Title: Impact of a solar lighting intervention on social determinants of health in rural Uganda: a mixed methods, randomized controlled trial

Authors: Radhika Sundararajan[1,2*], Helen D'Couto[3*], Joseph Mugerwa[4], Mellon Tayebwa[4], Nicholas Lam[5], Eli Wallach[5], Matthew Wiens[6], Debbi Stanistreet[7], Alexander C. Tsai[3, 8], Jose Vallarino[9], Joseph G. Allen[9], Daniel Muyanja[4], Edwin Nuwagira[4], Peggy S. Lai[3, 7, 8]

[1] Department of Emergency Medicine, Weill Cornell Medicine, 525 East 68th street, New York, New York, 10065 USA

[2] Weill Cornell Center for Global Health, 402 East 67th Street, New York, New York 10065 USA

[3] Massachusetts General Hospital, 55 Fruit Street, Boston, Massachusetts, 02114 USA

[4] Mbarara University of Science and Technology, PO Box 1410, Mbarara, Uganda

[5] Schatz Energy Research Center, Humboldt University, 1 Harpst Street, Arcata, California USA

[6] University of British Columbia, 2329 West Mall, Vancouver, British Columbia Canada

[7] Royal College of Surgeons in Ireland, 123 Saint Stephen's Green, Saint Peter's, Dublin, Ireland

[8] Harvard Medical School, 25 Shattuck Street, Boston, Massachusetts, 02115 USA

[9] Department of Environmental Health, Harvard T.H. Chan School of Public Health, 677 Huntington Avenue, Boston, Massachusetts, 02115 USA

* These authors contributed equally and should be considered co-first authors.

Corresponding Author: Peggy S. Lai, MD MPH, Division of Pulmonary and Critical Care Medicine, Massachusetts General Hospital, Bulfinch 148, 55 Fruit Street, Boston, MA 02114, pslai@hsph.harvard.edu; +1 617-726-1721

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RESEARCH IN CONTEXT

Evidence before this study

We first reviewed the literature in PubMed for the impact of household air pollution (HAP) on morbidity and mortality using the search terms "household air pollution", "morbidity", "mortality", and "pneumonia." We identified 6 systematic reviews and meta-analyses along with several observational and survey-based studies which identify HAP as a leading cause of disability adjusted life years (DALYs), respiratory illness, and pneumonia in women and children. We also searched PubMed for global health intervention trials addressing HAP with additional search terms in addition to the prior including, "biomass stoves", "efficient cookstoves," "efficient cooking fuel," and "improved cookstoves." We reviewed 6 systematic reviews and reviews which included all trial designs including observational and randomized controlled trials (RCTs) from PubMed, OVID, OVID Embase, and SCOPUS. 3 RCTs, 4 qualitative studies, and one mixed methods study on the impact of efficient cookstove and fuel designs found minimal impact on HAP and respiratory illness. Prior household air pollution intervention trials focused on cleaner cooking technology have been limited by poor uptake; study participants often do not view cleaner cooking appliances as a health intervention and prioritize other factors such as household energy costs. Literature on the effects of lighting on HAP was identified in PubMed using the search terms, "kerosene lighting", "kerosene lamps", "solar lamps", and "household air pollution." One systematic review and 4 quantitative studies were reviewed which demonstrate that indoor lighting source contributes to HAP with cleaner lighting sources resulting in reduced HAP. No previous trials have evaluated clean lighting as an intervention to reduce HAP. We also did not find interventions in PubMed for HAP interventions which used social determinants of health as an outcome metric.

Added value of this study

Using a mixed methods approach embedded in a clean lighting intervention randomized controlled trial, we demonstrate that uptake of the lighting intervention was high and led to improved health-related quality of life. In qualitative interviews, participants viewed the solar intervention as transformative, improving multiple aspects of social determinants of health including household financial stability, educational opportunities for their children, safer home and neighborhood environment, social status, and perceived health.

Implications of this study

Clean lighting interventions to reduce household air pollution have important collateral psychosocial benefits. Analyses focused only on traditional health outcomes may underestimate their overall value to the end user. Future household air pollution studies should consider incorporating outcomes related to social determinants of health.

ABSTRACT (242/250 words)

Background. Clinical trials to reduce household air pollution have largely focused on cookstoves and have been in part limited by suboptimal adoption of cleaner cooking technologies. Less is known about the adoption and perceptions of clean lighting interventions.

Methods. As part of a randomized controlled trial of indoor solar lighting systems (ClinicalTrials.gov NCT03351504), we conducted a mixed methods study to identify contextual factors determining uptake and perception of the solar lighting intervention. Sensors were incorporated into the intervention solar lighting system to measure uptake and use over time. Health-related quality of life was measured with the EQ-5D-5L. Qualitative interviews were conducted with all trial participants.

Findings. Uptake of the intervention solar lighting system was high with daily use averaging 8·23 ± 5·30 hours per day. In mixed effects regression models, the intervention solar lighting system increased the EQ5D index by 0·083 [0·024 - 0·141], p = 0·006. Qualitative data suggest that solar lighting was associated with numerous benefits to study participants, including improved household finances, improved educational performance of children, increased household safety, improved family and community cohesion, and improved perceived household health.

Interpretation. Uptake of the solar lighting intervention was high and led to improved health-related quality of life. The solar lighting intervention was a transformative household energy technology which improve multiple domains of the Social Determinants of Health (SDOH). Trials focused only on traditional health outcomes may underestimate the overall value of clean household energy interventions to the end user.

