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Effect of a solar lighting intervention on fuel-based lighting use and exposure to household air pollution in rural Uganda: A randomized controlled trial

Eli S. Wallach[1], **Nicholas L. Lam**[1], **Edwin Nuwagira**[2], **Daniel Muyanja**[2], **Mellon Tayebwa**[2], **Linda Valeri**[3], **Alexander C. Tsai**[4,5], **Jose Vallarino**[6], **Joseph Allen**[6], **Peggy S. Lai**[5,6,7]

[1]Schatz Energy Research Center, Humboldt State University

[2]Mbarara University of Science and Technology

[3]Department of Biostatistics, Columbia University Mailman School of Public Health

[4]Mass General Global Health, Massachusetts General Hospital

[5]Harvard Medical School

[6]Department of Environmental Health, Harvard T.H. Chan School of Public Health

[7]Division of Pulmonary and Critical Care Medicine, Massachusetts General Hospital

Abstract

Solar lighting is an alternative to polluting kerosene and other fuel-based lighting devices relied upon by millions of families in resource-limited settings. Whether solar lighting provides sustained displacement of fuel-based lighting sources and reductions in personal exposure to fine particulate matter ($PM_{2.5}$) and black carbon (BC) has not been examined in randomized controlled trials. Eighty adult women living in rural Uganda who utilized fuel-based (candles, kerosene lamps) and/or clean (solar, grid, battery-powered devices) lighting were randomized in a 1:1 ratio to receive a home solar lighting system at no cost to study participants (ClinicalTrials.gov NCT03351504). Among intervention group participants, kerosene lamps were completely displaced in 92% of households using them. The intervention led to an average exposure reduction of 36.1 μg/m^3 (95% CI −70.3 to −2.0) in $PM_{2.5}$ and 10.8 μg/m^3 (95%

Corresponding author: Peggy S. Lai, Division of Pulmonary and Critical Care Medicine, Bulfinch 148, 55 Fruit Street, Boston, Massachusetts, 02114. pslai@hsph.harvard.edu.

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Data availability: The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

DATA SHARING
Study protocol, statistical analysis plan and informed consent forms are available upon reasonable request to the senior author (PSL, pslai@hsph.harvard.edu).

Trial registration: ClinicalTrials.gov NCT03351504

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CI −17.6 to −4.1) in BC, corresponding to a reduction from baseline of 37% and 91%, respectively. Reductions were greatest among participants using kerosene lamps. Displacement of kerosene lamps and personal exposure reductions were sustained over 12 months of follow-up. Solar lighting presents an immediate opportunity for achieving sustained reductions in personal exposure to $PM_{2.5}$ and BC and should be considered in household air pollution intervention packages.

Keywords

Household air pollution; fine particulate matter ($PM_{2.5}$); black carbon (BC); lighting; kerosene; solar home system; energy access

INTRODUCTION

Household air pollution is responsible for 2.2 million deaths per year and is among the top ten risk factors for premature mortality in low and middle income countries[1–3]. In some regions, identifying and mitigating sources of high emissions originating in households will be critical for addressing national burdens of disease [4,5], improving air quality [6] and providing near-term mitigation of short-lived climate forcers [7–9]. Energy poverty leads household to choose inefficient fuels or appliances with high emissions, and there is a growing recognition that energy poverty is part of a vicious cycle that worsens health and educational disparities[10,11]. Interventions that address sources of household emissions present an opportunity to increase access to essential energy services and have the potential to address broader social and economic inequities that influence social determinants of health[12,13]. Access to adequate and affordable energy services have also been shown to deliver social benefits that improve the wellbeing of families[10]. In resource-limited settings, women are exposed to higher levels of household air pollution compared to men and represent a vulnerable subgroup[14] who would benefit from targeted interventions.

At least 789 million people living largely in resource-limited settings lack access to electricity [15], while another 1.5 billion lack access to reliable electricity [16]. In the absence of electricity, households may turn to kerosene lamps, candles, and other polluting fuel-based lighting devices as a stopgap technology for illumination[17]. Most of these households are likely to concurrently rely on solid fuels for cooking[18,19]. Kerosene lamps, particularly open (simple) wick lamps, are potent sources of indoor fine particulate matter ($PM_{2.5}$) composed of mostly black carbon (BC) [20–22]. Inhaled fossil fuel-derived particles have been found to have high tissue deposition and penetration into the systemic circulation [23,24], and may be more toxic than particles resulting from biomass burning [17,25]. This possibility is supported by a recent randomized control trial of ethanol stoves in pregnant women, where the intervention reduced diastolic pressure in baseline kerosene but not baseline biomass stove users [26]. The idea that emissions from kerosene are as or more toxic than emissions from biomass fuel is further supported by observational studies showing strong associations between household kerosene use and tuberculosis but not household biomass fuel use and tuberculosis [27,28], and between household kerosene use and acute lower respiratory infection [29].

Recent cross-sectional and pre-post studies provide evidence that fuel-based lighting can contribute meaningfully to exposure and that off-grid solar lighting products available in local markets are viable replacements that may reduce air pollution exposure. In an observational study conducted in rural southwest Uganda, participants using open wick kerosene lamps had 1.91 times higher $PM_{2.5}$ and 4.7 times higher BC concentrations in living rooms as compared to participants using solar-based lighting, even after adjusting for household wealth [19]. In a pre-post study among Kenyan households using kerosene as a primary lighting source, introduction of three portable solar lamps per household displaced kerosene lamp use by over 90% over a three-month follow-up period and reduced personal $PM_{2.5}$ exposure by 50% among women and 73% among teenage pupils, despite continued use of solid fuels for cooking.

We conducted a randomized controlled trial of indoor solar lighting systems in rural southwest Uganda in order to examine the longer-term effect of introducing a home solar lighting system on $PM_{2.5}$ and BC personal exposure among women living in households using a mix of lighting solutions, which is common in many rural communities. We hypothesized that introduction of a home solar lighting system, even before implementing a cookstove intervention, would lead to displacement of fuel-based lighting sources (such as kerosene) and reduce personal exposure to $PM_{2.5}$ and BC.

