Development and Implementation of Sustainable Air Ventilation Systems for Rural Nicaragua

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I. Abstract

Research Questions: There are four essential questions:

1. Is it possible to build, install, and maintain an air ventilation system in rural Nicaragua?
2. Will such a system be accepted by and utilized by participant households?
3. Will indoor air quality be improved after installation of the ventilation units?
4. Will the overall health of the families be improved due to improved air quality?

Background, significance, and rationale:
Wood fires are commonly used in the developing world for multiple purposes including heating the home and cooking. Exposure to smoke is particularly high in women and children due to traditional roles of fire preparation and child rearing. Exposure to harmful pollutants produced by wood fires has been linked with negative health impact ranging from respiratory problems to cardiovascular issues, headaches and more. Our goal was to implement a low-cost ventilation system in a small cohort of homes across rural Nicaragua with the goal of improving respiratory health outcomes in the subject population.

Materials and methods:
A solar-powered air ventilation system was design for $60/unit and installed in 12 homes in rural Nicaragua. Due to low initial compliance with the use of the solar-based system, an unpowered hood and chimney system was developed and subsequently installed in the place of the solar units. This unit was installed in 17 households and environmental air quality and health outcomes were assessed.

Environmental air quality was assessed using a novel field measurement approach that leveraged filter paper and a free spectroscopy web application ("Albedo"). This provided a low-cost, portable, estimate of relative air quality before and after the application of both interventions (solar-vent, hood-vent).

Wellness of participants was measured using a survey and measurement of vitals and exhaled carbon monoxide (ECO). These data were obtained at baseline and after a minimum of 8 months post-installation of the hood unit. A total of 20 individuals (13 females and 7 males) completed both baseline and post-data.

Results:
It was possible to install an effective low-cost ventilation system with hood systems being preferable to solar-powered systems due to low acceptance/compliance of the solar vent. The hood systems grossly reduced household air pollution in target households. ECO was significantly improved among both males and females (females $P<0.001$, males $p<0.011$). After a minimum of 8 months of hood use, several health parameters significantly improved. Among females (n=13), there was strong evidence for a reduction in coughing ($p=0.010$), chest tightness ($p=0.021$), and itchy watery eyes ($p=0.030$); among males (n=7), there was strong evidence for a

reduction in coughing (p=0.023) and vision problems (p=0.023), and moderate evidence for reduced in headaches (p=0.043) and fatigue (p=0.043).

Conclusion: It is possible to build a low-cost ventilation system that effectively reduces indoor air pollution. Hood-type systems achieve effective reduction in pollution while achieving superior use compliance in rural Nicaragua. Health measures associated with ventilation and hood systems demonstrated significant evidence of reduced health complaints and objective measurements of household air pollution (HAP) exposure via ECO and field spectroscopy.

II. Research Questions

The overarching goal of the project was to improve wellness among low-income individuals living in rural Nicaragua by implementing an air ventilation system for use over household wood fires. Historically, solutions have been implemented by third parties, but these solutions have not stood the test of time due to lack of relevance for the socioeconomic context in which they were implemented.

In an effort to achieve this goal, the following four research questions were posed:

1. Is it possible to build, install, and maintain an air ventilation system in rural Nicaragua?
2. Will such a system be accepted by and utilized by participant households?
3. Will indoor air quality be improved after installation of the ventilation units?
4. Will the overall health of the families be improved due to improved air quality?

Hypothesis: We hypothesized that the installation of solar-powered air ventilation units over home wood-fires used for cooking would result in decreased inspiration of household air pollution (HAP) including harmful particulate matter. We hypothesized that reduced HAP would result in an improvement of reported and observed medical outcomes including self-reported health parameters (survey) and physical examination findings (vitals, exhaled carbon monoxide).

III. Introduction, Significance and Rationale

A. Introduction

Ten percent of the world lives in energy poverty[1] and 13% lack access to modern electricity.[2] This lack of energy access leads to the use of solid fuels for cooking, illumination, and warmth. Today, more than 3 billion people worldwide use indoor fires fueled by kerosene or biomass (wood, plant material, dung) on a daily basis.[3-6] The simplest of these arrangements consist of a simple pit with a few large rocks for cooking surrounded by a simple structure with minimal windows or ventilation. The poorest households tend to use highly inefficient fuel sources such as crop waste or wood (see figure 1).

Figure 1: The Energy Ladder (Source WHO)

These rustic stoves are very inefficient and emit high levels of indoor air pollution including carbon monoxide and particulate matter (PM). PM <2.5 um diameter ($PM_{2.5}$) is considered the most dangerous for human inhalation, while coarse particulate matter (2.5um-10um diameter) (PM_{10}) is also considered harmful.[7] These small soot particles penetrate deep into the lungs and inflame the airways, decreasing oxygen carrying capacity and impairing the immune response.[6] This can cause severe health problems ranging from acute respiratory infections to pneumonia and lung cancer via a mechanism that is "qualitatively similar to the burning of tobacco in terms of PM and gases".[9] Such a process is postulated to involve local oxidative stress leading to activation of macrophages causing injury to epithelial cells and consequent initiation of the inflammatory process.[9]


Figure 2: Cooking in rural Nicaragua (interior view)

The problem with poor indoor air-quality due to biomass or kerosene use is most severe in the developing world, where low incomes and long-standing traditions prevent the use of safer alternatives.[3,4] Given the lack of access to electricity or fuel alternatives, safer cooking practices have been out-of-reach for many of the world's low and middle-income countries. In many such households, pollution levels are in excess of 1000mg/m^3 PM—greater than 40 times World Health Organization's recommended exposure levels for PM.[9]


Figure 3: Rural Nicaragua cooking areas typically have low ventilation, and high build-up of particulate matter.

In a typical household in rural Nicaragua, for example, multiple family members live in one or multiple buildings constructed of wood, tin, and other recycled materials. They prepare meals in a cooking area that generally consists of an indoor wood fire and three stones used for direct cooking (see figures 2-4). Wood is collected from the mountainside and used to prepare cooking fires multiple times during the day. These fires tend to be prepared in the pre-dawn hours and the fire is revived prior to preparation of meals several times during the day, sending plumes of black smoke into the air. Women traditionally tend the fires and young children frequently accompany the women of the households through daily chores, thus elevating HAP exposure among women and children.


Figure 4: Cooking space in rural Nicaragua (Exterior view)

B. Significance

Global nature of the problem

The World Health Organization (WHO) estimates that over 3 billion people use indoor fires using solid fuels such as biomass, coal, and wood. Studies by the WHO indicate that ~3.8 million people die each year from chronic respiratory diseases that are associated with these cooking practices.[3] There is a strong correlation between indoor air pollution from solid fuel use and respiratory diseases such as Chronic Obstructive Pulmonary Disease (COPD) and acute respiratory tract infections and other respiratory problems like asthma, tuberculosis, and interstitial lung disease[10]. Indoor air pollution is also associated with headaches, eye and vision problems, cardiovascular disease, and stroke.[3]

Exposure to high levels of indoor air pollution has been highlighted as an urgent global health concern by the WHO. It is an underlying issue targeted by the United Nations for improvement through the UN's Sustainable Development Goals (SDGs). The SDGs were drafted in 2015 and include 17 goals with the overarching goal of achieving a better and more sustainable future for all by addressing issues such as poverty, hunger, health, gender equality, energy, and climate (figure 5). Implementation of solutions to address household air quality may address multiple SDGs including 3.Good Health and Well-being, 5.Gender equality, 7.Affordable and clean energy, and 13.Climate action.

