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The thermodynamics of indoor air pollution: A pilot study emulating traditional Kenyan homesteads

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ABSTRACT

This study examined the addition of natural ventilation (i.e., windows) in traditional Kenyan homesteads and other similar dwellings in developing countries. There is a particular need for the reduction of indoor air pollution in Kenya and other countries where traditional cooking relies on unrefined biomass fuels. For the purposes of this study, a cardboard tower equipped with thermocouples and an 80-watt heat source was constructed. As the recreation of smoke was deemed unfeasible, temperature differentials were measured within the tower and examined how varying temperature conditions might contribute to the accumulation of smoke indoors. Two scenarios were tested: windows-open and windows-closed. In the windows-open scenario, decreased temperature differentials were consistently observed throughout the sampling process with an average of 4.8 °C less than with the windows-closed ($p = < 0.0001$). As existing research on smoke movement and temperature demonstrates, a decreased temperature differential will contribute to smoke stratification and an increased exposure to indoor air pollution. This study suggests that additional natural ventilation in isolation does not necessarily improve indoor air quality among households that use traditional cooking practices similar to Kenya's. Rather, alternative interventions should be designed, including the placement of an exterior stove that is shielded from the elements but accessible to those indoors.

1. Introduction

1.1. Indoor pollution in developing nations

While the worldwide annual death toll of indoor air pollution is estimated to be at 3.1 million premature deaths per year, this burden is disproportionately borne by developing nations (World Health Organization, 2019). This excessive rate is likely due to the wide reliance on biomass fuel (i.e., organic material such as crop residue, wood, or dung) to heat homes or prepare food in rapidly developing countries (Sidhu, Ravindra, Mor, & John, 2017). Biomass fuels have a low combustion efficiency that results in high levels of smoke and incomplete combustion, e.g., the production of charcoal from wet wood (Jafta, Jeena, Barregard, & Naidoo, 2019). The burning of cow dung alone produces four times the pollutants as a liquid petroleum gas (Sidhu et al., 2017). This process produces pollution that includes fine particulate matter (e.g., PM2.5), carbon monoxide (CO), hydrocarbons, free radicals, etc. (Fullerton, Bruce, & Gordon, 2008; Smith, 2002), all of which have been linked to respiratory diseases, lung cancer, cardiovascular disease (CVD), asthma, and adverse pregnancy outcomes. The reliance on biomass fuels for cooking and the low efficiency of biomass fuels create a situation in which vulnerable populations (i.e., women and young children, who are typically tasked with food preparation or nearby) are frequently exposed to dangerous levels of indoor air pollution (Bruce, Perez-Padilla, & Albalak, 2000). Countries in sub-Saharan Africa, such as Kenya, experience high rates of under-five mortality that is likely associated with this phenomenon (Owili, Muga, Pan, & Kuo, 2017). Kenyan cooking is almost totally reliant on biomass (Okoko, Wymann von Dach, Reinhard, Kiteme, & Owuor, 2018). Given the high mortality and poverty rates of Kenya (UNICEF, 2019), there is a desperate need to find low-cost and energy-efficient interventions that will promote resilience among traditional Kenyan homesteads.

Research on creating sustainable solutions such as those needed here has found that the most effective interventions are tailored to the

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specific needs of each community (Department of Economic and Social Affairs of the United States Secretariat (DESA) (2019)). Understanding cultural needs and economic pressures is critical to avoid ineffective "one size fits all" solutions (Pattanayak & Pfaff, 2009). This quandary can be witnessed in the interventions that have been previously proposed in Kenya, which include different fuel sources, cooking stove designs, and the addition of chimneys (Nyambura, 2019; Osiolo & Kimuyu, 2017; Owili et al., 2017). Each of these have experienced mixed-to-moderate success but several complicating factors have hindered full implementation. For example, the movement to dry wood-burning from dung-burning continued to produce excess air pollution and has led to severe deforestation in Kenya (Osiolo & Kimuyu, 2017). Other interventions, such as the addition of chimneys (Osiolo & Kimuyu, 2017), have required high levels of outside funding and have failed to entirely eliminate exposures to smoke and hazardous incomplete combustion byproducts (Fullerton, Bruce, & Gordon, 2008; Islam, 2018). Proposed improvements to the stove itself are of limited feasibility due to the expense of implementation and resistance to changing traditional cooking methods (Owili et al., 2017). One project found that the installation of improved biomass cookstoves in Kenyan homesteads did reduce the measurements of PM2.5 and CO, but exposure levels remained substantially above WHO air quality guidelines (Yip et al., 2017). Perhaps most importantly, none of these projects have addressed the need for sustainable, culturally-respectful, and environmentally-friendly interventions.

