course of the intervention.

weeks of pre-stove dissemination SUMs data, no significant difference ($p = 0.2$) was found in percent stove days of kerosene usage between both study arms.

In the intervention arm, average percent of stove days for the kerosene stove was 85% prior to receiving the CleanCook stove. After the dissemination of the CleanCook, the average percent stove days for kerosene cookstoves dropped to approximately 25% in the first month and at or below 5% for subsequent months.

Among the 25 intervention arm participants, 21 (84%) gave their stove(s) away during the course of the intervention and used the CleanCook stove exclusively for the remainder of the study period. Of these 21 participants, 14 gave their stove(s) away within the first month of receiving the CleanCook stove, four participants during the fifth month of the study, close to child birth, and three in study months 2–4.

As it is difficult to pinpoint the exact date the participants gave their stoves away, the day of stove removal from the household was estimated as the last day SUMs data was downloaded from the removed kerosene stove. Once the kerosene stove was given away (or both kerosene stoves given away, if the participant had two), every subsequent study month was assumed to have zero stove-days for that kerosene stove.

Stove usage analysis

Controlling for study month, CleanCook users cooked an average of 17 min less per day than kerosene users; however, the difference was not significant ($p = 0.15$). Kerosene stoves were in use for an average of 131 min per day (95% CI = [114, 151]), while average duration of CleanCook stove use was 114 min per day (95% CI = [99, 130]). No statistical differences were found in the number of cooking events per day between the CleanCook and kerosene groups, after controlling for study month; $p = 0.5$. Over the entire study period, the average number of cooking events per day was 1.84 (95% CI = [1.65, 2.19]) for kerosene stove users and 2.05 (95% CI = [1.78, 2.36]) for CleanCook stove users.

Cooking lengths were log transformed to meet the assumption of normality. The average length of a cooking event on kerosene stoves was 56 min (95% CI = [52, 61]), with the CleanCook stove being used an average of 45 min (95% CI = [42, 49]). The eleven minute difference was statistically significant; $p = 0.001$. The average cooking length in the second and third study months were not statistically different from that of the first study month ($p = 0.9$ & $p = 0.2$, respectively) within both study arms. However, in the fourth month of the study, there was a significantly higher increase in average length of a cooking event among the control arm participants compared to the intervention group ($p_{interaction} = 0.003$). The average cooking length on kerosene stoves in study month four was 62 min (95% CI = [58, 67]) and 46 min (95% CI = [43, 50]) on CleanCook stoves.

Pre-stove dissemination stove usage analyses

Twenty-three of the 25 intervention participants had at least seven pre-stove dissemination SUMs monitoring-days on their kerosene cookstove. The 23 kerosene cookstoves had between 12 and 14 days of monitoring, combining to a total of 303 pre-CleanCook stove dissemination SUMs monitoring-days in the analysis. When comparing the number cooking events per day on kerosene stoves used by intervention arm participants, prior to receiving the CleanCook stove, to the number of cooking events per day for CleanCook, there was no statistical difference ($p = 0.2$). Kerosene cookstoves were used an average of 1.97 times per day (95% CI = [1.68, 2.32]) by intervention arm participants, pre-stove dissemination, compared to an average of 2.05 events per day (95% CI = [1.78, 2.36]) on CleanCook stoves.

No cooking event length analysis was completed due to the low kerosene cookstove usage among intervention arm participants. Seventeen of the 25 control arm participants had at least 7 days of SUMs monitoring pre-randomization (range = 11–14), for a total of 219 SUMs monitoring-days. The average number of cooking events per day was 1.83 (95% CI = [1.49, 2.24]) pre-stove dissemination compared to 1.84 events per day (95% CI = [1.65, 2.19]) during the trial. There was no statistical difference ($p = 0.9$). Cooking events per day compared between control and intervention groups pre-stove dissemination were not statistically significantly different ($p = 0.4$).