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BACKGROUND

Household air pollution (HAP) contributes to an estimated 3·8 million premature deaths annually[1], is one of the top 10 contributors to disability adjusted life years (DALYs) worldwide[2] and accounts for approximately 4·5% of the global burden of disease.[1] HAP has been identified as a common cause of acute and chronic respiratory diseases in women, and is a leading cause of pneumonia in children.

Due to the burden of disease attributable to HAP, tremendous efforts have been made to mitigate this problem. Because HAP largely arises from indoor combustion sources such as cooking, lighting, and heating, much of the focus on reducing HAP in resource-limited settings has been on developing cleaner cookstoves and fuels with the aim of reducing pollution. These efforts have produced mixed results. A randomized trial of improved biomass stoves in Guatemala did not find a reduction in the primary outcome of pneumonia among children although there was a reduction in the secondary outcome of severe pneumonia[3]. A subsequent randomized trial of more efficient biomass stoves in Malawi did not demonstrate significant reductions in severe pediatric pneumonia[4]. A four year randomized study of improved cooking stoves in India showed poor uptake, marked declines in use over time, and no health benefits[5]. Overall, systematic reviews of improved biomass cookstove interventions demonstrate no significant reductions in measured air pollution[6] or reduce lower respiratory tract infections in children[7] and adults[8] although trials of cleaner cooking fuels are ongoing.

Limited uptake of improved cookstoves or cooking fuels may explain some of the negative results from current cookstove trials. A trial of biomass stoves in place of traditional open fires in Mexico had only 50% uptake of the intervention[9]. A systematic review found a broad range of factors influencing cookstove adoption, including finances, education, and household characteristics[10]. Another survey study in Senegal identified that while women valued improved cookstoves, their benefits did not outweigh what they valued about traditional cooking such as rapid heating and large cooking capacity.[11] Qualitative studies have illustrated that cost, taste, social norms, and adequate training strongly impact utilization of cookstoves.[12 13] Perhaps most importantly, even though improved cookstove trials are designed by investigators as an intervention to improve health, trial participants did not view these stoves as a health intervention. Rather, they are viewed as providing tangible benefits in the form of reduced cooking times[14] and reduced fuel consumption[15], though these advantages are outweighed by the high cost of the stoves.[16] These studies suggest that for target end users of cleaner cooking technology in low-resource settings, reducing exposure to pollution may not be a top priority.

An often-overlooked source of HAP is kerosene-based lighting. Simple open-wick kerosene lamps are widely used in resource-limited settings as the primary household lighting source[17], and produce fine particulate matter ($PM_{2.5}$) concentrations up to eight times the World Health Organization recommended limits[18]. Research in Kenya showed that provision of portable solar lamps displaced kerosene lamp use[19], suggesting a potential strategy for reducing HAP. Our recently completed observational study in rural southwest Uganda showed that after adjusting for wealth quintile, participants using open wick kerosene lamps had 1·91 times higher $PM_{2.5}$ and 4·7 times higher black carbon levels in the home, compared to those using solar lighting.[20] Guided by these observational findings and by feedback from study participants requesting widespread distribution of solar lighting, we conducted a randomized controlled trial of solar-based lighting in this community (ClinicalTrials.gov NCT03351504). While the primary trial outcome focused on changes in air pollution exposure, in this study we employed an explanatory sequential mixed methods study design to identify contextual factors determining uptake and perceptions of the solar lighting intervention.

METHODS

Study design and population

Between 2018 and 2019, we conducted a one-year parallel group, randomized wait-list controlled trial of indoor solar lighting systems in Nyakabare parish of southwest Uganda. We recruited 80 women of childbearing age from 7 villages.

Following enrollment, home visits were conducted prior to randomization, and at 3, 6, and 12 months after randomization to administer surveys and gather data on use of the intervention lighting systems. At 9 months following randomization, we began conducting qualitative interviews with trial participants.

Written informed consent was obtained from study participants. This study was approved by the Mbarara University of Science and Technology (Protocol #02/11-16) and the Partners Human Research Committee (Protocol 2017P000306/PHS), the Ugandan National Council of Science and Technology (Protocol #PS 42) and the Ugandan President's office.

Randomization and masking

Randomization was performed in a 1:1 ratio using a random number generator stratified by their primary lighting source (national electrical grid or battery-powered devices, solar lamps or systems, candles, hurricane kerosene lamps, and open wick kerosene lamps) to receive an indoor solar lighting system at the time of randomization (intervention group) or after one year at the end of the study (control group). Blinding of participants and field staff was not possible due to the nature of the study intervention.

Procedures

The study intervention was an indoor solar lighting system costing approximately $150 U.S. dollars, obtained from a local vendor based in Mbarara township (Allmar Solar Systems). These lighting systems were deployed in the intervention households between February and April 2018. The solar system comprised of a 30 watt-peak (Wp) solar panel, 18 Amp-hour (Ah) battery, 5 Amp charge controller, four lighting points, installation services, and a two-year service warranty. Participants selected the location for each of the four bulbs in their homes. In order to provide equitable treatment for study participants, between June and July 2019 the control group received the same solar lighting system.

Quantitative methods

Monitoring of solar system utilization

At the time of installation of the indoor solar system, we incorporated a sensor to track use of each light bulb. These four channel event loggers (Onset UX120-017) monitored the date and time when each light bulb was switched on and off throughout the one-year study period. Data was downloaded by research assistants at the time of solar lighting system installation to verify correct functioning of the sensor, and thereafter at 1 week, 3 months, 6 months, and 12 months after randomization. The hours of lighting use per day from each light bulb was subsequently calculated.