Figure 5: UN Sustainable Development Goals

Potential interventions to address the SDGs might include a broad variety of approaches including leveraging alternative and green energy sources (electrical heat, propane gas, solar, wind), installation of more efficient heating vessels (stoves, chimney systems), and installation of air ventilation systems. Despite the clear call for action, progress toward significant change has been slower than anticipated by the WHO.[5]

In Nicaragua and Honduras alone, there are approximately 3 million people living in energy poverty[1]. Approximately 65% of the inhabitants of these nations live in rural areas that do not have access to electricity.[1] This creates a pervasive issue for education, family, and women's empowerment, and health and safety.[11]

In many countries, efforts toward improving indoor air quality have incorporated strategies such as employing alternative fuels such as propane or installing alternative cook stoves. These strategies often prove unsustainable as low incomes make purchasing alternative fuel untenable[5] for many inhabitants of developing areas, and culture and tradition make it difficult to gain support for changing the cooking apparatus with an alternative stove. Simple hood-type ventilation systems may be costly and sometime require electrical power which is not available off-the-grid.

Indoor air pollution from using combustible fuels for household energy caused 4.3 million deaths in 2012,[2] with women and girls accounting for 6 out of every 10 of these.[2] Of these, 27% are from pneumonia, 27% are from ischemic heart disease, 20% are from COPD, 18% from stroke, and 8% are from lung cancer[3]. In adults, indoor air pollution is a contributor to COPD, and nearly one quarter of global COPD deaths are attributed to household air pollution. Dr. K. Sood of the University of New Mexico has established that there is also a strong correlation between indoor air pollution and acute respiratory tract infections and a somewhat weaker association with other respiratory problems like asthma, tuberculosis, and interstitial lung disease.[11] There is additional evidence of a link with stroke, ischemic heart disease, and vision loss.[11]

The problem is most acute among women and children living in poverty as these groups have the highest levels of exposure.[3,4,6,9] For example, women who breathe high volumes of indoor smoke are more than twice as likely to suffer from COPD vs. women who use cleaner heating tools.[4] Children often accompany female members of the household during cooking times—increasing their exposure and likelihood of developing negative health consequences. Among children, exposure to household air pollution almost doubles the risk for childhood pneumonia and is responsible for 45% of pneumonia deaths in children less than 5 years old.[3,4]

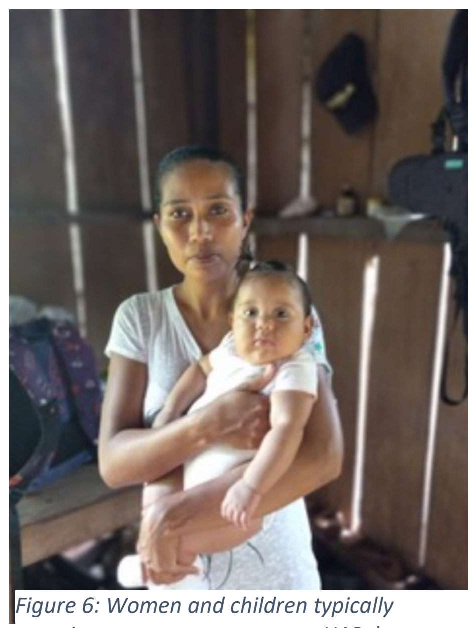

Figure 6: Women and children typically experience greater exposure to HAP due to traditional roles of fire preparation, cooking, and childcare.

State of research in improving health through reducing household air pollution (HAP):

The correlation between HAP and chronic medical conditions is well established, but there has been more difficulty linking a specific intervention with measurable improvement in health parameters. Foundational research in interventions in the developing world have repeatedly shown that qualitative measures of health can be improved by an improvement in HAP, but identifying such outcomes quantitatively has been more difficult.

The Randomized Exposure Study of Pollution Indoors and Respiratory Effects (RESPIRE) study in Guatemala showed that it was possible to reduce qualitative respiratory complaints through the installation of a wood stove (“Plancha”). Researchers found that there was a significant reduction in wheeze (relative risk (RR) = 0.42, 95% confidence interval (CI): 0.25, 0.70) and reduced reporting of respiratory complaints over the course of the 18 month study, however there was no significant reduction on lung function 12-18 months among the 504 female participants.[13]

Long-term follow-up of the RESPIRE study population was reported in the Chronic Respiratory Effects of Early Childhood Exposure to Respirable Particulate Matter (CRECER) study. Investigators found that after 4-6 years of follow-up of 306 women (265 with an acceptable spirometry session), there was no significant improvement in any measure of lung function measured with spirometry.[14] They concluded that “more substantial reductions in exposure” may be necessary to impact lung function and postulated that COPD from HAP develops more slowly and at a later age.[14] A case control study of women exposed to biomass smoke in Turkey gives evidence for this claim. The study found that exposure to HAP was linked to lung disease, but the duration needed for existence of small airway disease was 16 years and 17 years for restrictive and obstructive diseases, respectively.[15]

A few studies did show it is possible to improve measurable improvement in lung function in specific populations. A study in rural Rwanda showed that it was possible to achieve a significant improvement in forced expiratory volume (FEV1) at 9 months among those with pre-existing obstructive lung disease (N=31. $FEV1_{F9}$ = 1.70 L; $p < 0.01$ vs $FEV1_{BL}$ = 1.58 L, $p < 0.01$). Of note, no improvement was seen among those *without* pre-existing lung disease.[16] Zhou et al. documented a larger prospective cohort study of 996 individuals over the age of 40 in a remote area in China in which they considered whether the use of improved ventilation and/or an alternative fuel source would improve lung function. Over a 9 year period, both interventions were associated with a reduced decline in FEV1 (reduction of 12 mL for clean fuels, 13 mL for ventilation, 16 mL for both) compared to no intervention. Moreover, reduced risk for COPD was noted with an odds ratio of 0.28 (95% CI, 0.11 to 0.73) for both improvements.[8]

There are many other health problems associated with HAP beyond respiratory complaints. Headaches are among the most frequent medical problems in households with high levels of HAP. A follow-on study of 453 pregnant or recently pregnant women in Guatemala found that reported headache frequency decreased upon installation of the “Plancha” stove. Significant reduction in headache frequency occurred after 18 months (OR 2.43, 95% CI 1.30 to 4.52).[17] Eye health is another area of concern. Aung et al. showed that eye irritation improved after installation of a “rocket stove” (single pot biomass cookstove) among a group of rural Indian participants (N=111, all age >25) despite the fact that the study did NOT effectively reduce PM. They postulated that a component other than PM may have been responsible for symptomatic improvement.[18]

Vital signs may also be impacted by HAP. There is evidence for an association between elevated blood pressure and exposure to high levels of particulate matter. One review shows that there is an estimated 1-5mmHg increase in blood pressure for every 10ug/m^3 increase in PM2.5 and that this is a possible mechanism for relationship between increase stroke risk, myocardial infarction, and heart failure among those with high exposure to air pollution.[19] There is also evidence of an association between $PM_{2.5}$ and oxygen saturation. One study of a group of older females showed an association between $PM_{2.5}$ and reduced oxygen saturation with a peak negative correlation at 6 hours following exposure to $PM_{2.5}$ (6 hours mean, -0.173%, 95% CI -0.345 to -0.001) and 6.5 hours after exercise (6 hours mean, -0.0173%; 95% CI -0.332 to -0.014). It is postulated that this is due to inflammation of the small airways of the lungs following exposure to environmental pollution.[28]

Several studies leveraged the use of exhaled carbon monoxide as proxy mechanism for measuring the effectiveness of the intervention. Diaz's study in Guatemala found that exhaled CO was significantly reduced after installation of a wood stove with chimney (9 ppm baseline vs. 5 ppm at 18 months).[17] The study showed that respiratory symptoms (cough, phlegm, wheeze, chest tightness) were positively associated with breath CO at the time of symptom reporting[8] and ECO has been used in multiple other studies as a method of approximating pollutant exposure.[8,14,17]

