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Kerosene lighting contributes to household air pollution in rural Uganda

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Abstract

The literature on the contribution of kerosene lighting to indoor air particulate concentrations is sparse. In rural Uganda, kitchens are almost universally located outside the main home, and kerosene is often used for lighting. In this study, we obtained longitudinal measures of particulate matter 2.5 microns or smaller in size (PM_{2.5}) from living rooms and kitchens of 88 households in rural Uganda. Linear mixed effects models with a random intercept for household were used to test the hypotheses that primary reported lighting source and kitchen location (indoor vs. outdoor) is associated with PM_{2.5} levels. During initial testing, households reported using the following sources of lighting: open wick kerosene (19.3%), hurricane kerosene (45.5%), battery powered (33.0%), and solar (1.1%) lamps. During follow-up testing these proportions changed to 29.5%, 35.2%, 18.2%, and 9.1%, respectively. Average ambient, living room, and kitchen PM_{2.5} levels were 20.2, 35.2, and 270.0 µg/m³. Living rooms using open wick kerosene lamps had the highest PM_{2.5} levels (55.3 µg/m³) compared to those using solar lighting (19.4 µg/m³; open wick vs. solar, *p* = 0.01). 27.6% of homes using open wick kerosene lamps met World Health Organization indoor air quality standards compared to 75.0% in homes using solar lighting.

INTRODUCTION

Indoor air pollution from solid fuel use leads to 3.9 million premature deaths a year globally¹, and is one of the most important environmental risk factors contributing to the global burden of pulmonary, cardiovascular, and cerebrovascular disease². In low and middle income countries like Uganda, over 95% of the population relies on biomass fuel for heating, cooking, and lighting³, with women and children disproportionately affected due to the time spent indoors during high exposure activities^{4,5}. Particulate matter, a component of

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indoor air pollution, is thought to be associated with adverse acute and long term respiratory effects including an increased risk of acute respiratory infections, chronic obstructive pulmonary disease, and lung cancer^{6,7}. For example, a dose-response relationship between indoor particulate levels and acute respiratory infections has been identified in rural Kenya⁸, whereas a recent cross-sectional study in rural Uganda has also identified a high prevalence of early onset chronic obstructive pulmonary disease in women, with exposure to biomass smoke being the major risk factor⁹.

However, attempts to reduce indoor air pollution in resource-limited settings by reducing emissions from cookstoves have not been successful. A randomized controlled trial in Guatemala¹⁰ of improved wood stoves with a chimney vs. traditional open fires did not show a statistically significant decrease in the primary outcome of physician-diagnosed pneumonia, although there were significant reductions in carbon monoxide levels (as a surrogate measure of particulate matter levels) and fieldworker assessed severe pneumonia. A recent large randomized controlled trial of cleaner cookstoves in Malawi also failed to demonstrate a reduction in childhood pneumonia¹¹. Other randomized trials of improved cookstoves in Ghana¹² and Rwanda¹³ did not find a significant reduction in indoor air pollution; one explanatory factor may be poor compliance with use of the improved cookstoves. A field test of improved cookstoves in rural India did find reductions in indoor particulate matter and carbon monoxide concentrations. However, no improved cookstove was able to achieve reductions in indoor air pollution to levels below 25 $\mu\text{g}/\text{m}^3$.¹⁴ Although there is no clear “safe” threshold for $\text{PM}_{2.5}$ exposure, 25 $\mu\text{g}/\text{m}^3$ is an interim target for 24-hour averaged $\text{PM}_{2.5}$ exposure deemed acceptable by the World Health Organization (WHO)¹⁵. This measure, however, does not accurately reflect $\text{PM}_{2.5}$ levels at peak exposure that may be independently associated with acute health effects.

In contrast, kerosene used for lighting has not received significant attention as a contributor to indoor particulate levels. Studies in this area are limited, and particularly lacking when it comes to defining the contribution of kerosene lighting to indoor levels of fine particulate matter (particulate matter 2.5 microns and smaller in size, or $\text{PM}_{2.5}$). A recent review of available studies in the literature¹⁶ found mostly experimental chamber studies which demonstrate that kerosene lamps, particularly simple wick lamps, often lead to emissions of indoor $\text{PM}_{2.5}$ that exceed WHO recommended standards¹⁷.