Administration of surveys

At baseline, 3, 6, and 12 months after the study intervention, trained research assistants administered surveys in Runyankole, the local language, with responses recorded on an Android tablet using an offline survey app (QuickTapSurvey). Surveys administered included questions eliciting demographics characteristics, household assets, cooking practices, lighting practices, use of lighting sources, and the EQ-5D-5L scale, which measures health-related quality of life in the domains of mobility, self-care, activities of daily living, pain/discomfort, and anxiety/depression.[21]

Qualitative methods

Individual interviews were conducted from January to July 2019 with all 80 participants enrolled in the clinical trial; all interviews were conducted after the intervention group had received a solar system and prior to the control group receiving the study solar system. A follow-up interview was conducted in a subset of control and intervention participants in September 2019 after the control group had received the study solar system.

In-person interviews were conducted by four Ugandan research assistants (two male, two female). An interview guide was created by a multidisciplinary group of Ugandan and U.S.-based investigators in order to ensure consistent focus on core concepts, while allowing for exploration of novel concepts. Interviews explored the impacts of solar lighting on the participant's daily life (see **Supplement**). Interviews were conducted in Runyankole, the local language, in a private location at the participant's home and were audio recorded. After each day of completing an interview, research assistants translated and transcribed the interview into English verbatim within 72 hours, and before performing additional interviews. Translations were spot-checked by author MT, fluent in both Runyankole and English, in order to ensure the quality and fidelity of translations. PSL reviewed transcripts for quality and content as they were generated.

Following a reflexive thematic analysis approach, an *in vivo* coding framework was developed by author PSL to characterize patterns in the data. Through careful, repeated examination and iterative review of the dataset, codes were then grouped based on similarity of meaning into themes reflecting participants' experiences with solar lighting. During weekly conference calls between U.S. and Ugandan investigators, and research assistants, patterns in the data were discussed, and coding discrepancies resolved through consensus. A final list of themes was created and study transcripts were coded using the final thematic scheme via Dedoose (Version 8·0 ·35). Participant quotations illustrating these themes were selected and are presented here to demonstrate concepts relevant to our study. As an additional means of ensuring the validity of our qualitative findings, we conducted member-checking interviews in a random selection of 20% of the trial participants (N=16) during September 2019.

Outcomes

The primary outcome for the trial was air pollution exposure. Those results are presented elsewhere. Secondary outcome for the trial included health-related quality of life and qualitative perceptions of the study intervention. There were no safety or adverse events.

Statistical analysis

The sample size of 80 participants was selected for the primary trial outcome to detect a 50% reduction in exposure to air pollution exposure between study arms. Summary statistics were aggregated using mean ± standard deviation or number (percentage). In examining utilization of the solar lighting intervention, mixed effects regression models were used to estimate correlates of hours of lighting use per day in intervention participants. Covariates in this model included primary lighting sources prior to randomization (including both "clean" energy sources such as indoor solar systems, electrical grid, electrical flashlights or lamps, as well as fuel-based energy sources such as candles and kerosene [hurricane and open-wick lamps]), bulb location, and time since the intervention. To estimate the effect of the study intervention on quality of life (as measured using the EQ-5D-5L), valuation weights from Zimbabwe were used[22] to calculate utility scores, given that no validated valuation weights currently exist for the EQ-5D in Uganda. Higher values represent better health-related quality of life. Simulation studies have shown that the minimally important differences in EQ5D index ranges between 0·037 and 0·069 based on country.[23]

The change in calculated EQ-5D index from baseline was used as the primary outcome in a mixed effects model to determine the effect of the study solar system on health-related quality of life; besides intervention status, predictors also included primary lighting source at the time of randomization. All statistical analyses were performed in R version 3·6 ·1l.[24] The R packages *tidyverse* were used for data merging, wrangling and cleaning, *tableone* for generating summary statistics, *ggplot2* for plotting, and *mgcv* for mixed effects models. Two-sided p-values $< 0·05$ were considered significant. There was no data safety monitoring committee used for this trial. This study was registered at ClinicalTrials.gov as #NCT03351504.

Role of the funding source

The funding sources had no role in the design, implementation, and interpretation of trial results.

FINDINGS

In January 2018, 88 women of childbearing age living in Nyakabare parish were assessed for eligibility, and 80 were successfully enrolled into the study between January and December 2018. Forty women were randomized to the intervention arm, and 40 to the control (**Figure 1**). Baseline characteristics of the study cohort stratified by trial arm is depicted in **Table 1**. The cohort was composed of women, the majority of whom were married or cohabiting, with no or primary school level of education. Household assets such as car or motorcycle ownership were rare, and the majority did not live in homes with cement walls or floors, nor did they have access to a ventilated improved pit latrine. The majority of the day (~16 hours) was spent indoors, with 4 – 5 hours of self-reported light use daily. The most common primary source of lighting was kerosene or solar based, though simultaneous use of multiple lighting sources was common. Few participants had access to the national electrical grid.

In the intervention, solar lighting was used for $8·23 \pm 5·30$ hours per day. In mixed effects models, primary lighting source prior to randomization was not correlated with use of the study solar lighting system ($p = 0·763$), i.e., there were no statistically significant differences in overall number of hours of light used per day between participants who already possessed clean lighting technology (solar panels, electrical grid access) and those who did not (kerosene and candles) at the time of randomization. There was no decline in the number of hours of lighting use per day over the entire study period overall (beta = 0·0 [0·0 – 0·0], p = 0·310). The location of light bulb placement chosen by participants is shown in **Table 2**. The most heavily utilized light location was the outdoor security light which was used on average 6·0 [5·1 – 6·8] hours per day, followed by the master bedroom, living room, kitchen, and children's bedroom.