C. Rationale

Given the data on cultural and economic obstacles associated with changing fuel source or cooking methods to reduce HAP, we developed and installed low-cost air ventilation systems for application in homes in rural Nicaragua. The initial design proposed was a solar air ventilation system built to leverage solar systems already installed in the region (see methods below). Early in the course of the project, we found low compliance with use of the solar-powered units and a need for excessive maintenance as filters required frequent cleaning. We subsequently replaced the units with a hood-type ventilation system. The rationale for selection of this intervention is as follows:

Effective: The viability of ventilation systems in the reduction of HAP has been well-established: A 2016 study by McNamara and Thornburg highlighted the value of the application of even modest improvements in ventilation to the achievement of significantly improved indoor air quality with good compliance and continued use of the systems.[4,21] They showed that the application of even a low-efficiency, low-cost air filter can be effective for reducing particulate matter.[4,21] Similarly, Zhou et al.'s study in China found that ventilation was an effective mechanism for reducing age-related decline in lung function (FEV1).[5]

Our intervention incorporates the development of a low-cost mechanism that roughly gauges indoor air quality using simple tools that are available in a remote, resource-limited area. This novel tool is helpful in a remote environment where measuring total exposure to environmental pollutants with traditional tools can be a significant barrier to implementation. The WHO reports that "measurement of smoke particles in the home is technically quite demanding…[and that] these methodological complexities are one reason why the direct measurement of pollution exposure has rarely been carried out, and why the development of methods for exposure are a priority for further work in the field."[5]

Culturally relevant: The negative health-impact associated with the use of solid fuels outlined above was addressed using an intervention that considers cultural norms and socioeconomic realities that will likely exist long after investigators move on to the next research project. Leininger's Theory of Culture Care and Diversity and Universality is a framework that can be used for the basis of design and implementation of sustainable projects in the developing world. Leininger holds that care should be delivered within a cultural context in order to positively influence human health, well-being, and survival.[11] We propose that a low-cost air ventilation system is likely to provide the most scalable and readily adopted means of reducing indoor air pollution in a resource-poor environment.

Sustainable: Sustainable solutions require consideration of not only environmental impact, but also social equity/ humanitarianism and economic viability (figure 7). This study investigates whether it is possible to create a meaningful improvement in air quality through low-cost materials that will be adopted by users and sustained over time. We propose to install a simple air ventilation system to traditional wood-fire systems in a small cohort of homes across rural Nicaragua. The proposed intervention was designed by the Texas Christian University (TCU) Department of Engineering to incorporate no more than $60 in materials per home with ease of construction that can be achieved by local technicians.

Figure 7: Pillars of sustainability, source: University of Nottingham

D. Relationship with the Beyond the Light Project (BTLP)

Some of the infrastructure leveraged in the deployment of the intervention is built upon existing work by the Beyond the Light Project (BTLP) already working in Latin America (Nicaragua, Honduras, Peru). This non-profit organization is recognized as a 501c and was founded in 2016 to help alleviate energy poverty in Nicaragua and Honduras. BTLP consists of a team of leaders, academic partners, and local technicians. The goal of the organization is to leave behind a sustainable energy economy that improves peoples' lives.

Figure 8: Sample household solar panel produced by BTLP

BTLP has research interests in the effects of solar electricity for rural families and schools in off-grid areas. BTLP is invested in evaluating and promoting social business systems that promote entrepreneurship in rural communities. Together, BTLP's team designs, builds, installs, and maintains solar electrical systems (figure 8) in schools and households. BTLP's team hires and trains local technicians to repair maintain and assemble power systems and the ventilation interventions outlined in this report. As of 2021, BTLP had installed solar projects in 170 homes, 30 schools, and 3 churches in Guaimaca, Honduras, El Carmen, Nicaragua, La Mora Nicaragua, and additional pilot projects were installed in 2022 in Lima, Peru.

BTLP's approach to development of solar electrical assemblies includes a process of technical education for local technicians, in-country sourcing, and assembly of parts, wiring of control systems, and inventory and testing followed by a thorough installation process (see figures 9,10).

Figure 9: BTLP solar panel DEVELOPMENT & ASSEMBLY process

Figure 10: BTLP solar INSTALLATION process

The activities and methods described for the ventilation research project were performed by BTLP and an established network of community partners. Early phases of the present research incorporated the methods outlined in figures 9 and 10 and subsequent addition of a solar-powered air ventilation unit as described in the materials and methods section below. Hood and chimney later replaced the solar ventilation systems, but not the solar panels used for other purposes in the households.

IV. Research Materials and Methods

A. General Study Details

17 Households in two rural villages in rural Nicaragua were identified to receive a no-cost ventilation system and maintenance which extended during the study period. Funding occurred via start-up funding from Texas Christian University (TCU) and supporters of BTLP.

B. Subject Identification

Participant households were selected on the basis of having previously received a solar electrical system from BTLP. These households were interviewed with surveys regarding their lifestyle, overall health, and interest in receiving an air ventilation unit. Participants were selected by the Principal Investigator based on the following criteria:

- The home has a solar electrical system.
- The household cooks on a wood burning oven with indications that the smoke is a major problem (walls are dark with soot)
- The household has some indication of a health issue
- The household agrees to the research and ventilation system

C. Additional Subject Stratification

Participants were categorized by gender, age, and history of smoking as well as hours spent in the kitchen (exposure) per day. Due to the small sample size, no additional criteria were used for stratification purposes.

D. Development and Installation of the Solar Ventilation System

TCU's engineering department designed a solar-powered air ventilation system (figure 11).

Figure 11: Initial design incorporated a filtration system run by solar electric power. All components were sourced for less than $50 and assembled in Nicaragua.

Solar ventilation parts were provided and shipped to Managua Nicaragua and transported to the target villages of La Mora, El Carmen and La Estrella (Matagalpa region of Nicaragua). 12 solar units were assembled in Nicaragua by the local technicians from BTLP (figure 12).

Figure 12: Assembly by BTLP technicians in El Carmen Nicaragua

After a thorough discussion and disclosures with the selected households, written consent was obtained and units were installed and tested in 12 households (figure 13). Air quality was measured, and households were instructed on how to use the solar ventilation system (figure 14).

Figure 13: Installation and functional test of solar vents

Figure 14: Subject households during educational program

E. Subsequent development and design of hood-type ventilation system

Due to low-compliance with powering the solar-powered unit and early results of air quality measures (see results section), the system was re-engineered to a hood and chimney ventilation design (figure 15). This design remained low cost (materials $30/unit, labor $30/unit, 2 hours installation). These were built in Nicaragua and installed by BTLP and did not require additional intervention (i.e., frequent cleaning, manually powering on/off) by participant households.

Figure 15: Redesigned hood and chimney ventilation unit

Ultimately, 17 households--the 12 solar households listed above and 5 additional households--received hood vents. There were 38 individuals who completed the baseline survey and at least one subsequent health survey. The final data analysis includes the 20 individuals who completed baseline and the final 8+ month survey. Potential causes of high rate of attrition are addressed in the discussion section.

F. Data Collection and Recording

A. Survey

Surveys were developed to gather information of participants' health and well-being. The surveys were delivered verbally in Spanish with the assistance of local health resources including nurses at the National Autonomous University of Nicaragua Managua Polisal School of Nursing. Parents/guardians aided in the responses for survey data for participants less than 18 years of age.

A detailed history was obtained including the participants' lifetime history of air-pollution and health complaints including but not limited to respiratory tract infections, COPD, asthma, headaches, neurological problems, and cancer. Appendix I contains the survey tool designed for and used throughout the experiment.

B. Physical examination

Investigators including nurses from Polisal University School of Nursing measured participants' vital signs (Blood Pressure, Respiratory Rate, Pulse, Oxygen Saturation, Temperature) and exhaled carbon monoxide (ECO) at baseline and after at least 8 months of use of the hood vent. Spirometry was not chosen as a measurement mechanism for multiple reasons including difficulty of repetition in the field and low probability of observing measurable differences in a relatively short study period (see State of current research in section III B). We included measurement of ECO because it has been repeatedly demonstrated as a leading indicator of recent exposure to air pollution.