In rural Uganda, the kitchen is almost always located outside of the main home, typically in a separate structure or outdoors. Concurrently, there is a heavy reliance on kerosene for indoor lighting. The primary aim of this epidemiologic study was to determine whether reported primary lighting source was associated with indoor $\text{PM}_{2.5}$ levels in the main home.

METHODS

Study population

We recruited women living in rural villages in Nyakabare Parish located in southwest Uganda. A survey of all households in Nyakabare parish was previously conducted as part of an ongoing population-based study evaluating the effect of different social, policy, and economic interventions. None of the households in this area are connected to the national

electrical grid. For this sub-study, we first held a series of community meetings with the village health teams, district health officials, and village leaders in order to explain the purpose of the project and to demonstrate the air sampling equipment. Trained fieldworkers were then paired with research nurses and a member of the village health team to visit a subsample of homes and obtain informed consent to participate in this study. 88 women from distinct households located in 7 village cells were enrolled.

Indoor environment assessment

Trained research assistants first conducted a walk-through of each home. Characteristics of the home including location of the kitchen, type of fuel used, type of indoor lighting, and materials used in home construction were recorded on a standardized questionnaire. A kitchen was considered to be indoors if it was located in a structure that had at least three walls. Kerosene lamps were categorized as either open wick lamps or hurricane lamps (see Figure 1).

Exposure assessment

Repeated measures of kitchen and living room $PM_{2.5}$ levels were obtained from 88 homes during two different time periods: between July and October of 2015, and between March and July of 2016, during which time weather and daylight hours were similar. Of note, this area has two rainy seasons. The first runs from March to May and the second from September to November. In order to obtain measures of ambient air pollution, repeated measures of $PM_{2.5}$ were also obtained during these periods from the public meeting places in each of the 7 villages, i.e., a centrally located outdoor location in each village.

24-hour integrated $PM_{2.5}$ levels were obtained using a compact multistage cascade impactor¹⁸ with two 2.5 μm cutpoints. Particles larger than the cutpoint are collected onto polyurethane foam as an impaction substrate at each impactor stage, allowing for particles smaller than 2.5 μm to be collected onto a final 37 mm, 2.0 μm pore size Teflon filter (Pall Life Sciences; Teflo). The sampler was attached to a custom-built battery-powered pump operating at 5 liters per minute. Flow was measured by a flowmeter (Omron D6F-P), with flow and time of use data recorded onto a datalogger (HOBO UX120 4-Channel Analog Logger). Samplers were positioned 4 feet above ground level. In kitchens, samplers were placed one meter from the cooking fire. In living rooms, pumps were placed in the center of the room; because lighting sources such as lamps were moved by participants at night, we were unable to place samplers at a consistent distance from the lighting source. All collected environmental samples were labelled with a unique identifier, and details of sample collection were recorded onto a standardized field log.

Filters were conditioned in a temperature and humidity controlled environment for at 48 hours prior to weighing on an electronic microbalance (MT-5 Mettler Toledo) in Boston, Massachusetts. This was done prior to sample collection and after sample collection in order to calculate $PM_{2.5}$ mass. The concentration of $PM_{2.5}$ was calculated by dividing the change in filter weight by the volume of air sampled to give a final concentration in micrograms per cubic meter. Following gravimetric measurement, Teflon filters from living rooms were analyzed for indoor black carbon (BC) concentrations by measuring filter blackness using a

smoke stain reflectometer (model EEL M43D, Diffusion Systems). We used the standard black-smoke index calculations of the absorption coefficients based on reflectance¹⁹. We assumed a factor of 1.0 for converting the absorption coefficient to BC mass^{20, 21}, which was then divided by the sampled air volume to calculate average BC exposure concentration.

Field blanks were used to account for potential bias in filter weight due to sampling methods. Average net weights of field blank samples were negligible (mean 0.009 ± 0.005 mg), thus we did not blank correct our samples.

Questionnaire

To assess respiratory symptoms, trained research assistants administered a modified version of the American Thoracic Society Questionnaire in Runyankole, the local language. Additionally, questions regarding demographics, household assets, cooking practices, primary lighting source, time use, and health of children in the household were also obtained.