Discussion

Sustained use of the CleanCook bioethanol cookstoves

We report sustained use during pregnancy of an ethanol fueled cookstove intervention within a cohort of Nigerian women living in an urban setting, with access to kerosene fuel. Unlike other studies which have included a cookstove intervention, we report minimal stove stacking. The average percent stove-days of the kerosene stoves in the intervention arm decreased to 5% by the second month of the subjects' participation in the study. The high usage of the bioethanol stove suggests that the stove met the needs of the participants to complete cooking tasks. Comparing the percent of stove days, as well as the number of cooking events the amount of stove usage was not statistically different between pre-and post-stove dissemination periods (Fig. 2), suggesting that the bioethanol stove did not alter cooking patterns. The bioethanol stove replaced the kerosene stove as shown by 85% of the participants in the intervention arm removing their kerosene cookstove from their household and adopting the CleanCook stove exclusively for all of their cooking tasks.

The conclusion that the bioethanol stove replaced the cooking tasks previously completed on a kerosene stove is also supported by the lack of statistical difference of the percent stove-days, average duration of cooking per day and average number of cooking events per day when comparing the intervention and control study groups. Table 1 shows no significant difference in participant-estimated average monthly amount of money spent on kerosene fuel and estimated monthly amount of kerosene fuel used, highlighting the initial similarity of cooking fuel use.

Sustained use of the CleanCook stove may be attributed to similarities between the kerosene and CleanCook stove. Both stoves utilize a liquid fuel, require one fueling event prior to stove usage (not continuous feeding), allow for modulation of temperatures, have similar size

Table 1
Characteristics of Nigerian women in HAP study.

Characteristic	Intervention (n = 25)	Control (n = 25)
Age (years) (mean (SD))	27 (5)	28 (5)
Number of children prior to pregnancy (count (%))		
0–1	9 (36)	7 (28)
≥2	16 (64)	18 (72)
Education level (count (%))		
Junior secondary or lower	8 (32)	9 (36)
Senior secondary or higher	17 (68)	16 (64)
Occupation (count (%))[a]		
Trader	12 (48)	19 (73)
Tailor	5 (20)	3 (12)
Other	9 (36)	4 (15)
PHC recruited from (count (%))		
Agbongbon	15 (60)	15 (60)
Oranyan	10 (40)	10 (40)
Participant estimated monthly kerosene usage at baseline (liters) (mean (SD))	14 (9)	17 (10)
Participant estimated monthly kerosene expenditure at baseline (Naira) (mean (SD))	1950 (1195)	2204 (1400)

Fisher's exact test used for categorical data; t-test used for age; Wilcoxon test used for all other continuous data.
All p-values > 0.1.
[a] Some participants have more than one occupation.