METHODS

Study design and population

Between 2018 and 2019, we conducted a one-year, randomized, delayed-start controlled trial of indoor solar lighting systems in Nyakabare Parish, a rural region of southwestern Uganda (ClinicalTrials.gov Identifier: NCT03351504). Nyakabare Parish is composed of 8 villages with most inhabitants relying on subsistence farming, animal husbandry, and petty trading for income generation; both food and water insecurity are highly prevalent in this region[30,31]. A community survey had previously been conducted to enumerate all households in Nyakabare Parish [32]. After community sensitization meetings were held to disseminate information about the study, a trained fieldworker was paired with a member of the local village health team to visit homes. Inclusion criterion for this study was women living in Nyakabare Parish with no prior history of chronic lung disease. Exclusion criterion was current active tuberculosis in any family member.

Randomization and masking

We recruited a total of 80 women who were based in 8 villages and randomized them in a 1:1 allocation ratio using a computerized random number generator (see Supplemental Figure 1 for the CONSORT diagram). Only women were recruited because they often serve as the primary cooks in the house and the purpose of the trial was to assess the effect of a lighting-only intervention on a sub-population that was also highly exposed to household air pollution from other sources, i.e., cooking. To avert chance imbalances by primary lighting source, we generated separate randomization schedules for subsets of study participants defined by strata of baseline primary lighting source, namely: fuel-based (hurricane or open-wick kerosene lamps, candles) vs. clean (national electrical grid, battery-powered devices, solar lamp or solar lighting system). Households assigned to the intervention group received an indoor solar lighting system at the time of randomization free of charge, while households assigned to the delayed-start control group received an indoor solar lighting system after one year (i.e., at the end of the study). Primary lighting source was determined at the time of recruitment using a single-item question, "What is your primary source of lighting?" We did not exclusively recruit kerosene lamp users, because our prior observational study[19] demonstrated significant seasonal variation in primary lighting source that was dependent on household finances, kerosene costs, and electrical grid failures. Participants reporting use of solar lighting systems were also included because lamp stacking is common in this context: most solar systems are too small (have too few light sources) to meet all lighting needs on an exclusive-use basis or are paid for on a monthly basis with the company remotely terminating the function of the solar system in the event of missed payments. Blinding of participants and field staff was not possible due to the nature of the study intervention.

The study intervention was an indoor solar lighting system purchased from a local vendor based in Mbarara Town (Allmar Solar Systems) that was composed of a 30 watt-peak (Wp) solar panel, 18 Amp-hour (Ah) lead acid battery, 5 Amp charge controller, 1-Watt LED bulbs, switches, wiring for 4 lighting points, and installation services. Participants were allowed to choose, based on their needs, the location where each of the 4 bulbs were placed. The solar lighting systems were provided free of charge to study participants and were procured from a local distributor for the unit market price of Ugandan shillings (UGX) $559,171 (approximately US dollars (USD) $158). The purchase price of each system included a two-year service contract where solar systems were repaired within 48 hours of notification of system failure. At the time of solar installation, and three months after solar installation, participants were provided with hands-on training and education about the proper care and use of the solar system. Besides the provision of the solar systems, no attempts were made to alter participants' choices of household fuel for lighting or cooking although during the consent process, participants were informed that fuel-based lighting may contribute to household air pollution. All intervention solar lighting systems were deployed between February 7, 2018, and April 2, 2018.

Study procedures

Field visits to participants' homes were conducted at baseline prior to randomization, and at three, six, and twelve months after the intervention. During these field visits, surveys were conducted, lamp usage monitors were installed on the participant's reported original primary fuel-based lighting source for a two-week period and living room and personal sampling for pollution exposure was conducted as described in more detail below. For intervention participants, the baseline study visit was conducted one week prior to solar lighting system deployment in order to capture short term changes in kerosene lighting use before and after the intervention (lamp monitors are placed on kerosene lamps for a two-week period). Voltage loggers were used to assess the use of solar lighting sources powered by the solar lighting system in intervention households.

A modified version of the World Bank Indoor Air Pollution District Survey Questionnaire [33] was administered to measure variables that may affect indoor pollutant levels, such as sources of ventilation, stove and kitchen location, primary and secondary lighting sources, household fuel use, trash-burning, and use of mosquito coils or heating devices (of which the latter two are extremely rare in our study site).

At each visit, all lighting sources in use by the household were catalogued. To assess usage of fuel-based lighting sources, a combined light and temperature monitor (HOBO Pendant Temperature/Light logger UA-002–64, Onset, Cape Cod, MA) was affixed to each fuel-based lighting source with a logging interval of one minute and deployed for two weeks. Loggers were placed in a location that did not interfere with the use of the lighting source (see Supplemental Figure 2). Participants were instructed to continue with their normal daily activities. At the end of each two-week period, field officers returned to retrieve the loggers, download the data, and inspect temperature and lighting plots. If the plots appeared unusual (e.g., no lighting events noted based on changes in temperature or light) the field officer cross-referenced participant report of lamp use in the previous two-week period to determine the possibility of monitor malfunction. Lighting events based on this approach could only be reliably calculated for kerosene-based lamps and were defined as increases in lighting intensity accompanied by a rise in recorded temperature. This was determined with an algorithm that uses threshold values for the rate at which the temperature changes and cross-references the lumen sensor reading in order to infer whether the lamp is on or off[18], allowing for the duration of a lamp lighting event to be calculated. Lighting events were summed on a per-day basis to obtain the duration of lamp lighting events for each day.

Monitoring of intervention solar light sources

At the time of installation of the indoor solar system, we incorporated a sensor to track use of each light bulb (Supplemental Figure 3). These voltage loggers (HOBO 4-Channel Pulse, Event, State and Run-Time Data Logger UX120–017, Onset, Cape Cod, MA) were powered by an internal lithium battery and recorded the dates and times when each light bulb was switched on and off throughout the one-year study period. The hours of lighting use per day was subsequently calculated. While more than one light bulb could be used at any given time, the daily duration of lighting use accounted only for whether any light bulb was in use at that time thus the maximal duration of lighting use was 24 hours per day.