Statistical analysis

Summary measures of $PM_{2.5}$ by location were calculated. In unadjusted analyses, the Kruskal-Wallis test was used to determine differences in $PM_{2.5}$ levels by location (outdoor, living room, kitchen) and by lighting source. In adjusted analyses, linear mixed effects models were used, with a random intercept for household to adjust for repeated measures of $PM_{2.5}$ levels in the same home. $PM_{2.5}$ level were natural log-transformed to account for the skewed distribution, and a categorical variable for sampling phase was used to adjust for seasonal trends. In order to adjust for household wealth as a potential confounder between lighting and indoor $PM_{2.5}$ levels, we calculated an asset-based index for household wealth that has been validated for use in resource-limited settings.²² This index is based on a series of 19 survey questions regarding both household assets and housing characteristics (e.g., number of plots of land owned, whether a household member owns a radio, whether the home has a cement floor, etc.). In order to test the hypothesis that $PM_{2.5}$ levels differed by location, a categorical variable for location (outdoor, living room, kitchen) was used. To test the hypothesis that kitchen $PM_{2.5}$ levels differed between indoor and outdoor kitchens, the kitchen indicator variable was further subdivided by kitchen location (indoor vs. not indoor), adjusting for sampling phase. To test the hypothesis that living room $PM_{2.5}$ and black carbon levels differed based on reported primary lighting source, the living room indicator variable was further subdivided by lighting source (solar, battery, hurricane lamp, open wick lamp). Sampling phase, use of a secondary stove in the main home, and household wealth were included as covariates. All statistical analyses were performed in R 3.3.0; the R packages *nlme*²³ and *ggplot2*²⁴ were used for mixed effects models and plotting, respectively. Two-sided p-values of <0.05 were considered statistically significant.

Ethics

Written informed consent to participate in this study was obtained from all participants. The study was given ethical approval by the Research Ethics Committee of the Mbarara University of Science and Technology, the Partners Human Research Committee, and the Office of Human Research Administration at the Harvard T.H. Chan School of Public

Health. Consistent with local guidelines, we also obtained clearance for the study from the Ugandan National Council for Science and Technology and the Research Secretariat in the Office of the President.

RESULTS

This study included 88 women from distinct households. The average age was 36.2 ± 9.0 years old, and 81 (92.0%) reported farming as their primary occupation. On average, participants spent 15.0 ± 2.8 hours indoors per day, of which 3.4 ± 1.4 hours were spent next to the cooking fire. Participants reported a history of the following healthcare worker diagnosed medical problems: allergies (27.3%), pneumonia (4.5%), and asthma (1.1%). The majority of participants reported cooking-related symptoms, with 84.5% reporting itchy eyes or runny nose, 48.8% reporting cough, 16.7% reporting wheezing, and 17.9% reporting difficulty breathing while cooking. There were on average 3.5 ± 1.3 children per household, and 93.2% of the children spent time in the kitchen. A substantial number of participants reported prior healthcare worker diagnosed medical problems in their children, with 15.9% reporting allergies, 4.5% reporting asthma, and 12.5% reporting pneumonia.

Only 5 kitchens were located outdoors. Of the indoor kitchens, most (89.8%) were located in a structure separate from the main home, with only 1 participant reporting cooking inside the main home, and only during the rainy season. The average distance between the kitchen and home was 6.2 meters. Most (98.9%) participants used firewood as the main fuel for cooking. Seven (8.0%) reported having a secondary stove inside the house that was used for tasks such as boiling water, rewarming food, or for heating the home. During baseline testing, participants reported the following primary lighting sources: open wick kerosene lamp (19.3%), hurricane lamp (45.5%), battery-powered lamp (33.0%), and solar-powered lamp (1.1% of). However, during follow-up testing, reported primary lighting sources changed as follows: open wick kerosene lamp (29.5%), hurricane lamp (35.2%), battery-powered light (18.2%), and solar lighting (9.1%).

A total of 14 outdoor, 110 living room, and 129 kitchen integrated 24-hour $PM_{2.5}$ levels were obtained from 7 outdoor locations and 88 homes during the two sampling periods. In our first sampling period, we sampled 85 kitchens and 31 living rooms. In the second sampling period, we sampled 44 kitchens and 79 living rooms. Average 24-hour ambient $PM_{2.5}$ levels in this rural location were $20.2 \mu\text{g}/\text{m}^3$. Indoor $PM_{2.5}$ levels were higher and differed based on cooking vs. non-cooking environments, with average $PM_{2.5}$ levels in living rooms measured at $35.2 \mu\text{g}/\text{m}^3$ as compared to kitchens measured at $270.0 \mu\text{g}/\text{m}^3$ (ambient vs. living room vs. kitchen, $p < 0.0001$, Kruskal-Wallis test; $p < 0.0001$, linear mixed effects models; see Table 3 and Figure 2). Only 36.4% of living room and 2.3% of kitchens had particulate levels that met the WHO criteria of having acceptable indoor $PM_{2.5}$ levels of less than $25 \mu\text{g}/\text{m}^3$.