1.2. Kenyan homestead design

Traditional homesteads in rural Kenya are constructed with mud walls, brushwood, or other organic material that offers limited ventilation (CDC, 2013; Dowsing, 2016). Cooking is usually conducted in a hut specialized to this purpose, which may or may not contain one small window used primarily to admit natural light. See Fig. 1 for a photograph of traditional Kenyan cooking hut. The only ventilation present in this hut comes from the door, the potential window, and the gap between walls and roof (Hewitt, 2019). This design traps smoke from the traditional Kenyan cookstove (i.e., a 3-stone fire pit which contains biomass fuel) (CDC, 2013; Dowsing, 2016). The lack of ventilation and the nature of the fuel burned with these cookstoves have led to exposure to air pollution concentrations that are between 20–100 times higher than the levels recommended by the World Health Organization (WHO) (Olopade et al., 2017). Women, who are the primary cooks and are often accompanied by small children, may spend up to three to seven hours a day inside these structures (Islam, 2018).

Fig. 1. A photograph of a traditional Kenyan cooking homestead.

1.3. Ventilation interventions and challenges

It is well understood that poor ventilation is a significant contributor to indoor air pollution (Fullerton et al., 2008a), and other interventions, such as improved cookstoves, require updated ventilation in order to make a positive difference (Engineering for Change, 2019). Murray et al. (2012) found that appropriate household ventilation in Bangladeshi homes contributed to lower rates of acute respiratory illness among children (Whelan, 2015). However, ventilation is an infrequent focus of interventions, perhaps in part because it may require substantial alterations to the dwelling itself (Engineering for Change, 2019). Additionally, window placement and the ability to harness wind patterns are of key importance in creating effective natural ventilation (Murray et al., 2012). Other factors such as pressure difference and the properties of the particles ensure that the mere addition of windows is not sufficient to counter indoor air pollution (Park, Jee, & Jeong, 2014). The fact that biomass fuels produce excessive levels of smoke presents another challenge for ventilation-based interventions. Studies examining cigarette smoke (which produces PM 2.5 and other byproducts like those of biomass burning) found that a passive ventilation design in itself was not sufficient to move smoke out of the breathing zone (Kolokotroni et al., 1999; Ma & Sun, 2016).

To properly assess the impact of ventilation interventions, it is important to understand the physical and chemical properties of smoke and other byproduct gases. Air, including that which contains smoke particles, expand (becoming less dense) as it is heated and contracts (becoming more dense) as it is cooled. The less dense, hot air, is more buoyant, which in turn "floats" above cooler air (*Why does hot air rise?*, 2013). Buoyancy is the interaction of objects of differing densities and it strongly governs the movement of smoke (Vaux & Pretrel, 2013). Fire creates a characteristically buoyant smoke plume because of the greater temperature when compared to the surrounding air (Kolokotroni et al., 1999). As smoke is cooled, it becomes denser and loses its buoyancy force, causing smoke and gases to linger closer to the ground. This concept is called "smoke stratification," where smoke and gases cease upward movement due to a loss in buoyancy. The potential for stratification is dependent on the temperature differentials within the confined space (Botha, 2014). Consequently, with low temperature differentials inside a confined space (e.g., Kenyan cooking huts), smoke can linger in the "breathing zone" of an enclosed space.

1.4. Study objectives

The purpose of understanding the relationship between adding natural ventilation and the resulting temperature differentials is to evaluate the influence that window ventilation has on the concentration of smoke and hazardous byproducts in traditional homesteads. This study hypothesizes that adding windows to a traditional Kenyan homestead would not improve the concentration and exposures to the smoke and other gaseous byproducts from traditional cookstoves.

2. Methods

2.1. Study design

This study was designed to assess the ventilation efficiency of windows inside a simulation of the unique architecture of a traditional Kenyan homestead used for cooking. To simulate the heat and air movement inside a typical Kenyan homesteads, a temperature tower was constructed to mimic the homestead's enclosed structure. The tower was equipped with a consistent heating source and a series of thermocouple temperature probes to assess changes in the vertical air temperature profile due to ventilation openings.