C. Environmental Assessment

As previously mentioned, low-cost, easy to implement measurement tools to approximate environmental air quality are a significant barrier to evaluation of interventions for air quality in resource limited environments. Tools specifically designed for the purpose of environmental analysis are often, costly, bulky, and unsuited for long-term placement in a household environment. They additionally may pose a risk for damage or theft. An ideal tool for evaluation of the environment in such a setting would be accurate, precise, low-cost, and available locally.

With these considerations in mind, our team developed a novel field measurement approach. We used simple filter paper and a free spectroscopy application ("Albedo" available for free on Google Play®) to provide a rough analysis of the amount of particulate matter accumulating in the cooking area. The process was built upon the theory that blue light reflectance is a reliable indicator for the level of air pollution. Higher reflectance indicates that fewer pollutants are present in the sample. We would expect to see that an effective ventilation system would increase blue reflectance due to the presence of less particulate matter.

The process for analysis was as follows:

1. Filter paper (standard white coffee filters) were pinned near fire source in the kitchen and in living areas of participant homes and remained in place for 1 week during the following 4 time periods:
    a. Time 0 (T0): For 1 week prior to installation of any intervention
    b. Time 1 (T1): For 1 week immediately following installation of solar vent
    c. Time 2 (T2): For 1 week 4 months after installation of solar vent
    d. Time 3 (T3): For 1 week following installation of hood system
2. Filter samples including unused controls were collected and sent to the US based research team for analysis in a laboratory environment with controlled (fluorescent) lighting
3. Albedo application was downloaded from the Google Play® Store
4. Albedo was calibrated using 18% photography paper prior to analysis of each sample
5. Random analysis of a representative portion of the filter paper was performed using the Albedo application
6. Information was input into Excel® for statistical analysis

D. Statistical Analysis

Surveys were tallied using a Likert scale. Surveys and physical exam results were reported as means and standard deviation for each at baseline ("pre") and at least 8 months ("post") installation of the hood vent. Participants >70 years of age were excluded from final results due to multiple confounders (other chronic illness, Covid-19 epidemic, etc.). There was an insufficient sample size to control for other variables. Statistical significance was determined through a single-tailed paired t-test to determine directionality (increase or decrease). Significance level was determined to be $p<0.05$.

V. Results

A. Solar Lighting (without ventilation system) BLTP observations

We gathered information about general household characteristics and the impact of solar systems prior to ventilation system installation. These data incorporated a larger data set (N=50+) and enable greater visibility to the effects of health and quality of life when solar lighting is installed. This information served as a useful baseline for comparison vs. homes that received solar-powered ventilation systems. This information provides insight into potential confounding factors such as the impact of increased light (alone) vs. the impact of increased light plus ventilation.

1. **The addition of solar lighting had a significant impact on the average wake-up time of household members.** There was a significant change in wake up time associated with installation of solar lighting. Mean wake up time for households was 4:11am +/-0.995 hours before installation and increased to 4:38am +/-1.30 hours after solar panels were installed. Mean difference is 27 minutes (p=0.013). There was no similar change in the average time at which participants went to sleep.

Descriptive Statistics

Sample	N	Mean	StDev
Wakeup Pre	105	4.18	0.995
Wakeup Post	69	4.64	1.30
Sleep Pre	105	19.83	1.00
Sleep Post	69	19.83	1.28

Two-Sample T-Test and CI: Pre and post

	Difference	95% CI	T-Value	P-Value
Wake	-0.464	(-0.828, -0.100)	-2.53	**0.013**
Sleep	-0.005	(-0.366, 0.356)	-0.03	**0.979**

2. **The addition of a solar lighting system was not associated with a statistically significant decrease in time spent in front of the fire.** While it would seem plausible that the addition of light would decrease the amount of time spent in front of the fire (theory: fire being used as a light source in addition to heat and cooking entity), there was no evidence that household members experienced a change in the amount of time exposed to wood-burning fires on the basis of availability of light alone. This was a subjective measurement based on participant recollection.

Descriptive Statistics

Sample	N	Mean	StDev
Cook Time Pre	92	3.80	1.35
Cook Time Post	12	4.42	2.61

Two-Sample T-Test and CI: Pre and post

Difference	95% CI	T-Value	P-Value
-0.618	(-2.304, 1.069)	-0.81	**0.437**

3. **The solar lighting group reported decreased health measures vs. baseline survey especially increased breathing and allergy problems**. Weighted Likert findings (1=worst, 5=best) of a health survey similar to Appendix I showed a decline in perceived personal health (p=0.025). Breathing and allergy problems increased significantly during the measured timeframe (p=0.005). These findings likely reflect factors such as seasonal illness, allergies, and the COVID-19 pandemic.

Over-all health:

Descriptive Statistics

Sample	N	Mean	StDev
Health Rating Pre	53	3.02	1.10
Health Rating Post	69	2.580	0.991

Two-Sample T-Test and CI: Pre and post

Difference	95% CI	T-Value	P-Value
0.439	(0.057, 0.821)	2.28	**0.025**

Breathing and allergy problems

Descriptive Statistics

Sample	N	Mean	StDev
Breathing Prob Pre	64	1.61	1.03
Breathing Prob Post	52	2.288	0.977
Allergy Prob Pre	65	1.97	1.30
Allergy Prob Post	50	2.58	1.01

Two-Sample T-Test and CI: Pre and post

Difference	95% CI	T-Value	P-Value
-0.611	(-1.038, -0.184)	-2.83	**0.005**

4. **Many participants reported subjective improvements in health and quality of life.** While survey results reflected a decline in some health measures listed above, subjective feedback from most participants was overwhelmingly positive. Feedback included statements such as:
   "My life is different. I feel so happy."
   "My life has changed because now I have lights"
   "I no longer have to wake up early"

B. Baseline Demographic Data: Installed Ventilation Systems

Ventilation systems were installed in 17 households. There were 38 participants that completed at least the baseline and 1 follow-up survey. Age range for participants was 12-87 years with a mean age of 39. There was a roughly equal distribution of female: male participants (18:20). 26% of participants reported difficulty breathing in the past. 31.5% reported using medications for breathing. 76.3% reported no history of smoking, 15.8% were active smokers and 7.9% were previous smokers. Active or past history of smoking was far more common among men (40% of males had smoking history vs. 6% of females).

Overall, an average of 2.5 hours was spent in the kitchen daily. Females and children spent an average of 3+ hours in the kitchen vs. 2 hours for males. Actual exposure times were likely higher because it is known that fires are

Age Spread (years)

average	39.0
minimum	12
maximum	87

Gender (Respondents)

Female	18
Male	20

Answered if there was difficulty breathing (Y/N)

Difficulty Breathing Y	10
Difficulty Breathing N	28

Answered if they are taking medications for breathing (Y/N)

Medications for Breathing Y	12
Medications for Breathing N	26

Answered if they are smokers (Never/Past/Present)

Smoking Never	29
Smoking Past	3
Smoking Present	6

Figure 16: Demographic data for study group (ventilation system installed)

maintained throughout the day and not all time spent tending the fire was likely reflected in reported "cooking time."

Initial health status was reported by survey and results were tabulated using a Likert scale. The weighted average of these responses is listed in Figure 17. Headaches, vision problems, and dry, itchy eyes were the most prevalent complaints based on a weighted average. Women were more likely to report frequent headaches at baseline.

Vital signs and exhaled CO data were collected. Baseline ECO was higher among men, particularly smokers (6.8ppm average for men vs. 5.6 average for women). There was an association between hours spent in the kitchen per day and diastolic blood pressure value (N=38, Correlation 0.329, 95% CI for p 0.010-0.587, p=0.044) and pulse (N=38, Correlation 0.537, 95% CI for p 0.263-0.731, p=0.001). There was no such correlation between hours in kitchen per day and other vital signs (pulse oximetry, systolic bp) or ECO.