When evaluating kitchens specifically, there were no statistically significant differences in $PM_{2.5}$ levels between outdoor and indoor kitchens in both unadjusted (181.3 vs. 274.4 $\mu\text{g}/\text{m}^3$, outdoor vs. indoor, $p = 0.43$, Kruskal-Wallis test) and adjusted comparisons ($PM_{2.5}$ levels were 1.65 [0.63 – 4.33] times higher in indoor vs. outdoor kitchens, $p = 0.30$),

although only 5 outdoor kitchens were sampled. In these mixed effects models, the only statistically significant predictor for kitchen PM_{2.5} levels was sampling phase (PM_{2.5} levels taken in March-July 2016 were 0.69 [0.49 – 0.98] times lower than those taken in July-October 2015, $p = 0.04$).

When evaluating living rooms PM_{2.5} levels, there were significant differences in PM_{2.5} levels based on type of lighting used in both unadjusted and adjusted analyses ($p = 0.03$, Kruskal-Wallis test; $p = 0.02$, mixed effects models). Most (75.0%) of the homes that reported using solar lighting met WHO-defined 24-hour PM_{2.5} standards, whereas only 27.6% of homes that reported using open wick kerosene lamps met WHO standards. In adjusted analyses, compared to solar lighting, homes using open wick lamps had 2.53 [1.14 – 5.64] times higher PM_{2.5} levels ($p = 0.02$). There were no statistically significant differences when comparing PM_{2.5} levels between homes using hurricane lamps vs. solar lighting, and battery-powered lighting vs. solar lighting. Reported use of an additional stove inside the home was not associated with differences in living room PM_{2.5} levels ($p = 0.95$), although we did not verify that the secondary stove was in use during the 24 hours in which we conducted environmental sampling. There was no statistically significant association between sampling phase and living room PM_{2.5} levels ($p = 0.09$). In a sensitivity analysis to determine whether very high living room PM_{2.5} levels drove the observed association between open wick lamps and PM_{2.5} levels, living room PM_{2.5} levels greater than or equal to 500 $\mu\text{g}/\text{m}^3$ were excluded from the analysis. There was no significant change in the observed association between lighting source and measured PM_{2.5} levels, with homes using open wick kerosene lamps having 1.91 [1.07 – 3.42] times higher PM_{2.5} levels than homes using solar lighting ($p = 0.01$).

Similarly, when evaluating living room black carbon levels, there were significant differences in black carbon levels based on primary lighting source ($p = 0.002$, Kruskal-Wallis test). Average black carbon levels by lighting source were as follows (see Table 4): 0.75 (solar), 1.90 (battery), 2.71 (hurricane), 4.53 (open wick) $\mu\text{g}/\text{m}^3$. In mixed effects models adjusting for sampling phase, use of a secondary stove, and household wealth, lighting source remained a significant predictor of indoor black carbon levels ($p = 0.007$), with black carbon levels being 4.72 [1.63 – 13.64] times higher in homes using open wick kerosene lamps compared to homes using solar lighting ($p = 0.01$).

Correlation of measurements within the same kitchen between sampling phases was low (Spearman $\rho = 0.38$). Similar patterns were also observed in the same living rooms between sampling phases (Spearman $\rho = 0.29$).

DISCUSSION

In this epidemiologic study describing the contribution of cooking and lighting to household air pollution in a resource limited setting, we found that indoor PM_{2.5} levels were higher in cooking as compared to non-cooking environments. In non-cooking environments, reported primary lighting source was significantly associated with indoor PM_{2.5} levels, with homes relying on open wick kerosene lamps having higher indoor PM_{2.5} and black carbon levels compared with solar lighting. Our study has a number of practical implications. First, we

identify primary lighting source as an important contributor to indoor particulate levels, and our findings suggest that in large epidemiologic studies where measurement of indoor pollutant levels is not possible, survey questions regarding lighting may identify individuals at risk of exposure to high indoor particulate levels. Average indoor particulate levels in homes using open wick kerosene lamps were $55.3 \mu\text{g}/\text{m}^3$, whereas levels in homes using primarily solar lighting were $19.4 \mu\text{g}/\text{m}^3$. These differences in indoor $\text{PM}_{2.5}$ levels is clinically significant, and suggests that the use of less-polluting forms of lighting such as solar lighting may be one strategy to reduce indoor air pollution in resource limited settings.