2.2. Tower construction

Issues of size, expense, and available materials meant that it was not feasible to build a recreation of a Kenyan homestead. In lieu of a recreation, the decision was made to create a temperature tower that would permit temperature measurement inside the structure. The design of the tower was based on convenience considerations for ease of movability, testing, and heat source placement. Cardboard was the material of choice to construct the tower, due to the affordable nature of the materials and the ease of manipulation. The tower was built to a height of 154 cm, with an 18 cm-wide square base. Originally, the tower was intended to use a candle for a heat source, so ventilation slits were placed at the base of the tower to facilitate free convection. Thermocouple temperature probes placed at 31 cm, 69 cm, 104 cm, and 140 cm. inside the temperature tower provided data describing the changes in the adiabatic lapse rate. Two ventilation openings meant to approximate windows (and hereafter referred to as windows) were created by adding rectangular openings directly across from each other. The windows were 10 cm × 5 cm in size, and were placed at a height of 23 cm from the base of the tower.

Visual portals were cut and covered with plastic to allow researchers to see inside the tower. See Fig. 2 for a visual schematic and photograph of the temperature tower. These windows were engineered to open and close in order to test both ventilation scenarios. Initially, the tower roof was designed to open and close as well, but due to issues of implementing roof-open conditions in actual Kenyan homesteads, it was determined that the most effective method of testing would be with the tower roof closed.

2.3. Study location

All data was collected at Boise State University in Boise, Idaho in Dr. Uwe Reischl's Ergonomics lab located in the Health Science Riverside building. The experimentation was performed indoors to control for ambient temperature and atmospheric conditions that might produce artificially effective ventilation.

2.4. Preliminary experimentation

Initially the researchers assumed that, as the focus of the study was minimizing smoke exposure, it would be best to attempt to recreate smoke within the tower. Two portals were cut in the tower and covered with plastic to allow for visualization of smoke opacity. The first attempts to create measurable smoke was with incense, but this failed to produce sufficient smoke generation for visualization of changes. Following that, dried sage was utilized, but this too failed due to the variability of smoke produced as well as the short amount of time that the sage would burn without additional fuel. Finally, emergency smoke generators were placed inside the tower, but these conversely produced too much smoke and overwhelmed the system. Following these three attempts, a decision was made to shift focus away from the more subjective measurements of smoke opacity to measuring temperature differentials within the tower. To determine whether natural ventilation changed the vertical temperature profile within the tower, temperature differentials were collected for both windows-open and windows-closed scenarios and compared to each other.

Fig. 3. Incandescent bulb placed in tower. Note surrounding slits that facilitate free convection.

2.5. Temperature differential

To measure temperature differentials, an 80-watt heat source (i.e., an incandescent lightbulb) was placed in close proximity to the floor of the tower to create controlled thermal convection conditions. See Fig. 3 for an image of the heat source.

The incandescent lightbulb heat source was connected via a power strip and variable transformer. The variable transformer, which helps interconnect the systems, was necessary because the lightbulb and the power supply operate at different voltages. The variable transformer was connected to a watt monitor (via the power strip) that measured the electrical power of a circuit in watts.

The tower thermocouples were connected to four separate Traceable Thermometers (Fisher Scientific, Waltham, Massachusetts). A thermocouple, also connected to a "K" thermometer (Fisher Scientific, Waltham, Massachusetts) was also used to measure the ambient temperature.

2.6. Quality control

To ensure quality control, testing was conducted to determine the appropriate amount of time for the tower to equalize prior to sampling.

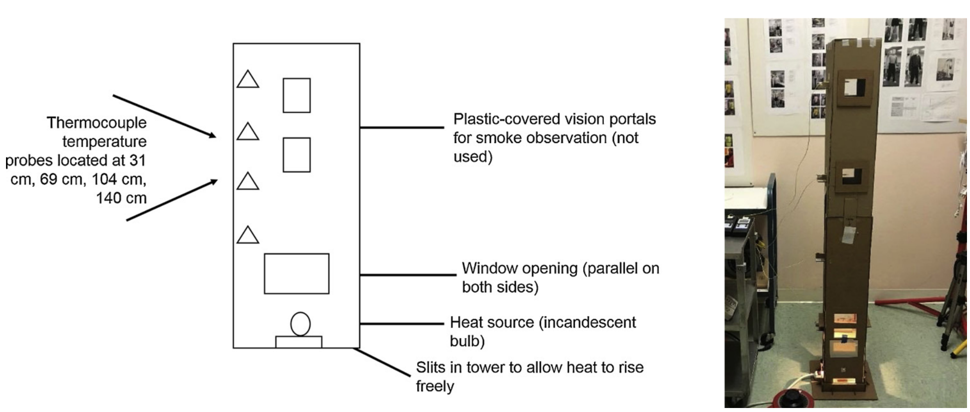

Fig. 2. Temperature tower schematic and photograph of tower.