Results of the EQ5D-5L survey administered longitudinally to both the intervention and control groups are detailed in **Supplementary Table 1**. Changes in the EQ5D index stratified by intervention group are depicted in **Figure 2**. In mixed effects models, the intervention solar lighting system increased the EQ5D index by 0·083 [0·024 - 0·141], p = 0·006.

Qualitative interviews revealed that the solar lighting intervention was a transformative household energy technology, with a broad array of benefits attributed to the solar lighting system. We identified five themes in the dataset: 1) improved household finances; 2) improved educational performance; 3) increased household safety; 4) improved family and community cohesion; and 5) improved household health. We will consider each theme below, with supportive examples.

One of the most frequently described benefits of the solar lighting intervention was overall improvement in household finances. Participants reported decreased expenditures for household energy, increased capability for income-generating activities, and the ability to divert funds to pay for other critical household expenditures. For example, participants used savings towards competing expenses such as other household goods or for children's school tuition and books.

> *This solar has helped a lot on minimizing home expenditures. We used to buy kerosene a lot but these days, instead of buying kerosene, we can use that money to do other things…items like washing soap, or saving money for school fees so the children are not sent home.* [Nyakabare village, 37 years-old]

> *I have been able to divert my savings to only buying kids school materials and school fees … that was the same money I used to spend on buying dry cells [batteries] for the torch*. [Bukuna village, 39 years-old].

The solar lighting system also contributed to improved finances by extending the workday, allowing for more time spent towards income-generating activities.

> *As I've told you, what I use that solar for ... if I am still outside, [now] I can see for stone quarrying. Yes, I work. I hit those stones and at times I stop at 11PM.* [Nyamikanja village, 40 years-old]

Second, participants noted that solar lighting systems improved educational performance among their children. Prior to receiving solar lighting, participants describe rationing lighting fuel, which negatively impacted their children's ability to complete homework in the evenings.

> *There is a huge change [after receiving solar lighting] because before the children say, '[teachers] told us to read our books'. Then you would tell them, 'No please, we don't have enough kerosene.'* [Bukuna village, 41 years-old]

With the receipt of the solar lighting system, light no longer needed to be rationed and children had sufficient lighting to perform homework in the evenings. The ability to do homework after sunset translated into tangible improvements in school performance among participants' children, and less worry among parents.

> *They [my children] were performing very badly [in school], they would be the last ones in class. I was very worried and I was about to get [high] blood pressure. I was worried about getting school fees and the performance of my kids at school was also discouraging. It all looked like money is being wasted. But now, I am very okay… I see that when they [my children] come back they spare some time to read books and they are performing very well these days. The school reports are good.* [Bukuna village, 41 years-old]

Third, lighting was intrinsically linked with improvements to the participants' home and neighborhood. Specifically, participants reported an increased perceived sense of safety after installation of the solar lighting systems, stating that the solar lighting system was instrumental in preventing crimes at night and enabling community policing.

> *[The solar lighting] helps me outside for security reasons. If it is on, even the thief can't hang around my house. They know that someone may see them and know who they are. Because of light, the whole place will clear and you can see everything. Since there is no darkness, the thieves fear to come around, and in that way I benefit from the solar light outdoors.* [Bukuna village, 41 years-old]

In addition, anxiety about open-flame lighting sources as a fire hazard were alleviated with solar lighting systems.

> *Imagine you have left the children in the house with something that produces fire for light. You have to be worried [about starting a fire in the home]. I am sure even if I died today, I would die happy knowing that my children would never sleep in darkness. Light is secured for them because you gave them their solar.* [Bushenyi village, 32 years-old]

Fourth, the solar intervention was reported to improve family and community cohesion. Solar lighting was described as reducing economic stressors associated with purchasing lighting fuel, previously a common source of conflict. After receiving solar lighting systems, participants report improved relationships with their spouses.

> *Whenever we would lack kerosene, we would quarrel almost every day. I would be like, 'now that we don't have kerosene, how we will eat meals, lay kids to bed, or how will kids read their books?'. Or, at times I had to change kids' nappies [diapers] in the dark, so conflicts would never end in my house. It was really a hard experience. But now that I have solar, life is better and conflicts are reduced. My family now has peace.* [Bukuna village, 32 years-old]

Lighting also allowed families to spend more time together as the duration of waking hours could be extended.

> *We used to sleep very early because of the need to save kerosene usage. However, after getting the solar, our [family] relationship has improved because after eating dinner, we now get time to sit and chat together … the solar has given us enough time to talk at night. So, it has helped us to understand each other very well.* [Bukuna village, 30 years-old]

The solar intervention also was reported to bring prestige to participants within their communities, as other households could reap benefits from the lighting systems. Solar lighting systems were perceived as status symbols, which served to decrease social isolation and strengthen relationships between neighbors.

> *After getting this solar ... neighbors [who] have got no solar now send their children to come and study at my house. They are also benefiting from this study solar. And by this, their parents are giving me more respect, which makes me feel important to the community.* [Bushenyi village, 32 years-old]

Finally, with introduction of the solar lighting systems, participants remarked on noticeable health improvements within their households. Participants were aware of the health dangers of household smoke generated from fuel-based lighting, and described how soot would gather in their children's noses or how soot would be visible in the participant's expectorated sputum. Recurring respiratory infections and illness were attributed to use of the open-wick kerosene lamps, but were considered the unavoidable cost of having affordable lighting in the home.