Exposure assessment

Exposure assessment was performed using integrated stationary and personal samplers deployed for 48-hour periods (Supplemental Figure 4). Samplers were custom built and consisted of a compact multistage cascade impactor [34] with a 2.5 μm cutpoint. Particles larger than the cutpoint are collected onto silicone grease as an impaction substrate, allowing for particles smaller than 2.5 μm to be collected onto a pre-weighed 37 mm, 2.0 μm pore size Teflon filter (Pall Life Sciences; Teflo). The sampler was attached to a lithium battery-powered pump operating at 0.8 liters per minute. Flow was measured by a flowmeter (Omron, Hoffman Estates, IL), with flow and time of use data recorded onto a HOBO datalogger (Onset, Cape Cod, MA). Area samplers were positioned 1.2 meters above ground level in the living room, which was self-defined by the participant and in all cases was a location separate from cooking and sleeping areas. Personal samplers were incorporated into commercially available running vests to allow the participants to comfortably wear the vests for a long period of time and during periods of heavy manual labor as many participants were subsistence farmers. Participants were asked to remove vests only when sleeping or bathing; during these activities participants were instructed to keep the vests within one meter of their persons. The samplers were positioned on the vest in the breathing zone. All collected environmental samples were labelled with a unique identifier, and details of sample collection were recorded onto a standardized field log.

After collection, filters were batched for shipment from Mbarara, Uganda to the Harvard T.H. Chan School of Public Health in Boston, Massachusetts where they were first conditioned in a temperature- and humidity-controlled room for 48 hours prior to weighing on an electronic microbalance (MT-5 Mettler Toledo). Following gravimetric measurement, Teflon filters from living rooms were analysed for indoor black carbon (BC) concentrations by measuring filter blackness using a smoke stain reflectometer (model EEL M43D, Diffusion Systems Ltd., London, United Kingdom). We used the standard black-smoke index calculations of the absorption coefficients based on reflectance [35]. We assumed a factor of 1.0 for converting the absorption coefficient to BC mass [36,37], 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.

Statistical analysis

This study was powered to detect a 50% reduction in $PM_{2.5}$ and BC exposure based on data from our prior observational study of the contribution of fuel-based lighting to household air pollution exposure[19]. The primary analysis used intention to treat principles; all participants with at least one follow-up measurement of living room and personal $PM_{2.5}$ and BC levels after the intervention were included. We fitted population-averaged linear models to the data, using the method of generalized estimating equations (GEE) to estimate the efficacy of the intervention on duration of kerosene lamp use, and personal exposure to $PM_{2.5}$ and BC. Randomization was stratified by primary lighting source at baseline (fuel-based vs. clean) and therefore was adjusted for in the regression models. We fitted linear GEE regression models of the form:

$$E\left[Y_{ij}\right] = b_0 + b_1 group_{sj} + b_2\ post_j + b_3\ group_{sj} * post_j + b_4\ season_j + a^T z_{ij}$$

where Y_{ij} is the pollution measure for subject i at time j, $group_{sj}$ is the indicator for group assignment, $post_j$ is an indicator variable for post-(versus pre-) randomization for a given visit, and z_{ij} is a vector of potential confounders in the event of imbalance in randomization. There were no group imbalances in randomization so in final models we only adjusted for baseline primary lighting source (which was included to account for the stratified randomization design) and season (wet /dry), which is represented by a categorical variable with 4 levels: Dry season (June – August), Wet Season (March – May), Wet Season (September – November) and Dry season (December – February). December – February is taken to be the intercept. The $group_{sj} * post_j$ term is the term of scientific interest and represent how post vs pre randomization changes in pollution exposure differ between intervention and control arms. Creation of summary statistics, figure generation and statistical analyses were performed in R version 3.6.1. The R package *geepack*[38] was used for statistical modeling. Two-sided p-values of <0.05 were considered statistically significant.

RESULTS

This study included 80 women from distinct households who were randomized in a 1:1 allocation ratio to the intervention vs. control (delayed-start intervention) groups (see Supplemental Figure 1 for CONSORT diagram). There was only one participant who was lost to follow-up (a control group participant at six months). There was no evidence of imbalance on observed covariates (Table 1). The average age was 39.7 years with most having either no formal education (13.8%) or having only a primary school education (62.5%). The average self-reported time spent indoors was 16.1 hours per day with 97.5% reporting that they had primary responsibility for food preparation, spending an average of 4.1 hours per day cooking. All but one participant reported using either firewood (95%) or charcoal (3.8%) as their main cooking fuel. Participants estimated that they used 4.75 hours of light a day, with 43.8% reporting primary fuel-based lighting (all but two reporting use of either open wick or hurricane lamps) while the rest reported primary clean lighting sources (flashlights, solar-based, or electricity from the national grid). Notably, use of kerosene-based lighting as a secondary lighting source was common, with 52.5% reporting secondary use of open wick kerosene lamps and 27.5% reporting secondary use of hurricane kerosene lamps.

Using light and temperature sensors to measure use of kerosene light devices, we found that the solar lighting intervention led to a complete displacement of kerosene lighting in 92% (N = 32) of intervention participants that used kerosene at baseline. At baseline, kerosene lamp usage was 2.22±1.36 hours/day among kerosene users, with a slight trend towards higher usage in the intervention group (control group 2.09±1.69 hours/day, intervention group 2.38±0.84 hours/day, p = 0.56). On serial measurement of kerosene-based light usage (Figure 1), the reduction in average daily kerosene lamp use by an intervention participant was sustained over the 12-month study period. Average daily lamp usages in the intervention group are as follows: 0.52±0.70 hours at one week, 0.26±0.67 hours at three months, 0.16±0.50 hours at six months, and 0.06±0.15 hours at 12 months. With baseline daily usage of kerosene lamps at 2.22 hours in intervention households, the results also indicate that most reduction in kerosene usage occurred sometime within the first three months following the solar lighting intervention – and for most households within the first week following the intervention. Control group kerosene users also had an overall decrease in kerosene usage, with average daily usages of: 1.73±1.79 hours at three months, 1.77±2.62 hours at six months, and 1.40±1.59 hours at 12 months. Using a linear GEE regression model, the intervention decreased kerosene lamp usage by 1.66 hours per day (95% CI: −2.53 to −0.80, p = 0.0002). Among all prior kerosene users there was a trend towards decreased kerosene light usage during the post-intervention period (−0.46 hours/day, 95% CI: − 1.19 to 0.27 to, p = 0.22).

The lamp use data also indicated that the proportion of any kerosene light use in the post-intervention as compared to the pre-intervention period decreased in both the intervention and control groups, although the proportion of participants who stopped using kerosene entirely was greater in the intervention compared to the control groups. The percentage of intervention participants using any kerosene-based lighting was 68% at baseline, 32% at one week, 14% at three months, 14% at six months, and 8% at 12 months. In contrast, the percentage of control participants using any kerosene-based lighting was as follows: 67% at baseline, 44% at three and six months, and 41% at twelve months.