Tabulated, Summed and Weighted Answers from Likert Questions (0-Never, 5-Always)

Response	Dry, Itchy Eyes	Vision Problems	Difficulty Breathing	Headaches	Stuffy Nose	Coughing	Chest Tightness	Exhaustion
0	16	21	26	5	11	12	24	24
1	4	0	3	3	18	17	1	2
2	4	1	2	9	4	3	4	5
3	5	2	1	14	3	3	6	3
4	4	4	2	5	1	0	2	1
5	5	10	4	2	1	3	1	3
score	68	74	38	93	44	47	40	40
rank	3	2	8	1	5	4	6	6

Figure 17: Baseline survey data from 38 participants. Likert scale was used, and responses were weighted and ranked.

C. Air Quality

Hood and chimney systems were installed in 17 households. Of these, a complete set of environmental data was available for 12 homes. Homes were fitted with filter paper for 1 week at each of the time points outlined above (T0=prior to installation of any intervention, T1=immediately following installation of solar vent, T2= 4 months after installation of solar vent, T3=1 week following installation of hood system).

The theory of our novel approach to field environmental air quality assessment is further described in the "methods" section. In short, blue light reflectance was the lowest in initial study (t=1, no intervention) indicating this parameter is a proxy for PM accumulation. We deduced that an increase in blue light reflectance represents a decrease in PM accumulation on the filter paper and consequent improvement in air quality.

Spectroscopy revealed a significant increase in blue light reflectance (i.e., a decrease in PM accumulation, improved HAP) after both the installation of the solar system (t=1, mean difference 0.13, p<0.001) and hood system (t=3, mean difference 0.15, p<0.002). There was a decrease in blue light reflectance (i.e., an increase in PM accumulation, poorer HAP) four months after installing the solar system (t=2, mean difference -0.16, p<0.003). It is postulated that this is related to households failing to power-on the system and due to lack of cleaning of the systems (see discussion), and this along with participant feedback served as the impetus for replacement of solar systems with hood-type systems.

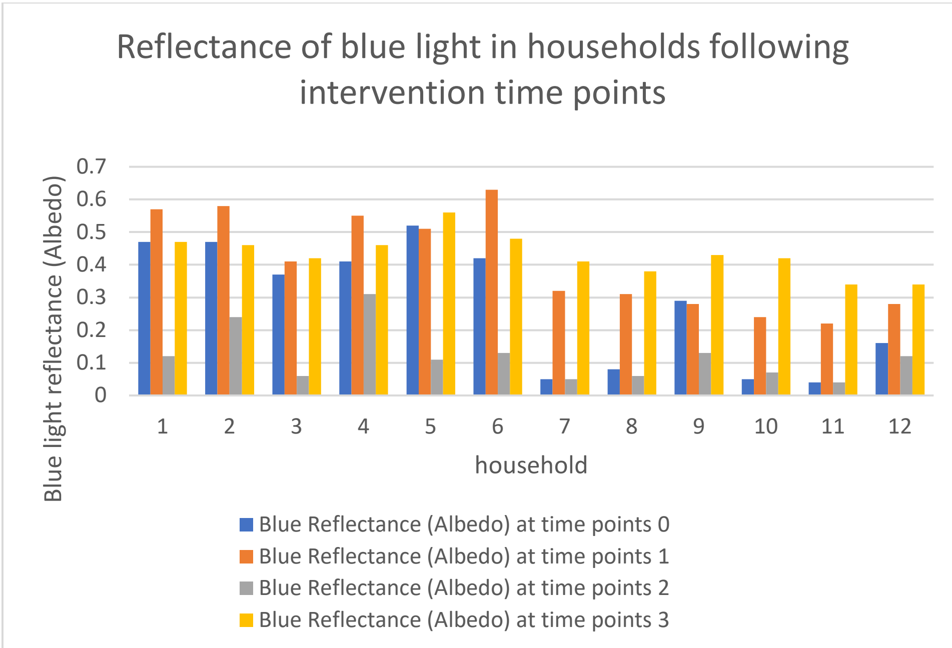

Figure 18: Blue light reflectance trends by households at time points. T0=baseline, T1=Installation of solar, T2=4 months after installation of solar, t3=Installation of hood

	Blue Reflectance (Albedo) at time points			
	0	1	2	3
1	0.47	0.57	0.12	0.47
2	0.47	0.58	0.24	0.46
3	0.37	0.41	0.06	0.42
4	0.41	0.55	0.31	0.46
5	0.52	0.51	0.11	0.56
6	0.42	0.63	0.13	0.48
7	0.05	0.32	0.05	0.41
8	0.08	0.31	0.06	0.38
9	0.29	0.28	0.13	0.43
10	0.05	0.24	0.07	0.42
11	0.04	0.22	0.04	0.34
12	0.16	0.28	0.12	0.34
Mean	0.2775	0.408333	0.12	0.430833
Standard deviation (SD)	0.18883	0.150565	0.080792	0.061859
Mean difference (MD) vs baseline		0.130833	-0.1575	0.153333
Single-tailed T test (t vs baseline)		0.000206	0.002392	0.00175

Figure 19: Spectroscopy data (blue light reflectance only) and related statistics.

D. Results of the solar ventilation system

There were subjective benefits to the solar vent system. Participants reported numerous benefits after 4 months of installation including a reduction in dry, itchy, watery eye complaints, (n=7), improved breathing/reduced stuffiness (n=5), and benefits related to throat and headaches. Verbatim examples of these comments are translated in figure 20.

Despite these benefits, users stated that the ventilation system used too much battery and half of the systems had functional problems. Participants stated that they were "saving the battery" for light and that they consequently did not use the ventilation system. There was also significant accumulation of smoke/film on the systems that may have impacted effectiveness.

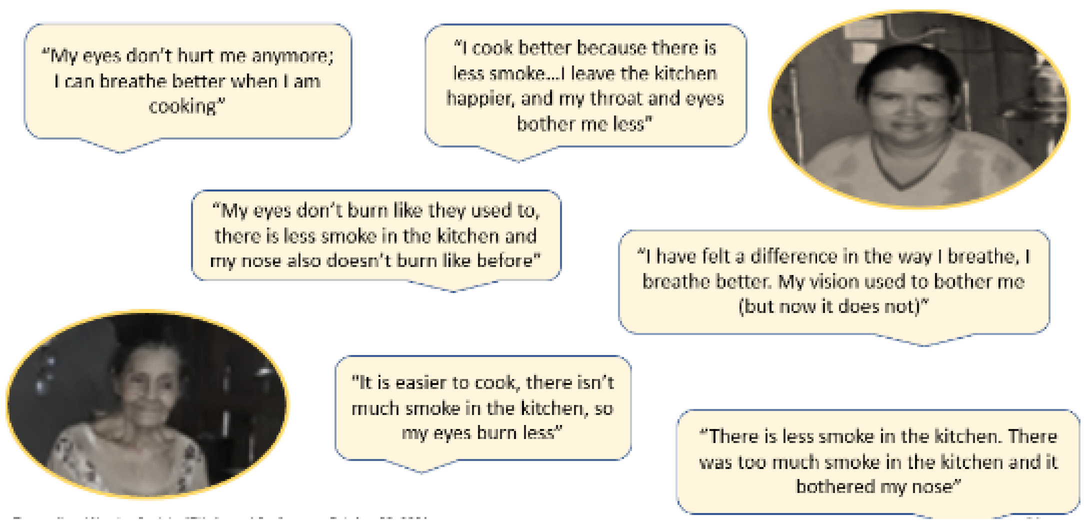

Figure 20: Verbatim comments of benefits of solar vent system

Based on these comments, it was decided that, while viable, solar vents achieved poor adoption. The system was consequently re-designed in favor of a non-powered hood vent and the solar vent observations were discontinued. Results of the hood vent are outlined in the section E.