> *Solar has no bad effect, it has only good things …. you do not get sick all the time. You do not spend a lot of money on the sicknesses of the children and the old people that live in our household.* [Nyamikanja village, 33 years-old]

Integration of quantitative and qualitative data reveal the broad impacts of solar lighting systems on participant's lived experiences (**Table 3**). The increase in EQ5D index after introduction of the study solar lighting system may be explained by wide-ranging benefits to household economy, education, safety, family/community relationships, and health noted in interviews. Trial results also demonstrate high uptake of the intervention solar system regardless of whether participants already had access to clean lighting technology prior to the start of the trial. Choice of lighting locations in the trial correlates with several of the benefits described in qualitative interviews. Participants noted an increased sense of security, which correlates with high utilization of the outdoor security bulb. Improved educational opportunities for children was a frequently mentioned theme, reflecting frequent placement of a solar lightbulb in the children's bedrooms. Increased sense of well-being is multifactorial, and may explain why study participants deeply desired the solar lighting system provided in this trial: "What I want most is light. Light helps me so much." [Rwembogo village, 45 years-old].

Solar lighting in particular "helps" in concurrent and intersecting ways. This quote illustrates how solar lighting affected many aspects of a participant's lived experience, including household economy, security, and community cohesion:

> *I would sometimes lack money to buy kerosene, then I would go to the nearby shop and beg for a debt [store credit]. The shopkeeper would pretend as if he has not heard my request. Then I would kneel down and beg him in front of people, 'please give me kerosene. My kids are going to sleep in the dark'. It was too much shame and humiliation seeing an old woman kneeling down in the mud before a young man begging for kerosene of 1000 shillings ($0·30 USD). Ever since I got this solar, I have never asked for salt or a matchbox from the neighborhood. This solar has helped me a lot.* [Bukuna village, 50 years-old]

DISCUSSION

In this randomized wait-list controlled trial of indoor solar lighting systems in rural Uganda, we found that uptake of the solar lighting intervention was high and was not affected by pre-existing ownership of clean lighting technology. The intervention led to a significant improvement in health-related quality of life. Our qualitative data demonstrate the transformative nature of solar lighting on the participants' daily lives, with positive impacts on multiple dimensions of lived experiences. These positive impacts explain the high and sustained uptake of clean lighting technology.

Themes from our qualitative data closely parallel some domains which have been well described as part of the Social Determinants of Health framework (SDOH).[25] The SDOH are social, physical and economic conditions into which people are born and live, and which impact their health. In **Figure 3,** we illustrate how solar lighting systems can improve various components of SDOH. Prior studies on clean household energy interventions have not evaluated social determinants of health as an outcome, underscoring novelty of our findings, and raising the question of whether future trials should incorporate these outcomes which appear to be highly valued by the end user.

A key challenge to prior air pollution interventions in global health has been uptake as well as sustained use of introduced products or technologies[5]. To date, the majority of household air pollution intervention trials have focused on cookstoves. Prior interventions in cookstove technology aimed at reducing pollution and improving health outcomes have had mixed results with a major challenge being uptake and utilization of more efficient stoves. Participants in the Cooking and Pneumonia Study (CAPS), a randomized control trial of advanced cookstoves in Malawi, did not primarily see the intervention cookstove as a health intervention but rather as a device that reduced cooking times and fuel consumption, although participants found the cost of the intervention cookstove to be prohibitive.[16] Another cluster randomized trial of improved biomass cookstoves in Bangladesh corroborated these findings and found that demand for improved cookstoves was primarily driven by the cost of the stoves, and that participants rarely valued reductions in household air pollution over financial pressures.[26] Unlike cleaner cooking technology, clean lighting technology in the form of solar provides financial benefits by allowing participants to extend the amount of time they spent on income generating activities leading to overall financial gains.

However, the benefits associated with our study intervention extended beyond its financial impacts. Numerous improvements to the SDOH were reported by study participants, including improvements to educational opportunities for the children, home environment, social interactions both within and outside the participants' households, and perceived health. These benefits may explain the high uptake of the solar intervention. To date, these benefits have not been evaluated as outcomes in household air pollution trials, yet they are highly valued by study participants. Our work suggests that future research on air pollution could benefit from applying the SDOH as a framework for evaluating the impact of an intervention. This model can be used to evaluate other global health research. For example, deworming programs have been linked to improved school attendance in Kenya and thus facilitate education as a SDOH.[27] Similar results were found with iron supplementation and deworming in India.[28] A "patient-centered" approach to household air pollution interventions would suggest that we should consider judging the success of an intervention based on the priorities of the end user rather than those set by study investigators or sponsors.[29]

Our findings also suggest that traditional cost-utility analyses may underestimate the value of health interventions with higher up-front costs, such as clean lighting. For example, the World Health Organization cost-benefit frameworks[30] for evaluating household energy interventions do not account for impacts on SDOH. Therefore, cost-utility estimates of interventions such as clean lighting may be artificially devalued because the true benefits of the interventions have not been adequately measured.

Our study has several strengths. To our knowledge, it is the first mixed methods study based on a randomized controlled trial of a clean lighting intervention. We objectively monitored use of the solar lighting intervention with sensors. Qualitative interviews were conducted with all trial participants. Although mixed methods studies have been conducted in the context of randomized controlled trials of improved cookstoves, clean cooking and clean lighting technology provide fundamentally different benefits and thus results from clean cooking studies cannot be easily extrapolated to clean lighting studies and making our findings novel. Our study has some weaknesses. It is a single site study and lighting preferences may differ in other contexts. We were unable to quantitatively assess the impact of the qualitative themes identified. The qualitative outcome was not the primary trial outcome. However, our findings could be further assessed in future larger trials of clean household energy interventions.