For intervention participants, the most common locations for light bulb placement were the living room (36 participants), master bedroom (35 participants), outdoors as a security light (32 participants), and kitchen (20 participants). Voltage sensors embedded in the intervention solar lighting system confirmed that uptake of the intervention was high, with an average daily use of 8.23 ± 5.30 hours per day (out of a maximum possible 24 hours per day) in the intervention group. During the one year study period, we recorded three instances in which the study solar panel or the battery required replacement. This was covered by the existing service warranty.

Personal exposure to $PM_{2.5}$ and BC throughout the study period is shown in Figure 2. While there were no significant differences in baseline exposure levels between the control and intervention groups (Table 1), participants using primarily fuel-based lighting had significantly higher average personal $PM_{2.5}$ exposure compared to participants using clean lighting (97.6 [IQR 54.6, 150.7] vs. 36.9 [IQR 26.6, 66.8] $\mu g/m^3$, fuel-based vs clean lighting, $p = 0.001$) and black carbon (10.9 [IQR 5.2, 21.2] vs. 3.61 [IQR 2.4, 4.9] $\mu g/m^3$, fuel-based vs. clean lighting, $p < 0.001$). Living room levels of $PM_{2.5}$ and BC were also significantly higher among participants primarily using fuel-based as opposed to clean lighting ($PM_{2.5}$ levels 55.5 [IQR 18.5, 75.1] vs. 24.2 [IQR 13.2, 35.2] $\mu g/m^3$, fuel-based vs clean lighting, $p = 0.009$; BC levels 13.32 [IQR 3.0, 23.4] vs 2.9 [IQR 2.1, 3.7] $\mu g/m^3$, fuel-based vs. clean lighting, p 0.001).

The effect of the solar intervention on personal air pollution exposure concentrations is depicted in Table 2. Using a linear GEE regression model, introduction of the solar lighting system led to a 36.1$\mu g/m^3$ reduction in personal exposure to $PM_{2.5}$ (95% CI: −70.3 to −2.0, $p = 0.038$) and a 10.8 $\mu g/m^3$ reduction in black carbon (95% CI: −17.6 to −4.1, $p = 0.0017$). These reductions corresponded to an average reduction relative to baseline of 37% for $PM_{2.5}$ and 91% for BC.

The effect of the solar intervention on personal exposure on $PM_{2.5}$ and BC was greater among households using fuel-based lighting (largely kerosene, with two primary fuel-based lighting participants using candles). Among this user group, exposure concentrations fell by 44.3 $\mu g/m^3$ (95% CI: −103.7 to 15.0 to $p = 0.144$) for $PM_{2.5}$ and 20.7 $\mu g/m^3$ (95% CI: −33.2 to −8.3, $p = 0.0011$) for BC as a result of the intervention. These reductions corresponded to a 33% and 100% reduction in $PM_{2.5}$ and BC relative to the intervention group's baseline, respectively.

The effect of the study intervention on living room air pollution levels is depicted in Figure 3 and Table 3. Of note, living room levels of $PM_{2.5}$ and BC decreased in the post-intervention period for both the control and intervention groups. $PM_{2.5}$ decreased by 20.0 μg/m^3 (95% CI: −34.3 to −5.8, p = 0.0059) and BC decreased by 3.7 μg/m^3 (95% CI: −8.5 to 1.1, p = 0.13). The study intervention did not lead to additional decreases in living room levels of $PM_{2.5}$ and BC in the post-intervention period when comparing the intervention vs. the control groups and controlling for primary light source and seasonality.

DISCUSSION

In this one-year randomized, delayed-start controlled trial conducted in a rural region of southwestern Uganda, an indoor solar lighting system intervention had high uptake, reduced kerosene-based lighting use, and led to reduced personal exposure to BC and $PM_{2.5}$ over the one-year study period. Reductions in BC and $PM_{2.5}$ exposure concentrations were observed despite continued use of solid fuels for cooking. Participants who reported at baseline relying primarily on fuel-based lighting experienced greater reductions in air pollution exposure compared to those who reported it as a supplemental light source. There was an overall decrease in exposure to $PM_{2.5}$ and BC in the entire cohort in the post-intervention compared to the pre-intervention period, likely as a collateral effect of clinical trial participation (i.e., the consent process educated participants about the potential adverse health effects of air pollution exposure leading to decreased fuel-based lighting usage among participants assigned to the control group).

Our results provide further evidence that alternatives to fuel-based lighting may need to be considered as part of a package of household energy interventions aimed at reducing exposure and disease burden from household air pollution. Exposure reduction estimates from this study suggest that fuel-based lighting sources accounted for approximately one third of the daily $PM_{2.5}$ exposure burden among the average participant, and three quarters of their BC exposure. Results from a published before-after pilot study of solar lamps conducted in rural Kenya suggest the contribution to $PM_{2.5}$ could be much greater for household members that do not perform cooking tasks[18]. To date, interventions aimed at mitigating exposure to indoor air pollution occurring in households have focused predominantly on strategies to alter cooking practices, with far less focus on potential exposures from other household energy sources. Scalable cooking solutions that are effective at delivering meaningful and sustained reductions to exposure have proven elusive in many settings, particularly among the most disadvantaged and remote “last mile” communities. Reasons for program ineffectiveness vary but include low adoption and use of the intervention stoves, low displacement of incumbent polluting devices, and unreliability of intervention stoves (largely improved biomass stoves) to reduce emissions to a level thought to be effective for health improvements in the field setting [39,40]. Modern cooking solutions such as liquid petroleum gas (LPG) stoves and electric appliances show promise for achieving greater exposure reductions[41,42] compared with improved biomass stoves, but scaling these solutions beyond trial settings will present new challenges; notably those related to reliability of fuel supplies and issues around affordability [43–46]. While home solar lighting systems require an upfront investment for households, on a per-lumen basis solar lighting is less costly than fuel-based lighting as fuel-based lighting burns efficiently, allowing customers to eventually recoup their investment in a solar home system. In a separate publication from this trial, we have estimated that based on participant self-reported household lighting costs, assuming participants paid the up-front costs of the solar system used in this study, households converting from kerosene to solar lighting would recoup their investment after 2.76 years[13]. A study performed in Uganda for a more expensive home solar system than the one used in our study estimated a break-even point after 3.14 years[47] as well as additional benefits such as near-complete elimination of fires and burns attributed to fuel-based lighting. Other studies have corroborated that the potential benefits of a transition to solar lighting extend well beyond reductions in pollution exposure to include savings on household expenditures, increase in income generating activities, gender empowerment, social inclusion, and improved education due to more time spent on homework[12,13]. The benefits of kerosene lighting displacement observed in this study, combined with high adoption rates and widescale availability of solar lighting devices in resource-limited settings, suggest that coupling thermal (stove-related) and illumination services within household energy programs may be complementary.