E. Results of the hood and chimney ventilation system

Hood and chimney systems were designed and installed in 17 households. Installation occurred in phase thus post-intervention data represents a range of 8 months to 1.5 years of use of the hood system. 20 participants provided a full set of pre and post data. Ages ranged from 14 to 57 years of age. There were 13 females and 7 males who completed the final assessment.

Physical exam results: There was a significant improvement in ECO among both male and female participants (Mean difference (MD) -4.03, 95% CI 1.42-2.37, p<0.001). There was no significant improvement in systolic or diastolic blood pressure, pulse oximetry, or pulse.

Survey results: There was a significant improvement in multiple health measures as determined by participant responses to survey (appendix I). Likert responses were scored from 0=never to 5=always. Both men and women reported decreased coughing (MD -0.8, p=0.001). Among women, there was a significant reduction in dry, itchy, watery eyes (MD -0.9, p=0.030), and chest tightness (MD -0.8, p=0.02). Among men, there was significant reduction in reported vision problems (MD -1.8, p=0.02), and somewhat weaker evidence for reduction in headaches (MD -1.0, p=0.04), and fatigue/difficulty with tasks (MD -1.0, p=0.04).

There was no significant change in the report of difficulty breathing or congestion among males or females. There was no change in the amount of time spent in the kitchen for males or females and there was no change in number of medications used. It was not possible to further subdivide the population by exposure time or other health conditions due to small sample size.

Data is outlined in figures 21,22.

	Age (Start)	Systolic Blood Pressure (mmHg pre-intervention)	Systolic Blood Pressure (mmHg 8 month post-intervention)	Diastolic Blood Pressure (mmHg pre-intervention)	Diastolic Blood Pressure (8 month post-intervention)	Pulse Oximetry (% pre-intervention)	Pulse Oximetry (% post-intervention)	Pulse (BPM pre-intervention)	Pulse (BPM 8 month post-intervention)	Exhaled CO (PPM pre-intervention)	Exhaled CO (PPM 8 month post-intervention)	Hours in Kitchen per day (1(<1), 2(1-2), 3(3-5), 4(>6))pre-intervention	Hours in Kitchen per day (1(<1), 2(1-2), 3(3-5), 4(>6) 8 month post-intervention)
Females													
Average (DC 14 and 34)	34.2	119.2	122.7	79.2	78.8	97.9	97.6	79.6	80.0	5.7	1.7	3.1	3.0
Standard Deviation (DC 14 and 34)	14.0	17.1	17.1	11.9	12.4	1.0	2.2	11.9	10.0	2.0	0.8	0.8	0.9
Minimum (DC 14 and 34)	14	100	100	60	61	96	94	61	65	2.7	1	2	1
Maximum (DC 14 and 34)	57	150	157	100	99	99	100	100	94	8	3	4	4
sample size	13	13	13	13	13	13	13	13	13	13	13	13	13
t.test significance 1 tail			0.197		0.418		0.323		0.435		######		0.419
Significant			no		no		no		no		yes		no
Males													
Average (DC 14 and 34)	38.3	111.4	116.1	74.3	74.0	98.0	97.9	74.9	72.0	6.4	2.3	2.4	1.9
Standard Deviation (DC 14 and 34)	12.7	14.6	15.5	11.3	12.2	1.2	1.2	10.2	9.5	2.5	1.4	1.3	0.9
Minimum (DC 14 and 34)	14	90	91	60	55	97	96	59	63	3	1	1	1
Maximum (DC 14 and 34)	48	130	139	90	94	100	100	87	91	11	5	4	3
Sample size	7	7	7	7	7	7	7	7	7	7	7	7	7
t.test significance 1 tail			0.141		0.462		0.402		0.267		######		0.052
Significant			no		no		no		no		yes		no
ALL													
average	35.65	116.5	120.4	77.5	77.1	97.95	97.7	77.95	77.2	5.93	1.9	2.85	2.6
Standard Deviation	13.378	16.311	16.487	11.642	12.256	0.9987	1.8946	11.33	10.319	2.181	1.0208	0.9881	1.0463
Minimum	14	90	91	60	55	96	94	59	63	2.7	1	1	1
Maximum	57	150	157	100	99	100	100	100	94	11	5	4	4
t test significance 1 tail			0.0928		0.4083		0.2958		0.3617		6E-07		0.1745
Significant?			No		No		No		No		both		No
Sample size			20		20		20		20		20		20
Difference of the Mean (MD)			3.9		-0.4		-0.25		-0.75		-4.03		-0.25
										CI	0.4778		
95% CI											2.3778		

Figure 21: Pre and 8+months post installation of hood vent, vitals, ECO, basic demographics

	Dry, Itchy, Watery Eyes (0 - 5 Likert pre-intervention)	Dry, Itchy, Watery Eyes (0 - 5 Likert, 8 month post-intervention)	Vision Problems (0-5 Likert pre-intervention)	Vision Problems (0-5 Likert, 8 month post-intervention)	Difficulty Breathing (0-5 Likert pre-intervention)	Difficulty Breathing (0-5 Likert, 8 month post-intervention)	Headaches (0-5 Likert pre-intervention)	Headaches (0-5 Likert, 8 month post-intervention)	Stuffy Nose (0-5 Likert pre-intervention)	Stuffy Nose (0-5 Likert, 8 month post-intervention)	Coughing (0-5 Likert pre-intervention)	Coughing (0-5 Likert, 8 month post-intervention)	Chest Tightness (0-5 Likert pre-intervention)	Chest Tightness (0-5 Likert, 8 month post-intervention)	Fatigue/Difficulty with tasks) (0-5 Likert pre-intervention)	Fatigue/Difficulty with tasks (0-5 Likert, 8 month post-intervention)
Females																
Average (DC 14 and 34)	1.6	0.7	1.7	0.6	0.6	0.5	2.6	2.3	1.0	0.7	1.4	0.5	1.3	0.5	0.8	0.4
Standard Deviation (DC 14 and 34)	1.5	1.1	2.3	1.0	1.4	0.8	1.6	1.8	1.4	0.9	1.2	0.7	1.5	0.8	1.4	0.7
Minimum (DC 14 and 34)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum (DC 14 and 34)	4	4	5	3	5	2	5	5	4	3	3	2	3	2	4	2
sample size	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13	13
t.test significance 1 tail		0.030		0.055		0.318		0.274		0.132		0.010		0.021		0.127
Significant		yes		no		no		no		no		yes		yes		no
Males																
Average (DC 14 and 34)	1.9	2.0	2.1	0.3	0.0	0.0	2.1	1.1	0.9	0.3	1.0	0.3	0.0	0.3	1.0	0.0
Standard Deviation (DC 14 and 34)	1.7	1.0	2.2	0.5	0.0	0.0	1.2	1.3	0.7	0.8	0.8	0.5	0.0	0.5	1.3	0.0
Minimum (DC 14 and 34)	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum (DC 14 and 34)	5	3	5	1	0	0	3	4	2	2	2	1	0	1	3	0
Sample size	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
t.test significance 1 tail		0.432		0.023				0.043		0.086		0.023		0.086		0.043
Significant		no		Yes		no		maybe		no		yes		no		maybe
ALL																
average	1.7	1.15	1.85	0.5	0.4	0.3	2.45	1.9	0.95	0.55	1.25	0.45	0.85	0.4	0.9	0.25
Standard Deviation	1.5252	1.2258	2.207	0.8885	1.1877	0.6569	1.4681	1.7137	1.1459	0.887	1.0699	0.6048	1.3485	0.6806	1.3338	0.5501
Minimum	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Maximum	5	4	5	3	5	2	5	5	4	3	3	2	3	2	4	2
t test significance 1 tail		0.0962		0.0054		0.3147		0.0748		0.0362		0.001		0.0597		0.0221
Significant?		female		males		No		males		Yes		both		s		males
Sample size		20		20		20		20		20		20		20		20

Figure 22: Survey detail. Pre and 8+months post-installation of hood vent.