Several experimental chamber studies have examined kerosene-related combustion products. In one study, investigators described the particle size distribution and particle mass concentrations associated with diesel and kerosene lighting in a mock Kenyan market kiosk under high ventilation conditions¹⁷. They found that use of kerosene or diesel lighting was associated with $\text{PM}_{2.5}$ levels that consistently exceeded 24-hour WHO guidelines. Consistent with our findings, open wick lamps were significantly more polluting than hurricane lamps. The investigators found average $\text{PM}_{2.5}$ levels in this setting to be $500 \mu\text{g}/\text{m}^3$, whereas in our study, we report 24-hour integrated $\text{PM}_{2.5}$ levels of $55.3 [14.7\text{--}4,845.2] \mu\text{g}/\text{m}^3$ in homes primarily using open wick kerosene lamps. These differences may be explained by differences in study design. Apple et al measured $\text{PM}_{2.5}$ levels only while the lamps were lit, with sampling occurring 0.6 meters away from the lamps, and they used light-scattering rather than gravimetric methods to estimate $\text{PM}_{2.5}$ levels. In contrast, our study measured $\text{PM}_{2.5}$ levels with samplers placed in the center of living rooms, and estimated average concentration over 24 hours using gravimetric methods. Lamps were likely lit only during the night, and may not have been as close as 0.6 meters from the samplers. It is possible that if we had used real-time monitoring of indoor particulate matter levels, or if we had used personal monitors on participants rather than area samplers in a fixed location, and restricted sampling to nighttime, we would have measured significantly higher $\text{PM}_{2.5}$ levels than what we did observe. In another chamber study²⁵, mean particulate emission rates from simple wick lamps were found to be lower than from cooking fires, although there was some overlap between the lower range of emissions for cooking fires and the higher range of emissions for open wick lamps. Taken together, this body of work highlights the need to focus on reductions in indoor air pollution from both cooking and lighting activities.

Other field and epidemiologic studies on kerosene based lighting have been performed, although few have specifically addressed indoor particulate levels. Lam et al measured emissions from open wick lamps in the field in Southwest Uganda, and combined these measurements with tests simulating field conditions in a controlled laboratory setting to demonstrate that kerosene lamps emit particulate matter largely in the form of black carbon²⁶. We found a significant association between lighting source and both $\text{PM}_{2.5}$ and black carbon levels, further supporting the idea that lighting rather than other combustion sources are an important contributor to indoor particulate concentrations inside the main home. In a case control study, Pokhrel et al found that use of kerosene based lighting was associated with a striking 9.43 increased odds of active tuberculosis²⁷, highlighting the emerging literature on potential adverse health effects associated with kerosene-based lighting. Other studies on the use of kerosene either as a cooking fuel or for lighting have

focused on acute health impacts such as reduced risk of burns from accidental fire, accidental poisoning from kerosene ingestion, or economic outcomes^{16, 28}.

A strength of our study is that it is an epidemiologic study conducted in a large number of residential homes. Another strength is the longitudinal design, which allowed us to adjust for the effect of seasonality on both lighting source and particulate concentrations in our analysis. We note that choice of lighting source for the same participant changed over our sampling period, and may have reflected a spike in fuel prices between our first and second sampling phases. An additional strength is that rather than using carbon monoxide as a surrogate for PM_{2.5}, we directly measured PM_{2.5}. Although direct measurement of PM_{2.5} is more labor-intensive, some studies have shown that carbon monoxide does not serve as a reliable proxy for PM_{2.5} levels²⁹. Finally, while other studies from Uganda have focused on ambient air pollution in urban locations^{30, 31}, the issue of indoor air pollution from combustion sources is likely more relevant to most populations in low and middle income countries, who live predominantly in rural areas³².

