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

Amanda Northcross [a,b,*], Matt Shupler [a], Donee Alexander [e,1], John Olamijulo [c], Temitope Ibigbami [c], Godson Ana [d], Oladosu Ojengbede [d], Christopher O. Olopade [e]

[a] Department of Environmental and Occupational Health, School of Public Health and Health Services, The George Washington University, USA
[b] Global Alliance for CleanCook Stoves, USA
[c] Healthy Life for All Foundation, Ibadan, Nigeria
[d] University of Ibadan, Ibadan, Nigeria
[e] Center for Global Health, University of Chicago, USA

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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 μg/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.

* Corresponding author at: Department of Environmental and Occupational Health, School of Public Health and Health Services, The George Washington University, USA. Tel.: +1 202 994 3970.
E-mail address: northcross@email.gwu.edu (A. Northcross).
[1] DA is currently at the Global Alliance for CleanCook stoves.

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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