To our knowledge, this is the first randomized controlled trial to evaluate the effect of an indoor solar lighting system on personal exposure to household air pollution. We have previously shown in an observational study at this study site that primary lighting source was associated with higher living room levels of $PM_{2.5}$ and BC [19]. While we did not observe an impact on living room levels of $PM_{2.5}$ and BC, this may be attributed to the decrease in living room $PM_{2.5}$ and BC in the post-intervention period compared to the pre-intervention period for both control and intervention group participants, as well as changes in where participant spent their time as the intervention lighting system provided four lighting points. In addition, results from a pre-post comparison of personal $PM_{2.5}$ exposure after introduction of pico-solar lamps in peri-urban Kenya showed both high uptake of the solar lamps as well as average reductions in excess of 50% to personal $PM_{2.5}$ exposure among exclusive kerosene lamp users over a short three-month follow-up period [18]. The trial findings presented here extend our prior findings, using a randomized controlled design, to confirm that fuel-based lighting contributes to household air pollution exposure, and showing for the first time that a sustained decrease in personal BC and $PM_{2.5}$ exposure can be achieved, even without changes to cooking practices. Our result suggests, however, that the exposure benefits resulting from solar lighting technology are largely isolated to families primarily reliant on fuel-based lighting: kerosene light sources, and to a lesser extent, candles. In areas where use of fuel-based lighting is prevalent, clean lighting solutions may be an important and necessary component of the intervention strategies to reduce exposure to household air pollution.

Our study provides further confirmation that solar lighting technology is a viable and well received alternative to fuel-based lighting in resource-limited settings. In our trial, 36.8% of control participants primarily using kerosene-based lighting at study enrollment stopped using kerosene by the twelve-month follow-up period. In exit interviews with control participants, they cited greater awareness of air pollution as a reason for transitioning away from kerosene-base lighting. While this transition away from fuel-based lighting in all study participants reduced the calculated effect size of the study intervention on pollution exposure for intervention compared to control group participants in our study, it also suggests that the barriers to adoption of cleaner lighting technology are low relative to cooking and other household energy measures. Moreover, it may suggest that this transition can occur quickly and perhaps accelerated through focused policies and measures that lower economic barriers to accessing solar lighting solutions.

It is not surprising that the intervention led to greater reductions in exposure to BC as compared to $PM_{2.5}$. Emissions from kerosene are composed predominantly of BC, making it unique among other common particulate sources found in homes[21]. Similarly, it is not surprising that the reductions in personal exposure concentrations were greater than area monitoring of the living room. The dim light produced by kerosene lamps necessitates participants to sit in close proximity the light source where pollutant concentrations are higher[20], increasing the pollutant intake fraction and leading lighting sources to account for a larger fraction of total exposure than might be assumed from source emission rates alone. This near-field exposure effect, combined with the ability for lamps to be moved to different rooms of the house where environmental monitors may not be present, likely led to personal exposure monitoring being a far more accurate assessment of exposure in the context of the solar intervention. While the effect of the solar lighting intervention on pollutant exposure was largely driven by primary fuel-based light users, secondary use of fuel-based lighting sources was widely prevalent even among those who had access to the electrical grid or solar lighting due to frequent grid outages, insufficient lighting points from clean lighting sources, or due to payment interruptions leading to service termination of pay-as-you-go solar lighting devices.

Our study has several strengths. Our study population is representative of the broader rural population in Uganda where 70% of participants use kerosene lamps for light and where 90.2% of participants either cook outdoors or have a separate dedicated kitchen[48,49]. Group assignment was balanced across age and socioeconomic status, and all but two participants served as the primary cook in their household. We were able to objectively measure kerosene-based lighting usage and uptake of the intervention solar lighting system using sensors rather than relying on self-report; these novel approaches to monitoring lighting use may be helpful for other investigators performing household lighting studies. Finally, we measured device usage and personal exposure to $PM_{2.5}$ and BC longitudinally over the one year study period in order to assess sustained impact.

Interpretation of our findings nonetheless should be considered in light of several limitations. First, a non-trivial proportion of control group participants abandoned fuel-based lighting after trial enrollment. This would lead to an underestimate of the effect of the intervention on air pollution exposure and indoor air quality. Second, several intervention participants who relied on kerosene-based lighting at baseline continued to have infrequent use of kerosene-based lighting at 12 month follow-up. On exit interviews, some participants noted the need for a mobile source of lighting. For example, one participant owned a shop a short distance from her house and so continued to use her kerosene lamp at night in her shop while it was in operation. This suggests that, in some cases, the addition of a portable solar lamp in conjunction with an indoor solar lighting system may be more efficacious in displacing all fuel-based lighting. Third, this was a trial designed as a “proof of concept” study to determine the uptake of a solar lighting intervention and to identify the effect size on personal pollution exposure independent of cooking interventions. A larger sample size, and inclusion criterion restricted to participants primarily using fuel-based lighting, would have provided better precision of the effect estimate for clean lighting solutions targeted to fuel-based lighting users and allowed for exploration of outcomes that require longer-term follow-up, such as health outcomes. Fourth, the generalizability of our findings may be context-dependent as kerosene lamp use may be less prevalent in other geographic locations, as would other factors such as presence, location, and proximity of other sources of household air pollution such as cooking to indoor locations where participants spend the majority of their time. Finally, the primary unit of measure for this study was women who in most instances were the primary cooks for their families. As a result, exposure benefits measured here are not necessarily indicative of all household members, and in particular would underestimate the magnitude of reduction in those that do not regularly contribute to cooking duties. As with polluting cooking fuels, the burden of exposure likely varies along gender lines and roles within the household[14]. Results from a previous study in Kenya[18], for example, showed that the relative reduction in $PM_{2.5}$ exposure following introduction of portable solar lamps among teenagers was 1.5 times greater than the primary cook on average.