Our study does have limitations. PM_{2.5} levels were measured as integrated levels over 24 hours rather than with real-time monitoring; it is likely that the magnitude of peak exposure may be predictive of health effects as well. We did not measure air exchange rates limiting comparability with other studies. However, in rural Africa, homes are unsealed and therefore highly ventilated – tracer gases would be removed quickly and so it would be difficult to measure air exchange rates. We did not perform triplicate measures of the same location at the same time to demonstrate the potential variability of our sampling strategy. Living room and personal PM_{2.5} levels were likely underestimated. This is because we performed environmental assessment over a 24 hour period, while the home did not require lighting during the daytime, indicating that measured values do not reflect peak values. Area sampling is also not a good surrogate for personal measures, particularly since kerosene lamps are often carried from room to room at night. Furthermore, we did not use thermal monitors to verify that stoves in kitchens, secondary stoves inside homes, or kerosene lighting was used during the period in which we conducted environmental sampling. Although research assistants instructed participants to carry on with their daily activities as per usual, our study team was informed that in a few cases, participants were initially afraid to cook near the area samplers for fear of damaging them. This likely explains why some indoor kitchens had measured PM_{2.5} levels that approximated ambient levels, and also suggests that the overall PM_{2.5} levels in our study were likely underestimates. Due to budget limitations as well as initial concerns from the community regarding placing samplers inside the main home, we were unable to sample all living rooms and all kitchens in both sampling periods. However, we used mixed effects models to analyze the resulting unbalanced data. Finally, we focused on PM_{2.5} and black carbon, while kerosene has other combustion products such as carbon monoxide and nitrogen oxides.^{33, 34} However, PM_{2.5} remains an important pollutant with well-documented health effects and recommended exposure standards.¹⁵ Despite the limitations noted above, our study does demonstrate that primary lighting source is associated with indoor PM_{2.5} levels.

Hurricane lamps are likely less polluting than open wick kerosene lamps because the flame in a hurricane lamp is shielded from ventilation, leading to more efficient combustion. While

we were surprised to find that there were no statistically significant differences in PM_{2.5} levels between indoor and outdoor kitchens, a major limitation is that only 5 of the participants used outdoor kitchens during our study period, and thus we likely were underpowered to detect a difference.

One-fifth of the global population lacks access to electricity, and most rely on kerosene for lighting.¹⁶ Our findings highlight the important contribution of kerosene lighting to indoor air pollution. This has been a neglected area of research, as most epidemiologic surveys of indoor air pollution have focused on solid fuels used in cooking. Our findings suggest that in population-based health surveys conducted in rural resource-limited settings without access to a steady supply of electricity, it would be prudent to add questions targeted to lighting source, with a distinction made between open wick and hurricane lamps. Furthermore, our observational findings suggest that solar lighting has the potential to reduce household air pollution. Studies performed in other resource limited settings such as rural Malawi have demonstrated that introduction of solar lamps dramatically reduced reliance on kerosene lighting.³⁵ Solar lighting is already being used in some rural communities in Uganda, and community uptake may be higher than the use of improved cookstoves due to convenience and cost savings on fuel, although solar uptake will likely be limited by the high initial cost.³⁶

In conclusion, we have demonstrated in this field study that reported primary lighting source is significantly associated with indoor PM_{2.5} levels, with significantly higher PM_{2.5} levels in homes relying on open-wick kerosene lamps compared to homes relying on solar lighting. A solar lighting intervention has the potential to reduce exposure to indoor air particulate exposure in resource limited settings, and should be further studied.

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Practical Implications

In this epidemiologic study examining the contribution of lighting to household air pollution, we demonstrate that primary lighting source is associated with indoor particulate levels, with the highest levels detected in homes using open wick kerosene lamps. Our findings suggest that in population-based health surveys conducted in rural resource-limited settings without access to a steady supply of electricity, it would be prudent to add questions targeted to lighting source, with a distinction made between open wick and hurricane lamps. Solar lighting to reduce kerosene use may be one future strategy to reduce indoor air pollution in resource limited settings.

A. Kitchen (indoor)**B. Kitchen (outdoor)****C. Lighting (solar)****D. Lighting (battery)****E. Lighting (kerosene - open wick)****F. Lighting (kerosene - hurricane)****FIGURE 1.**

Sources of indoor air pollution in rural Ugandan home. **A.** Typical indoor kitchen. **B.** Typical outdoor kitchen. **C.** Solar lighting, with solar lantern (left) or solar panel (right), see red arrow. **D.** Battery-powered light. (left) Homemade flashlight composed of batteries wrapped in a banana leaf and rubber strip, with attached wiring and light bulb (left) vs. commercially available flashlight (right). **E.** Open wick kerosene lamp (locally referred to as a “tadooba”). **F.** Hurricane kerosene lamp.