In conclusion, a solar lighting intervention has high sustained uptake, improves multiple SDOH, and leads to improved health-related quality of life. Clean lighting interventions to reduce household air pollution have important collateral psychosocial benefits. Analyses focused only on traditional health outcomes may underestimate their overall value. Future household energy intervention trials should consider evaluating the success of the trial using a SDOH framework.

Contributors

PSL conceptualized, designed, and secured funding for the study. JM, MT, DM, EN, PSL collected the data. RS, HD, JM, NL, EW, PSL analyzed and interpreted the data. RS, HDC, PSL wrote the original draft of the manuscript, and all authors contributed to writing, review and editing. All authors approve of the final manuscript.

Declaration of interests

We declare no competing interests.

Data sharing

Anonymised data and the data dictionary for this study will be made available to others upon reasonable request to the senior author (PSL, pslai@hsph.harvard.edu). Study protocol, statistical analysis plan and informed consent forms are also available from PSL.

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FIGURES

Figure 1. CONSORT Study Flow Diagram.

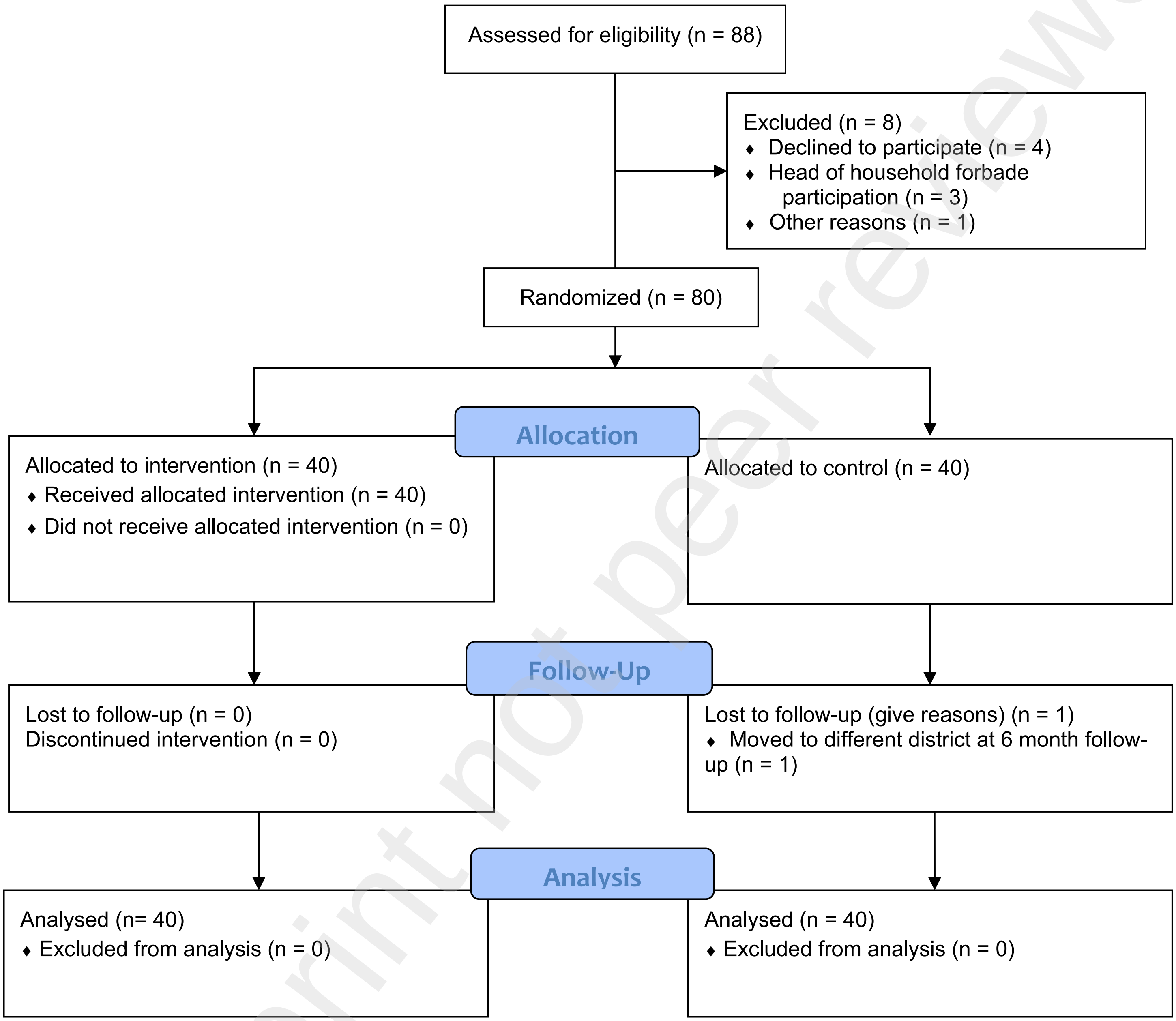


Figure 2. EQ5D index over time, stratified by intervention group. An index of 1 represents full health. At baseline no group had received a solar lighting system. At 7 days, the intervention group had received a study solar system. At 12 month follow-up the control group had also received a solar lighting system. In a mixed effects model, the solar lighting intervention led to a 0.083 [95% CI 0.024 - 0.141, p = 0.006] increase in the EQ5D index value. C = control group. I = intervention group.