In conclusion, we found that a clean lighting intervention was highly effective in displacing fuel-based lighting, had high uptake, and led to significant reductions in personal exposure to BC and a trend towards reduction in $PM_{2.5}$. Longitudinal measurements conducted over a 12-month period show that benefits are sustained. The effect of solar lighting on reducing in personal exposure was observed despite an overall decrease in exposure among controls, likely resulting from the control group's own displacement of fuel-based lighting. Our study provides further confirmation that when present, fuel-based lighting can be an important contributor to household air pollution exposure that may need to be addressed alongside efforts to mitigate high emissions from cooking and other stove-related (thermal) service needs. As such, future strategies aimed at addressing household air pollution exposure should consider complementary service bundles, such as clean lighting in addition to clean cooking, as part of the intervention package. While studies have suggested that kerosene-based emissions are more toxic than biomass-fuel based emissions [25–28], the health effects of clean lighting interventions are unknown and should be assessed in future studies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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PSL conceptualized, designed, and secured funding for the study. JV and JGA designed environmental monitoring devices. PSL, EN, DM, and MT collected the data. EW, NL, and PSL analyzed and interpreted the data. EW, NL, and PSL wrote the original draft of the manuscript, and all authors contributed to writing, review and editing. All authors approve of the final manuscript.

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PRACTICAL IMPLICATIONS

- Use of fuel-based lighting is widespread and contributes to household air pollution in many resource-limited settings
- Solar home systems for lighting leads to sustained displacement of kerosene lamps
- Even without a clean cooking intervention, introduction of solar lighting leads to a significant reduction in personal exposure to fine particulate matter and black carbon in women who rely on biomass fuels for cooking
- In geographic areas where fuel-based lighting is common, clean lighting interventions should be bundled with other household clean energy initiatives to achieve indoor air quality goals

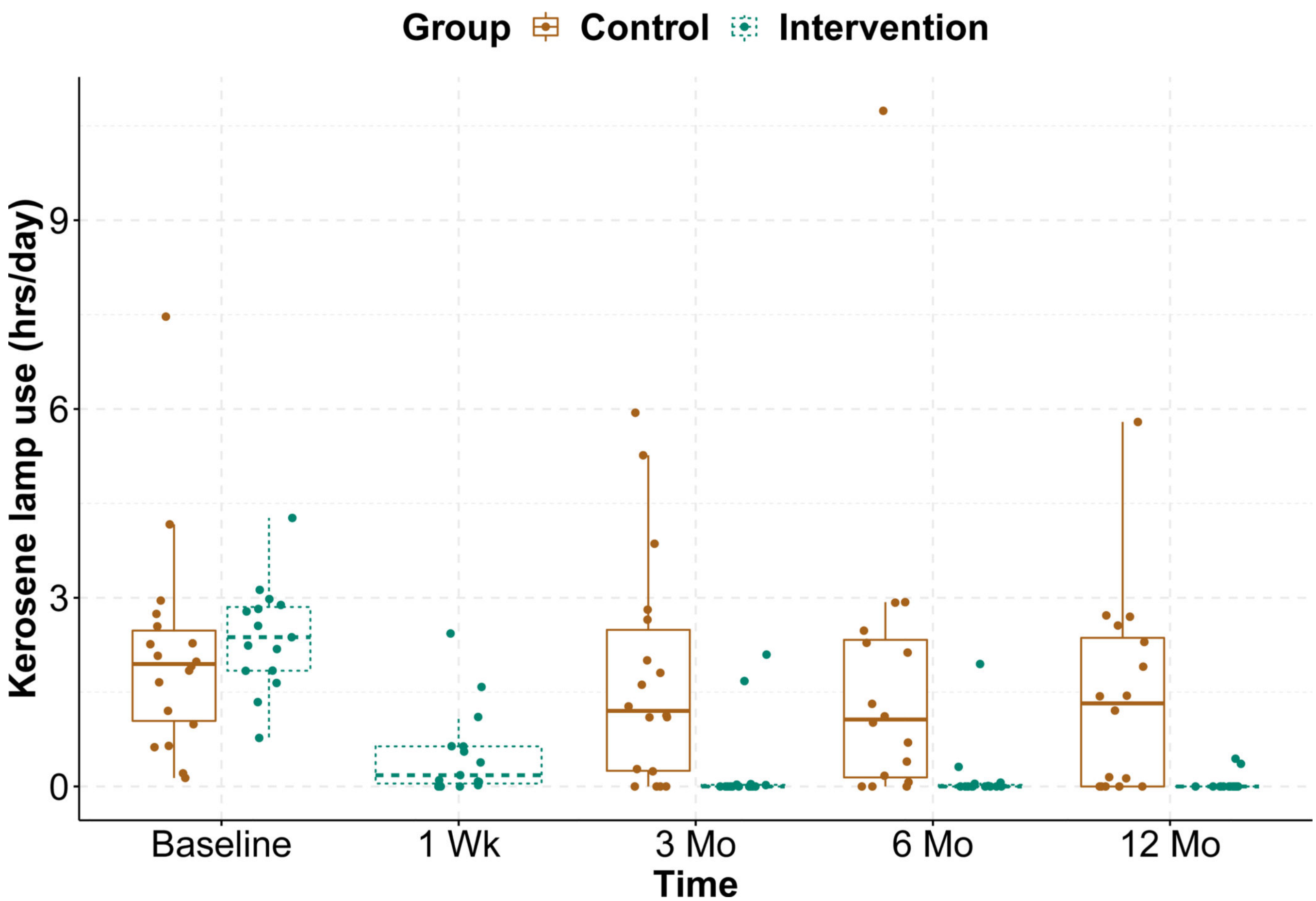

FIGURE 1:

Kerosene lamp use among control and intervention households across study phases. Boxplots indicate estimated hours of kerosene lamp use per day measured using light and temperature sensors