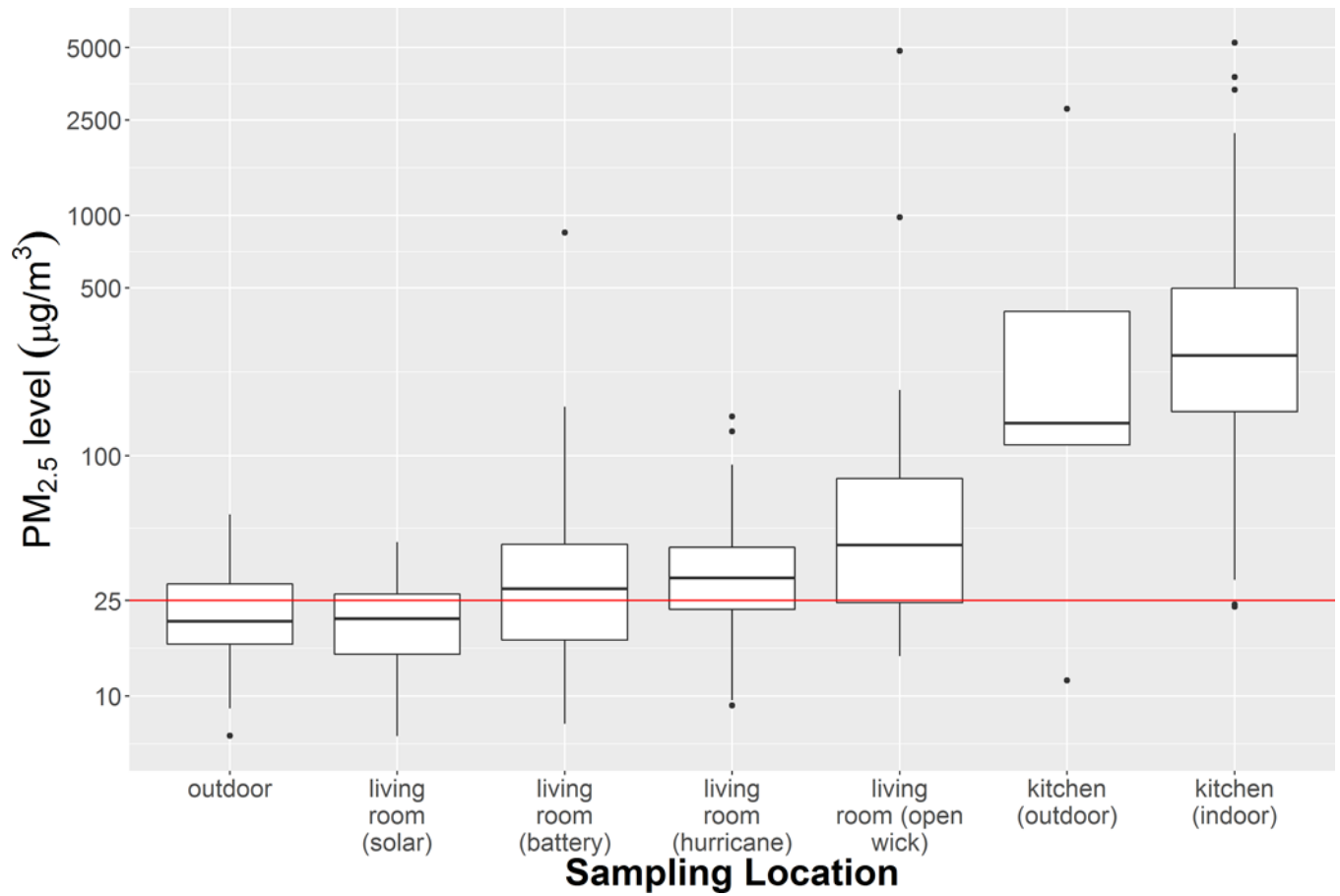


FIGURE 2. Fine particulate matter levels by location

Boxplots of integrated 24-hour PM_{2.5} levels by sampling location. Horizontal red line is at PM_{2.5} concentration of 25 micrograms/m³, the World Health Organization (WHO) guideline level for acceptable indoor 24-hour PM_{2.5} concentrations.