VI. Discussion and Innovation

Given the prevalence of excessive HAP in over 3 billion homes globally, there is an urgent need for identification of effective interventions that work within the constraints of financial limitations, locally available resources, and cultural nuances. Several other experiments have demonstrated the efficacy of costly interventions (gas stoves, powered chimney systems, etc.), but there was an opportunity to demonstrate the ability to build a functional non-powered ventilation system that did not require major changes in cooking methods or increased daily or financial responsibilities.

Other experiments have attempted to introduce alternative fuel sources ("green energy", propane gas, etc.) as the means for reducing exposure to HAP. We agree that this would be preferable in terms of carbon footprint, however the remote location of our subject population and the abject poverty in which they live make such solutions untenable. There have been previous interventions in neighboring regions that have resulted in installations of gas stoves and alternative cooking appliances that have been abandoned by families because of both economic constraints (can't afford fuel), availability (difficult to bring fuel to site), and cultural preference (different cooking approach).

Relevant cultural observations were documented for future work.

We were able to make several general cultural observations that are relevant for individuals interested in working in remote regions of Central America.

We found that most household members report waking up in the 4 o'clock hour and sleeping at approximately 8 o'clock pm. Household members responsible for meal preparation spend a great deal of time gathering wood and tending to the fire. While reported cooking time ranges from 2-3 hours across most participants, we found that in fact the fire is maintained throughout the day and stoked frequently. We believe that the greatest burden of HAP occurs when the fire is revived at mealtimes. Exposure levels were also highly dependent on the quality of wood gathered for daily fires. Participants noted that "bad wood" burns inefficiently and increases smoke and soot, and they noted worse health symptoms (increased eye irritation, coughing, congestion) when working with this wood.

We found that the majority of households had an average of 4.6 residents with some households including up to 11 members, often of multiple generations. The work among household members was largely seasonal with winter coffee harvest (October-February), thus performing interventions or health assessments during this time was a significant barrier. Our final sample of only 20 participants out of an original 38 enrolled reflects our unfortunate data collection timing (January) and the inability of many participants to miss work to participate in meetings with investigators. Further complicating the collection of data is the remote location of many participants. When assessments were made, some participants had to walk up to 10 miles to participate.

It is possible to build, install, and maintain a low-cost air ventilation system in rural Nicaragua.

We asked whether it was possible to build, install and maintain a low-cost air ventilation system in rural Nicaragua and found that it was, indeed, possible to do so. The hood and chimney design allowed for easy sourcing and reliable construction in Nicaragua even with the added supply chain challenges associated with the Covid-19 pandemic. We were able to design a hood and chimney system that cost approximately $30 in materials and $30 in labor. Laborers required only basic mechanical skills rather than specific capabilities in metalwork or construction. Installation required approximately 2 hours of labor.

A key learning in this process was the importance of working with an established network of community members for deployment. In our case, the Beyond the Light Project (BTLP) had already been established and was vital for countless reasons ranging from community rapport to real-time troubleshooting and ongoing sustainability. The BTLP team is known to the community, and they consequently are able to establish trust and communicate the benefits with community members who may be reluctant to accept change. Such a network also understands the needs of the community and potential barriers to adoption. The local network was also able to help navigate logistical challenges associated with the remoteness of our mountain community. For example, they were able to arrange for transport of our units via burro to some of the more remote homes, and they were also able to facilitate the arrival of participants to centralized locations where health assessments occurred.

Hood and chimney ventilation is accepted by and utilized by participant households.

We found that in a resource-limited setting where individuals lack basic necessities, individuals prioritize needs such as electricity, light, and ability to charge cellular phones over air quality. This appears to be true even where individuals understand that poor air quality can impact health. In our initial intervention (solar vent), we found that individuals felt better (fewer headaches, less congestion, breathing problems), but they still declined to use solar-powered ventilation systems if it came at the cost of losing light or the ability to power other devices. We found upon return visits that households were frequently charging cell phones, using usb-powered radios, and using lights powered by solar devices. They were very happy and requested increase capacity of the solar systems, but not for the purpose of achieving cleaner air.

When we switched to the system that did not require such a trade-off, we found high levels of acceptance and utilization. We found that word spread about the chimney systems and, to date, approximately 50 households from a neighboring community have requested installation of the hood and chimney system. We conclude that systems are most readily adopted by the community when human factors (ongoing maintenance, manual powering-on etc.) are removed and local preferences and continuous feedback are received from the community.

Air quality was directionally improved after installation of the ventilation units.

We demonstrated a novel approach to field-measurement of environmental air quality through the use of basic coffee filter paper and a free web application. While this has not yet been calibrated to a quantified reduction in particulate matter or other pollutants, we are confident that we have made a meaningful improvement in exposures based on physical observation (soot, filter paper results) and ECO levels of participants. Further development of this tool to calibrate reflectance to actual exposure levels will allow field technicians to gather vital environmental data without risking thousands of dollars in equipment in an unsecured setting.

The overall health of families appears be positively impacted by the hood and chimney system, but more work is needed to demonstrate positive long-term health outcomes.

Hood and chimney systems had a significant impact on several health factors. As was outlined above in our discussion of current data on interventions to reduce HAP in the developing world, our experiment similarly found it easier to demonstrate an improvement in qualitative health complaints (less coughing, eye irritation, fatigue, etc.) rather than vital signs or other objective measurements of health status. Our experiment demonstrated that even a basic ventilation system could achieve significant improvement in these health factors.

Quantitatively, we did not find a meaningful impact on vitals such as blood pressure, but we know from other experiments that measurable findings have required years to demonstrate measurable effects on vital signs. We agree there would be some utility to incorporating longitudinal assessment of vitals along with some measurement of lung function such as spirometry, however this would require additional planning and resources given that the test is difficult to duplicate in the field and there was a shortage of adequately trained staff in the area.

We acknowledge that our small sample size and relatively limited period of intervention limit the power of our findings, however we believe they remain a proof of concept—i.e., a low-cost intervention can be implemented to improve health without disrupting cultural norms.

The impact of Covid-19 on the intervention.

The research program was implemented during the height of the Covid-19 pandemic. This created significant barriers, not the least of which was infection of the community with the virus. As Covid-19 creates additional confounding health symptoms (respiratory effects, headaches, fatigue, etc.) in both its acute and chronic stages, it is impossible to surmise to what extent any health symptoms were impacted by acute or chronic Covid infection. The lack of public health resources further complicates matters as we cannot ascertain when/where viral peaks occurred. The pandemic further impacted our experiment as investigators were not able to visit the country with the frequency initially planned and some activities had to be carried out by proxy, other activities including scheduled installations were significantly delayed.

VII. Future Directions

The immediate future direction of this work is to expand installation of hood ventilation within the target community and in nearby areas. There is high demand for the systems and at least 50 households have placed requests for hood systems in a nearby community. This demand reflects the broad acceptance of the intervention and the relevance for Nicaraguans. The gross reduction in HAP on environmental quality and subsequent improved quality of life is highly desired by communities, and our ability to scale our impact rapidly is paramount to the future health of this population.

Other potential areas for future investigation including but not limited to:

Assess confounding variables: Our experiment represented a proof of concept with the goal of assessing whether it was possible to create a low-cost vent system that would be adopted by a local community. A larger population size would allow for a more accurate assessment of the validity of our results. We did not control for confounding variables such as seasonality, work status (unemployed vs actively working), other exposures (workplace exposure to pollution, infection status, etc.), impact of age on results, and a number of other results.

Establishing long-term impact on health: The health complaints included in our survey largely reflected acute conditions (coughing, congestion, fatigue, eye irritation etc.) rather than chronic health conditions (lung disease, cardiovascular disease, vision loss, etc.). Longitudinal evidence of the efficacy of a vent system on reducing chronic health conditions would be another area of continued investigation. This is especially important given that we are not advocating changing fuel source at this time and our intervention does not completely eliminate the presence of HAP.