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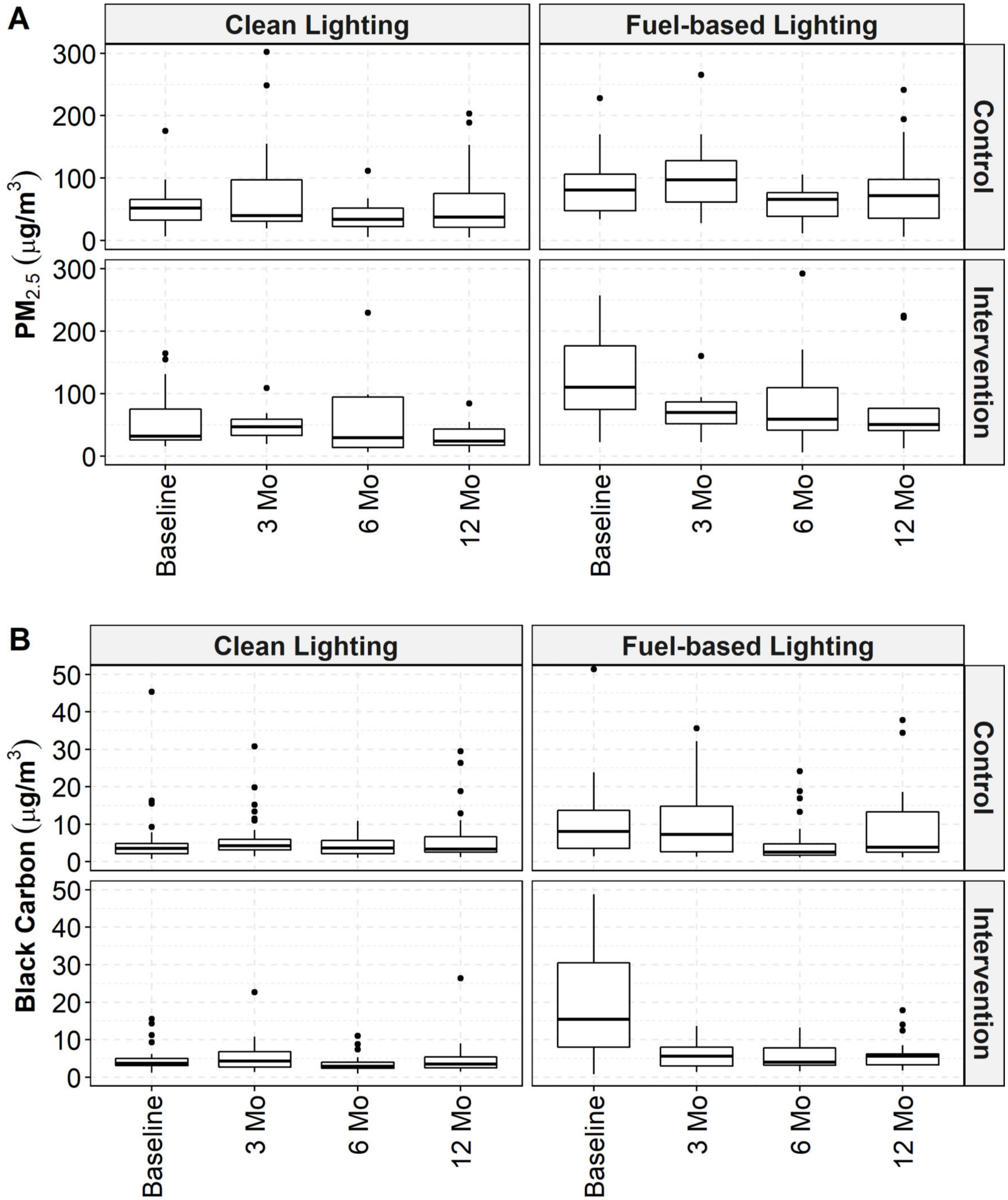

FIGURE 2:
Personal exposure concentrations of PM2.5 (panel A) and black carbon (panel B) across study phases among control and intervention households