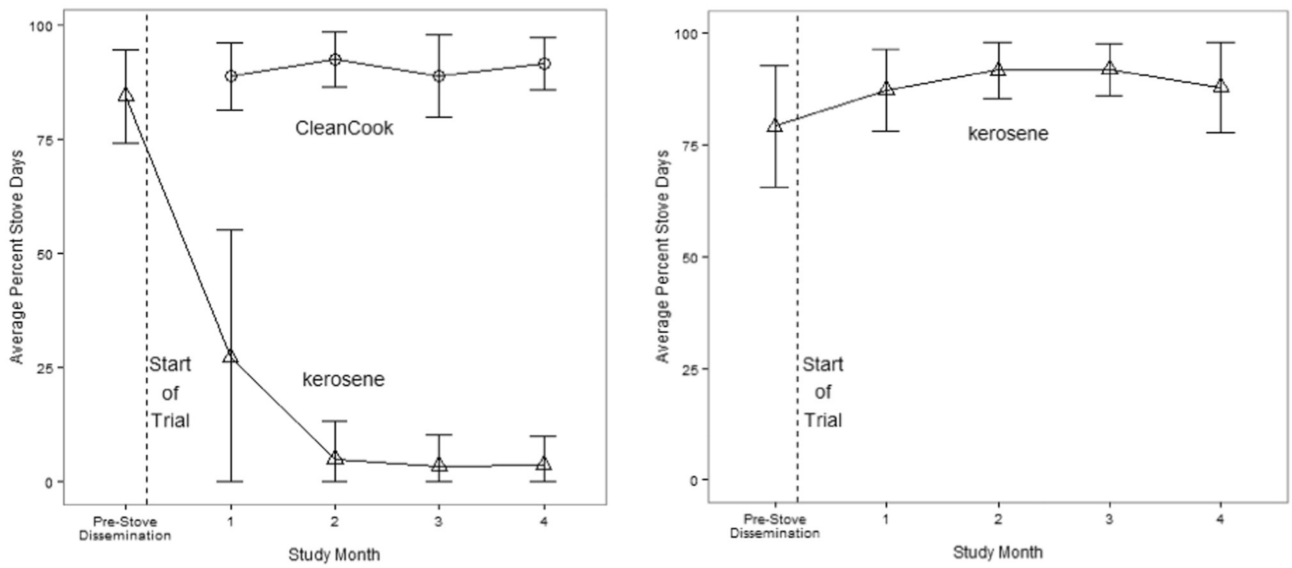

Fig. 2. (Left) The average percent stove days (95% CI) for each study month among intervention arm participants. (Right) The average percent stove days (95% CI) for kerosene stoves among control arm participants. Pre-stove dissemination data only includes 40 participants having at least seven SUMs monitoring days. Pre-stove dissemination percent stove days point estimates are representative of approximately two weeks of data.

burners, are portable and do not require electricity to operate. These similarities may have limited changes to the behavioral rhythm of cooking when the CleanCook stove was introduced. Behaviors of food preparation and meal cooking may be modified when improved biomass stoves require changes in the timing of feeding or processing of fuel compared to the traditional biomass stove, possibly accounting for the higher levels of stove stacking reported in previous studies (Pillarisetti et al., 2014; Bailis et al., 2007).

Potential impacts on exposure

A decrease in daily cooking time may lead to reductions in HAP exposures, and possibly increase the time that women have for other daily activities. The average of 17 min less time spent cooking per day on Cleancook stoves versus kerosene cookstoves over the four months studied may be due to the bioethanol stove having two burners compared to the single burner on the kerosene stoves (three participants did have two kerosene stoves). Cumulatively, there is almost two hours per week less cooking time among bioethanol stove users compared to the control group. The duration of daily cooking may be a possible proxy for personal exposures to household air pollution and more health-relevant statistic and a better measure of potential risk other proxy measures such as cooking fuel type, or kitchen concentrations (Pillarisetti et al., 2014).

SUMs algorithm to assess liquid fueled cookstove usage

To our knowledge, the algorithm presented is the first to account for household level variation in ambient temperatures within a study setting by establishing a unique threshold temperature for each participant with data collected from a single SUMs. The newly developed algorithm used in this analysis is cost-effective as it only requires temperature measurements captured from the SUMs deployed on cookstoves; no additional ambient temperature measurements or SUMs are needed. Developing within home temperature thresholds also reduces the need to correct for the differences in measured temperatures between SUMSs. Previously, deviations from local ambient temperature data (Pillarisetti et al., 2014) and time–temperature slope thresholds (Ruiz-Mercado et al., 2013) have been used in interventions in India and Guatemala, respectively. The individual threshold temperatures covered a range of 9 °C in this population. Use of a single ambient temperature to identify a single threshold temperature for the entire study population would result with an inaccurate estimate of cooking length, as possible number of cooking events.

The SUMs algorithm presented is applicable to the liquid fueled cookstoves used within the study, as the temperature rises and declines rapidly when the cookstove is turned on and off, respectively. The algorithm can be used with any stove with similar heating and cooling properties such as LPG. The only limitation is the requirement for a significant amount of ambient data to be collected. The EM algorithm requires the ambient temperature to have a normal distribution there for this algorithm may not work for short period of SUMs temperature data collection.

Study limitations

Providing participants with fuel during the length of the study may have resulted in higher usage rates compared to a natural experiment where women are solely given the stove and required to purchase their own fuel (Ruiz-Mercado et al., 2011). However, 76% of the participants have continued to purchase ethanol fuel and use the CleanCook stove since the conclusion of their participation in the study. This suggests that financial incentives, while potentially a factor in the initial uptake of the CleanCook stove, participants are satisfied with the CleanCook stove.

There may be important seasonal trends in cooking patterns in Nigeria due to characteristics such as religion and occupation of the participants. The analysis in this paper only focused on cooking patterns over the course of pregnancy, and not on calendar months, due to the study's ongoing recruitment. The sample size limited the power for detecting seasonal changes in cooking patterns. However, randomization evenly distributed measured population characteristics between the two study arms, theoretically minimizing potential residual bias introduced by seasonal cooking differences.