Streamlining survey tools: As discussed, deployment of an intervention in the developing world requires careful coordination of the investigators and in-country employees and volunteers. Complicated surveys covering a broad range of health indicators are time-consuming and they can be confusing for investigators. There is an opportunity to look more closely at more specific health outcomes (e.g., eye complaints, congestion, infection) and to more effectively communicate health status in a population with barriers such as language and illiteracy. One could incorporate the use of visual indicators of a narrower range of health outcomes to overcome these barriers or incorporate an application or video-chat to enable consistent surveying without requiring excess travel on the part of participants or investigators. This approach would be limited by the availability of good cell-phone bandwidth or Wi-Fi connectivity.

Investigating relevance of ECO as a leading indicator of health status: ECO measurement was easy to replicate and a highly accessible tool for lay people. ECO has been established as a near-term indicator of exposure to air pollution. The may be an opportunity to establish whether serial measurements of ECO can be correlated with longer-term health outcomes.

Calibrating the environmental field assessment tool: As outlined above, there is a need for low-cost field-worthy tools to evaluate air quality. We proposed our novel field tool which incorporated simple filter paper and a cell phone application analysis. We found this useful for gross measurement of filter efficacy, but there is an opportunity to calibrate this to quantified PM levels. Such an experiment might leverage placement of the filter paper alongside a calibrated Air Particle Counter and subsequent correlation analysis to link reflectance values to PM2.5 and PM10 levels.

Development of a sustainable adoption strategy: Our long-term goal is to establish widespread adoption of air ventilation systems that do not require the intervention of international investigators. To this end, it would be beneficial to embed a sustainable "social business model" that incorporates installation of the hood ventilation system with local economic development. Our support team through the BTLP lays the foundation for such a social business model, however it remains to be determined how we can offset the cost and maintenance of the systems in a social business model.

VIII. Conclusions

We have established that it is possible to install a simple hood system that is effective in achieving a meaningful relative reduction in air pollutants using simple materials that can be assembled in a resource limited environment for less than $60 in materials and labor.

Our approach did not require changing fuel sources, food preparation techniques, or daily activities and use was therefore sustainable over the study period. We did find that use of solar-type system was less sustainable given that users had to trade off "light for air quality" and they often chose the former. In contrast, development of a system that removes human factors (powering the system on, cleaning it frequently etc.) results in greater success.

We found that using a local team that incorporates members of the community is invaluable to long-term sustainability and trust in the deployed intervention. This approach also has its drawbacks considering that there is a considerable burden of education and ongoing support required to translate changes to new members of the team and this can be more difficult from a distance.

Installation of a system is only part of the solution. A major feature of a successful approach to intervention is a focus on education and continuous reinforcement of knowledge. Families were generally interested in learning about the risks of exposure to household air pollution and they indicated an increased willingness to work to improve their environment by working with the investigation team.

When such an intervention is successfully deployed, we have shown that we can make statistically significant improvements in ECO while reducing multiple health complaints including coughing, headaches, chest tightness, congestion and eye irritation.

IX. Compliance

IRB application was developed in February/March 2020. Review by Texas Christian University's IRB board occurred during April-May 2020. Dr. James Huffman, PhD, Principal Investigator, has completed CITI Responsible Conduct of Research for Health (human subjects compliance training). Dr. James Huffman holds the human subjects protocols and will continue to maintain all data in a secure location for a minimum of 3 years.

A consent form for participants was drafted and included in the IRB. This was required for all participants and included full disclosure of the research goals, investigators, obligations, risks/benefits, and confidentiality along with agreement to release data including photos to the investigators. The form is available at https://tcu.app.box.com/file/628914895147. Participants continued to see their regular primary care providers and were referred to their primary care physicians or other local health resources for primary or emergent healthcare needs.

There was no IACUC requirement.

X. References

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Appendix 1: Survey

Complete 1 per household / ***Cumple 1 por hogar***

Household / **Familia:** ______________________________

	You ***Usted***	Member 1 ***Hab #1***	Member 2 ***Hab #2***	Member 3 ***Hab #3***	Member 4 ***Hab #4***
List household members and ages ***Apunta los nombres de todos los habitantes de la casa y sus edades*** — Age/ ***Edad***	______	______	______	______	______
		*Check if yes / **Marca si es afirmativo***			
1. Have you or a member of your household had difficulty breathing in the last year? ***Ha presentado Ud. u otro miembro del hogar un problema respiratorio en al último año?***	Sí	Sí	Sí	Sí	Sí
If yes, answer the following questions / ***Si contesto que si, cumple los siguientes preguntas***					
What type of problem? / **Que tipo de problema?**	______	______	______	______	______
How long have they had this problem? / ***Cuanto tiempo ha tenido este problema?***	______	______	______	______	______
		*Check if yes / **Marca si es afirmativo***			
2. Have you or a member of your household visited a clinic/medical provider for breathing difficulty this year? ***Ha Ud. u otro miembro del hogar ha visitado algún centro de salud o medico por los problemas este año?***	Sí	Sí	Sí	Sí	Sí
If yes, answer the following question / ***Si contesto que si, cumple la siguiente pregunta***					
How many times? / ***Cuentas veces?***	______	______	______	______	______
		*Check if yes / **Marca si es afirmativo***			
3. Are you or a member of your household taking any medications to help with the breathing problems? ***Ud. u otro miembro del hogar esta tomando algún medicamento para los problemas respiratorios?***	Sí	Sí	Sí	Sí	Sí
What medication(s)? ***Cual(es) medicamento(s)?***	______	______	______	______	______
		*Check if yes / **Marca si es afirmativo***			
4. Do you or someone in your household have a history of smoking? ***¿ Ud. u otro miembro del hogar ha fumado?*** — Never ***Nunca***	Sí	Sí	Sí	Sí	Sí
Past ***Pasado***	Sí	Sí	Sí	Sí	Sí
Present ***Presente***	Sí	Sí	Sí	Sí	Sí

Complete 1 per family member / ***Cumple 1 por cada persona***

Household / ***Familia:*** ________________________________

Household Member/ ***Miembro del hogar:*** _______________

Respondant/ ***Quien Responde:*** _________________________

Hours in kitchen per day/ ***Cuanto tiempo permanece en la cocina por día?***	< 1 hour ***Menos de 1 hora***	1-2 hours ***1-2 horas***	3-5 hours ***3-5 horas***	6 or more hours ***6 horas o mas***
	☐	☐	☐	☐

5. How often do you experience the following problems?
Que tan seguido ha presentado los siguientes problemas?

Never/***Nunca*** → Always/***Siempre***

	Yearly or less ***Uno vez por año o menor***	Several times per year ***Varias veces por año***	Monthly ***Una vez por mes***	Weekly ***Una vez por semana***	Daily ***Cada día***	>1/day ***Mas que una vez por día***
Dry, Itchy or Watery Eyes ***Resequedad en los ojos, picazón, u ojos llorosos***	0	1	2	3	4	5
Vision Problems ***Problemas de visión***	0	1	2	3	4	5
Difficulty breathing ***Dificultad al respirar***	0	1	2	3	4	5
Headaches ***Dolor de cabeza***	0	1	2	3	4	5
Stuffy nose ***Congestión nasal o resfriado***	0	1	2	3	4	5
Coughing ***Tos***	0	1	2	3	4	5
Chest Tightness ***El pecho apretado***	0	1	2	3	4	5
Exhaustion / Difficulty performing daily activities ***Cansancio/ Dificultad con las actividades cotidianitas***	0	1	2	3	4	5

Physical Exam

Blood Pressure
Presion Sanguinea _____S
_____D

Oximetry _____%
Oximetro de pulso

Pulse _____
Pulso

Exhaled CO _____
Monoxido de Carbon (espirado)