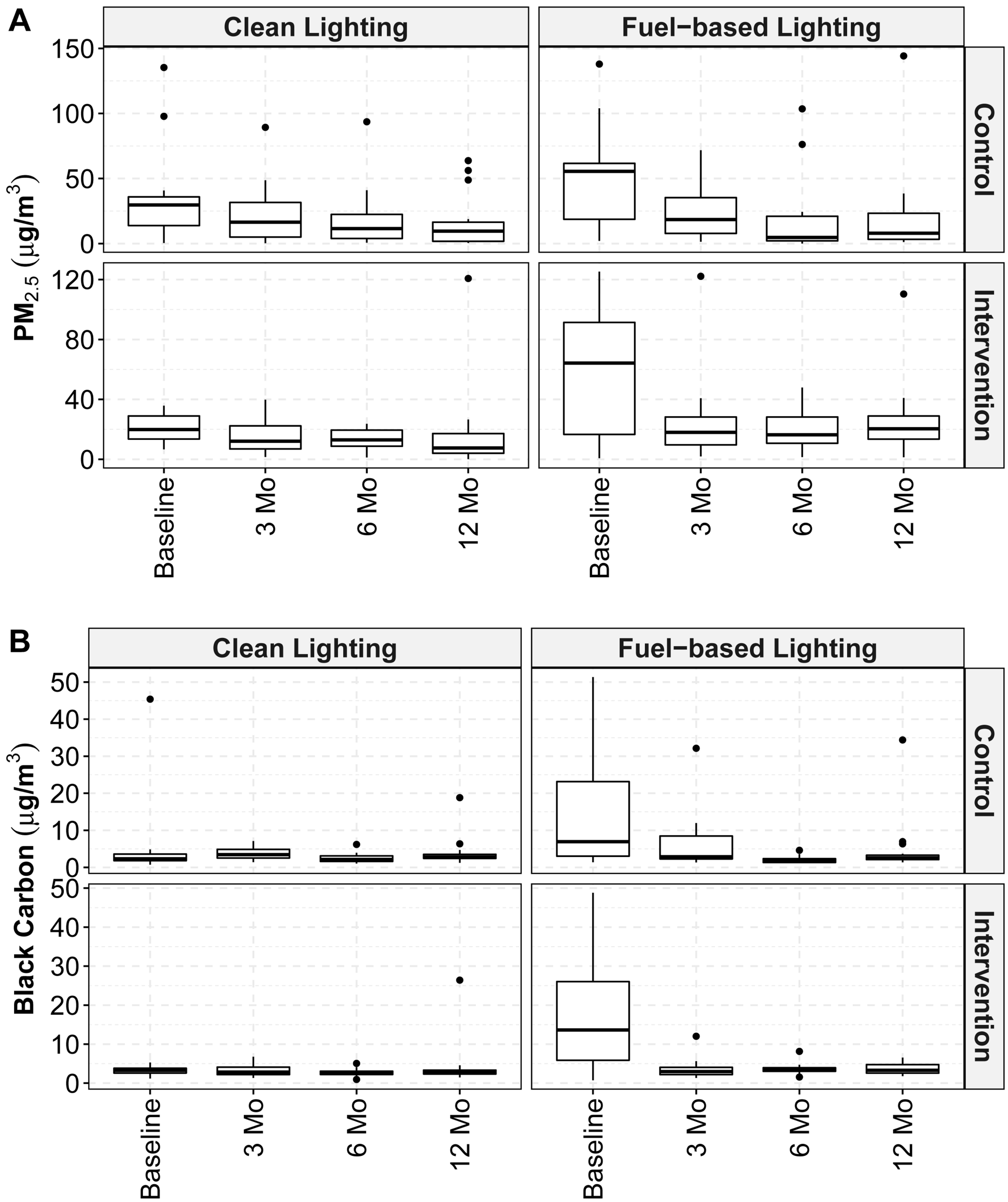

FIGURE 3:

Living room concentrations of PM2.5 (panelA) and blackcarbon (panelB) acrossstudyphases among control and intervention households

Table 1.

Baseline characteristics of study participants. Note only women were recruited for this trial.

	Control	Intervention	p-value
n	40	40	
Age (mean (SD))	38.06 (7.38)	41.30 (9.45)	0.091
Education (%)			0.754
None	4 (10.0)	7 (17.5)	
P1-P2	12 (30.0)	10 (25.0)	
P3-P6	15 (37.5)	13 (32.5)	
P7	9 (22.5)	10 (25.0)	
Marital status (%)			0.602
Married	35 (87.5)	36 (90.0)	
Cohabiting	4 (10.0)	4 (10.0)	
Separated/divorced	1 (2.5)	0 (0.0)	
Land ownership (%)	39 (97.5)	39 (97.5)	1
Owns a radio (%)	31 (77.5)	31 (77.5)	1
Owns a motorcycle (%)	6 (15.0)	4 (10.0)	0.735
Owns a car (%)	0 (0.0)	1 (2.5)	1
Wealth quintile (mean (SD))	2.90 (1.24)	3.08 (1.46)	0.562
Hours spent indoors daily (mean (SD))	15.81 (3.56)	16.43 (2.11)	0.352
Self-reported hours of light use daily (mean (SD))	4.35 (2.81)	5.15 (3.36)	0.251
Primary lighting source (%)			0.995
Candles	1 (2.5)	1 (2.5)	
Kerosene (open wick) lamp	12 (30.0)	12 (30.0)	
Kerosene (hurricane) lamp	4 (10.0)	5 (12.5)	
Flashlight	3 (7.5)	2 (5.0)	
Solar panel powered bulbs	14 (35.0)	13 (32.5)	
Electrical bulbs (national grid)	6 (15.0)	7 (17.5)	
Secondary lighting sources			
Candles	5 (12.5)	3 (7.5)	0.709
Kerosene (open wick) lamp	23 (57.5)	19 (47.5)	0.502
Kerosene (hurricane) lamp	13 (32.5)	9 (22.5)	0.453
Flashlight	1 (2.5)	2 (5.0)	1
Solar panel powered bulbs	14 (35.0)	15 (37.5)	1
Electrical bulbs (national grid)	5 (12.5)	4 (10.0)	1
Primary cook in house (%)	40 (100.0)	38 (95.0)	0.474
Hours spent cooking daily (mean (SD))	3.98 (1.49)	4.18 (1.65)	0.565
Cooking fuel type (%)			0.5
Charcoal	1 (2.5)	2 (5.0)	
Firewood	39 (97.5)	37 (92.5)	
LPG/Natural gas	0 (0.0)	1 (2.5)	
Trash burning (%)	9 (22.5)	8 (20.0)	1

	Control	**Intervention**	**p-value**
Baseline air pollution measurements			
$PM_{2.5}$ (living room), μg/m^3	32.93 [17.92, 55.48]	25.12 [13.87, 60.72]	0.714
$PM_{2.5}$ (personal), μg/m^3	56.20 [37.22, 87.65]	70.39 [28.86, 131.47]	0.555
Black carbon (living room), μg/m^3	3.10 [2.11, 5.38]	3.73 [2.49, 13.32]	0.360
Black carbon (personal), μg/m^3	4.48 [2.57, 8.68]	4.98 [3.16, 14.94]	0.158

Table 2.

Effect of solar lighting intervention on personal exposure concentrations to fine particulate matter ($PM_{2.5}$) and black carbon (BC). Estimates based on an intention to treat analysis using generalized estimating equations to determine the independent effect of the intervention on personal air pollution exposure.

Outcome	Subgroup	Participants (N)	Estimate ($\mu g/m^3$)	95% confidence interval	p-value
$PM_{2.5}$ (Personal)	All	80	−36.1	[−70.3, −2.0]	0.04
	Clean lighting	45	−16.5	[−45.1, 12.0]	0.26
	Fuel-based lighting	35	−44.3	[−103.7, 15.0]	0.14
BC (Personal)	All	80	−10.8	[−17.6, −4.1]	<0.01
	Clean lighting	45	−1.57	[−4.3, 1.2]	0.26
	Fuel-based lighting	35	−20.7	[−32.2, −8.3]	<0.01

Table 3.

Effect of solar lighting intervention on living room concentrations of fine particulate matter ($PM_{2.5}$) and black carbon (BC). Estimates based on an intention to treat analysis using generalized estimating equations to determine the independent effect of the intervention on personal air pollution exposure. Note that living room levels of $PM_{2.5}$ and BC decreased in the post-intervention period for both the intervention and control groups.

Outcome	Subgroup	Participants (N)	Estimate (μg/m^3)	95% confidence interval	p-value
$PM_{2.5}$ (Living Room)	All	80	1.2	[−16.5, 18.9]	0.89
	Clean lighting	45	8.0	[−7.4, 23.4]	0.31
	Fuel-based lighting	35	1.2	[−33.4, 35.8]	0.95
BC (Living Room)	All	80	−1.8	[−8.4, 4.8]	0.60
	Clean lighting	45	1.6	[−3.0, 6.2]	0.49
	Fuel-based lighting	35	−4.4	[−17.2, 8.4]	0.50