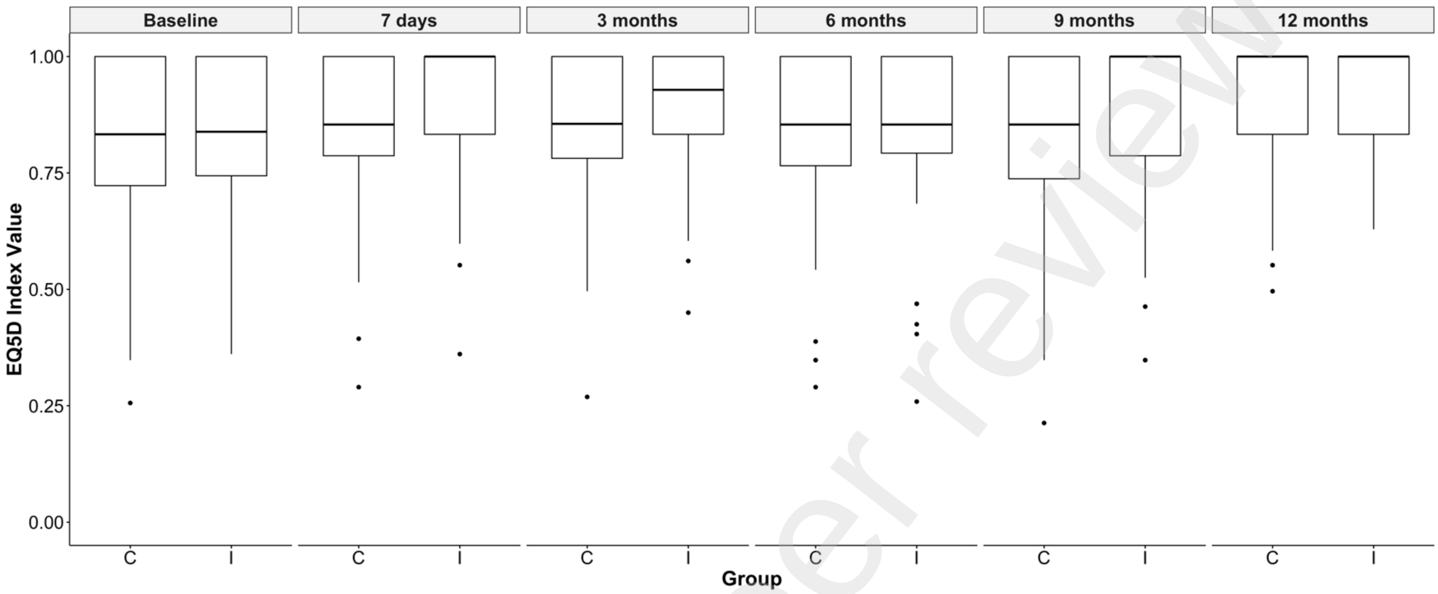
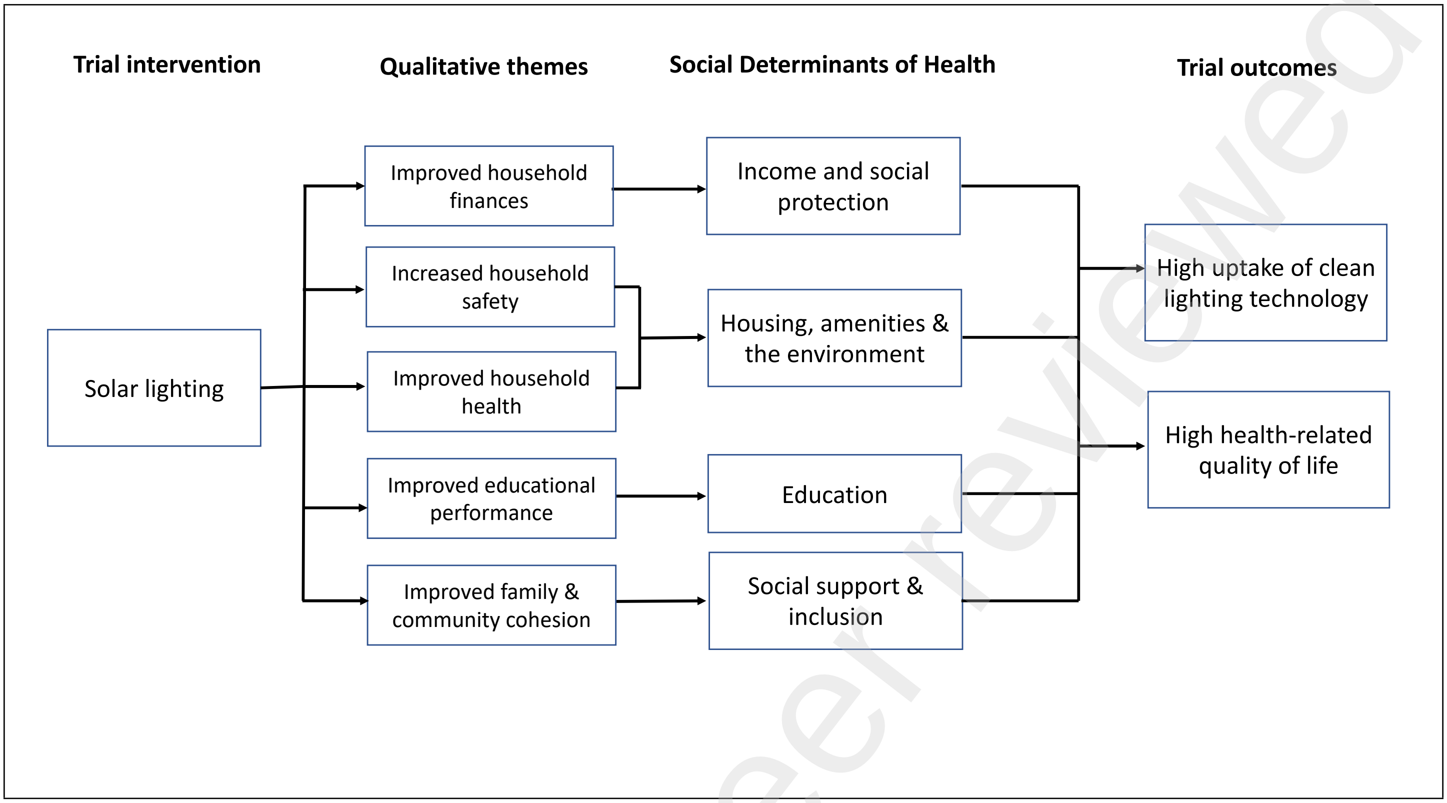