Author contributions

ALN contributed to the study design, training of field team for data collection, design of data collection instruments, statistical analysis and writing of the manuscript. MS conducted statistical analysis and contributed to writing of the manuscript. DA contributed to coordination of data collection, and writing of the manuscript. JO and TI contributed to data collection, coordination and manuscript editing. GA and OO contributed to study design, field work supervision and editorials. COO contributed to study design, manuscript writing and editing and had oversight over study design and administration.

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Appendix A. Supplementary data

Additional tables; methodology detailing sufficiency of SUMs monitoring-days; intraclass correlation coefficients from linear mixed models; accounting for different SUMs sampling intervals; sensitivity analysis of Expectation Maximization method. Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.esd.2016.05.003.

References

Bailis R, Berrueta V, Chengappa C, Dutta K, Edwards R, Masera O, et al. Performance testing for monitoring improved biomass stove interventions: experiences of the Household Energy and Health Project1. Energy Sustain Dev 2007;11(2):57–70.

Benaglia T, Chauveau D, Hunter D, Young D. Mixtools: an r package for analyzing finite mixture models. J Stat Softw 2009;32(6):1–29.

Habib G, Venkataraman C, Bond TC, Schauer JJ. Chemical, microphysical and optical properties of primary particles from the combustion of biomass fuels. Environ Sci Technol 2008;42(23):8829–34.

Johnson MA, Chiang RA. Quantitative guidance for stove usage and performance to achieve health and environmental targets. Environ Health Perspect 2015;123(8):820–6.

Lam NL, Smith KR, Gauthier A, Bates MN. Kerosene: a review of household uses and their hazards in low- and middle-income countries; 2012 [http://www.tandfonline.com/doi/abs/10.1080/10937404.2012.710134 accessed Apr 21, 2015].

Lim SS, Vos T, Flaxman AD, Danaei G, Shibuya K, Adair-Rohani H, et al. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 2013;380(9859):2224–60.

Martin II WJ, Glass RI, Araj H, Balbus J, Collins FS, Curtis S, et al. Household air pollution in low- and middle-income countries: health risks and research priorities. PLoS Med 2013;10(6), e1001455.

Obueh J. Methanol stoves for indoor air pollution reduction in Delta State, Nigeria — addressing the needs of people for clean energy. Boil Point 2006;52:27–9.

Pillarisetti A, Vaswani M, Jack D, Balakrishnan K, Bates MN, Arora NK, et al. Patterns of stove usage after introduction of an advanced cookstove: the long-term application of household sensors. Environ Sci Technol 2014;48(24):14525–33.

Pokhrel AK, Bates MN, Verma SC, Joshi HS, Sreeramareddy CT, Smith KR. Tuberculosis and indoor biomass and kerosene use in Nepal: a case–control study. Environ Health Perspect 2010;118(4):558–64.

R Core Team. R: a language and environment for statistical computing.; Vienna, Austria; 2014.

Rajvanshi AK. Ethanol fuel for rural households. Maharashtra India: Nimbkar Agric. Res. Inst.; 2006.

Ruiz-Mercado I. The stove adoption process: quantification using stove use monitors (SUMs) in households cooking with fuelwood; 2012.

Ruiz-Mercado I, Masera O, Zamora H, Smith KR. Adoption and sustained use of improved cookstoves. Energy Policy 2011;39(12):7557–66.

Ruiz-Mercado I, Canuz E, Smith KR. Temperature dataloggers as stove use monitors (SUMs): field methods and signal analysis. Biomass Bioenergy 2012;47:459–68.

Ruiz-Mercado I, Canuz E, Walker JL, Smith KR. Quantitative metrics of stove adoption using stove use monitors (SUMs). Biomass Bioenergy 2013;57:136–48.

Smith KR, Bruce N, Balakrishnan K, Adair-Rohani H, Balmes J, Chafe Z, et al. Millions dead: how do we know and what does it mean? Methods used in the comparative risk assessment of household air pollution. Annu Rev Public Health 2014;35(1):185–206.

Zhang J, Smith KR, Ma Y, Ye S, Jiang F, Qi W, et al. Greenhouse gases and other airborne pollutants from household stoves in China: a database for emission factors. Atmos Environ 2000;34(26):4537–49.