Table 1

Baseline characteristics of household members

Characteristic	Mean \pm SD or n (%)
Female, n (%)	88 (100%)
Age, years	36.2 \pm 9
Occupation	
Farming (without animals), n (%)	54 (61.4%)
Farming (with animals), n (%)	27 (30.7%)
Other, n (%)	7 (7.9%)
Time use, hours	
Indoors	15.0 \pm 2.8
Cooking	3.4 \pm 1.4
Cooking-related symptoms, n (%)	
Itchy eyes or runny nose	71 (84.5%)
Cough	41 (48.8%)
Wheezing	14 (16.7%)
Difficulty breathing	15 (17.9%)
Physician diagnosed problems, n (%)	
Allergies	24 (27.3%)
Asthma	1 (1.1%)
Tuberculosis	3 (3.4%)
Pneumonia	4 (4.5%)
Number of children in household, n	3.5 \pm 1.3
Children spend time in kitchen, n (%)	82 (93.2%)
Children with physician diagnosed problems, n (%)	
Allergies	14 (15.9%)
Asthma	4 (4.5%)
Pneumonia	11 (12.5%)

Table 2**Baseline characteristics of homes**

Note that during follow-up testing the primary lighting source changed as follows: open wick kerosene lamp (29.5%), hurricane lamp (35.2%), battery-powered light (18.2%), and solar lighting (9.1%).

Characteristic	
Homes, n	88
Kitchen location, n (%)	
Outdoors	5 (5.7%)
Structure attached to house	3 (3.4%)
Structure separate from house	79 (89.8%)
Inside house	1 (1.1%)
Distance between kitchen and house, meters	6.2 ± 11.1
Primary fuel for cooking, n (%)	
Firewood	87 (98.9%)
Charcoal	1 (1.1%)
Kitchen with chimney, n (%)	5 (5.7%)
Kitchen roof composition, n (%)	
Iron or tin	64 (70.5%)
Grass, banana fibers, leaves	19 (21.6%)
Other	5 (5.7%)
Secondary stove used inside house, n (%)	7 (8.0%)
Primary lighting source, n (%)	
Solar lamp or light	1 (1.1%)
Battery powered light	29 (33.0%)
Covered kerosene lamp	40 (45.5%)
Traditional kerosene lamp (“tadooba”)	17 (19.3%)

Table 3**PM_{2.5} levels by location**

Integrated 24-hour PM_{2.5} levels were measured by gravimetric methods from 88 distinct households over two time periods. WHO 24-hour PM_{2.5} standards refers to 24-hour PM_{2.5} levels less than 25 µg/m³.

Location	N	Geometric Mean (Range), µg/m ³	Meets WHO 24-hour PM _{2.5} standards
Outdoor	14	20.2 [6.8 – 57.0]	10 (71.4%)
Living Room	110	35.2 [6.8 – 4845.2]	40 (36.4%)
Solar	8	19.4 [6.8 – 43.7]	6 (75.0%)
Battery	29	30.6 [7.7 – 849.0]	12 (41.4%)
Kerosene (hurricane)	44	31.8 [9.1 – 145.9]	14 (31.8%)
Kerosene (open wick)	29	55.3 [14.7– 4,845.2]	8 (27.6%)
Kitchen	129	270.0 [11.6 – 5,241.1]	3 (2.3%)
Outdoor	5	181.3 [11.6 – 2,784.4]	1 (20.0%)
Indoor	124	274.4 [423.6 – 5,241.1]	2 (1.6%)

Table 4
Black carbon levels in living rooms by primary lighting source

Black carbon levels were measured over two time periods using reflectance to measure filter darkness. Primary reported source of lighting is a significant predictor of living room black carbon levels, with black carbon levels being 4.72 [1.63 – 13.64] times higher in homes using open wick kerosene lamps compared to homes using solar lighting ($p = 0.01$).

Location	N	Geometric Mean (Range), $\mu\text{g}/\text{m}^3$
Outdoor	14	1.19 [0.22 – 2.99]
Living Room		
Solar	8	0.75 [0.11 – 3.50]
Battery	29	1.90 [0.24 – 35.49]
Kerosene (hurricane)	44	2.71 [0.08 – 21.54]
Kerosene (open wick)	29	4.53 [0.55 – 19.01]