Figure 3. Schematic showing qualitative results as they correspond to selected domains of Social Determinants of Health



TABLES

Table 1. Characteristics of study participants. Note only women were recruited for this study.

	Control	Intervention
n	40	40
Age (mean (SD))	38.06 (7.38)	41.30 (9.45)
Education (%)		
None	4 (10.0)	7 (17.5)
Primary 1-2	12 (30.0)	10 (25.0)
Primary 3-6	15 (37.5)	13 (32.5)
Primary 7	9 (22.5)	10 (25.0)
Marital status (%)		
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)
Number rooms in house (mean (SD))	4.35 (1.23)	4.20 (1.64)
Owns a radio (%)	31 (77.5)	31 (77.5)
Owns a motorcycle (%)	6 (15.0)	4 (10.0)
Owns a car (%)	0 (0.0)	1 (2.5)
Access to a ventilated improved pit latrine (%)	1 (2.5)	1 (2.5)
Home has cement walls (%)	3 (7.5)	9 (22.5)
Home has cement floors (%)	6 (15.0)	12 (30.0)
Wealth Quintile (mean (SD))	2.90 (1.24)	3.08 (1.46)
Hours spent indoors daily (mean (SD))	15.81 (3.56)	16.43 (2.11)
Hours spent outdoors daily (mean (SD))	8.54 (4.34)	7.58 (2.11)
Self-reported hours of light use daily (mean (SD))	4.35 (2.81)	5.15 (3.36)
Primary lighting source (%)		
Candles	1 (2.5)	1 (2.5)
Kerosene (tadooba) 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)
Kerosene (tadooba) lamp	23 (57.5)	19 (47.5)
Kerosene (hurricane) lamp	13 (32.5)	9 (22.5)
Flashlight	1 (2.5)	2 (5.0)
Solar panel powered bulbs	14 (35.0)	15 (37.5)
Electrical bulbs (national grid)	5 (12.5)	4 (10.0)
Primary cook in house (%)	40 (100.0)	38 (95.0)
Hours spent cooking daily (mean (SD))	3.98 (1.49)	4.18 (1.65)
Cooking fuel type (%)		
Charcoal	1 (2.5)	2 (5.0)
Firewood	39 (97.5)	37 (92.5)
LPG/Natural gas	0 (0.0)	1 (2.5)
Use of secondary stove in house (%)	4 (10.0)	2 (5.0)
Trash burning (%)	9 (22.5)	8 (20.0)

Table 2. Frequency and location of solar bulb placement selected by intervention arm households. Each of the 40 intervention households was provided with four solar bulbs. This table summarizes a total of 159 bulb placement locations; one participant's home was small and there was no location to place a fourth bulb.

Bulb location	**Frequency (%)**
Living room	36 (22·6%)
Master bedroom	35 (22·0%)
Outdoor security light	32 (20·1%)
Kitchen	20 (12·6%)
Child's bedroom	17 (10·7%)
Storage room	8 (5·0%)
Dining room	6 (3·8%)
Guest bedroom	2 (1·3%)
Home office	1 (0·6%)
Corridor	1 (0·6%)
Chicken coop	1 (0·6%)

Table 3. Integration of quantitative trial results and qualitative themes

Trial results			**Qualitative theme**	**Qualitative example excerpt**
Increase in health-related quality of life	High uptake of clean lighting intervention		Improved household finances	"This solar has helped a lot on minimizing home expenditures. We used to buy kerosene a lot but these days, instead of buying kerosene, we can use that money to do other things…items like washing soap, or saving money for school fees so the children are not sent home."
		Household placement of solar bulb	Improved educational performance	"They [my children] were performing very badly [in school], they would be the last ones in class. I was very worried and I was about to get [high] blood pressure. I was worried about getting school fees and the performance of my kids at school was also discouraging. It all looked like money is being wasted. But now, I am very okay… I see that when they [my children] come back they spare some time to read books and they are performing very well these days. The school reports are good."
			Increased household safety	"[The solar lighting] helps me outside for security reasons. If it is on, even the thief can't hang around my house. They know that someone may see them and know who they are. Because of light, the whole place will clear and you can see everything. Since there is no darkness, the thieves fear to come around, and in that way I benefit from the solar light outdoors"
			Improved family and community cohesion	"Whenever we would lack paraffin, we would quarrel almost every day. I would be like, 'now that we don't have paraffin, how we will eat meals, lay kids to bed, or how will kids read their books?'. Or, at times I had to change kid's nappies [diapers] in the dark, so conflicts would never end in my house. It was really a hard experience. But now that I have solar, life is better and conflicts reduced. My family now has peace."
			Improved household health	"Solar has no bad effect, it has only good things …. you do not get sick all the time. You do not spend a lot of money on the sicknesses of the children and the old people that live in our household."