The variable transformer was first set so that the watt meter read 80 W. The heat source was activated and the tower left for 5 min prior to initial measurements. However, as this period of time was not sufficient to generate temperature differentials, the equalization time was increased to 10 min. This length of time was found to be acceptable, so this control was performed prior to each sampling period.

2.7. Data collection

Data collection occurred from May 2018 to March 2019. Two different ventilation scenarios, windows-closed and windows-open, were evaluated. Prior to turning on the heat source and manipulating the ventilation windows, a control sample was taken to ensure the correct operation of the thermocouples. Ambient temperature was also measured throughout the sampling period to ensure that it remained stable.

The first ventilation scenario evaluated was the windows-closed environment. Once the temperature tower had equalized, the thermocouple temperature readings were recorded in three-second intervals. A total of 25 samples per thermocouple location (100 in total) were recorded over the course of the sampling period.

The system was reset before a change in sampling scenario. To evaluate the second ventilation scenario (windows-open), the ventilation window was then opened and the tower was left to equalize for another ten minutes. Again, once the temperature tower had equalized, the thermocouple temperatures readings were recorded in three-second intervals. Just as with the windows-closed scenario, a total of 25 samples per thermocouple location (100 total) were recorded. See Fig. 4 for a flow chart of the sampling process.

2.8. Statistical analysis

The temperature differential was calculated based on the difference between thermocouple one (at 31 cm) and thermocouple four (at 140 cm). To test the temperature differential data for normality, a Shapiro-Wilk test was conducted in SAS (SAS Institute, Cary, North Carolina) with a W statistic of 0.986 and a $Pr < W = 0.973$. The data were found to be normally distributed and then analyzed with a paired sample *t*-test in Stata Software (StataCorp, College Station, TX). The dependent variable was temperature, measured at two different times (windows-open versus windows-closed). The analysis assessed whether those differences were different from zero.

3. Results

3.1. Temperature differentials

Averaged temperature differentials in windows-closed scenarios were found to be greater between every thermocouple location than in windows-open scenarios. See Tables 1 and 2 for a summary of the temperature differences between thermocouple locations in both ventilation scenarios.

See Fig. 5 for a box plot of temperature averages per thermocouple location.

On average, the temperature differential between thermocouple one (31 cm) and thermocouple four (140 cm) was only 5.0 °C during the windows-open scenario. Conversely, during the windows-closed scenarios, the temperature differential between the two thermocouples rose to 9.8 °C. Between the two scenarios, an average difference of 4.8 °C of decreased temperature differential was observed. The two scenarios, windows-open and windows-closed, differed significantly from each other ($p = < .0001$).

Table 1
Averaged temperature differences between thermocouple locations in windows-closed scenarios.

Windows-closed scenario	
Average difference from Thermocouple 1 (31 cm)	
Thermocouple 2 (69 cm)	5.1 °C
Thermocouple 3 (104 cm)	8.3 °C
Thermocouple 4 (140 cm)	9.8 °C

Table 2
Averaged temperature differences between thermocouple locations in windows-open scenarios.

Windows-open scenario	
Average difference from Thermocouple 1 (31 cm)	
Thermocouple 2 (69 cm)	2.3 °C
Thermocouple 3 (104 cm)	4.0 °C
Thermocouple 4 (140 cm)	5.0 °C

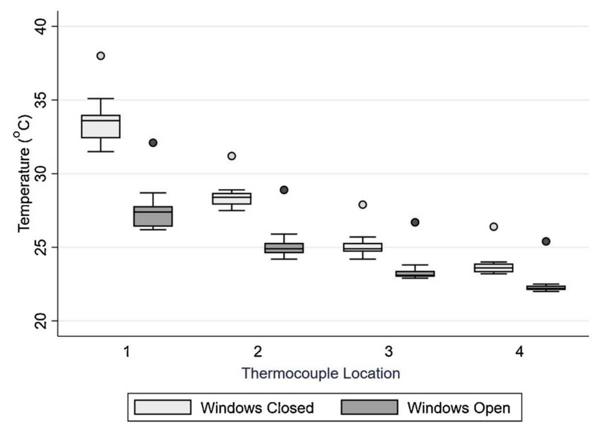

Fig. 5. A box plot of temperature averages per thermocouple location.

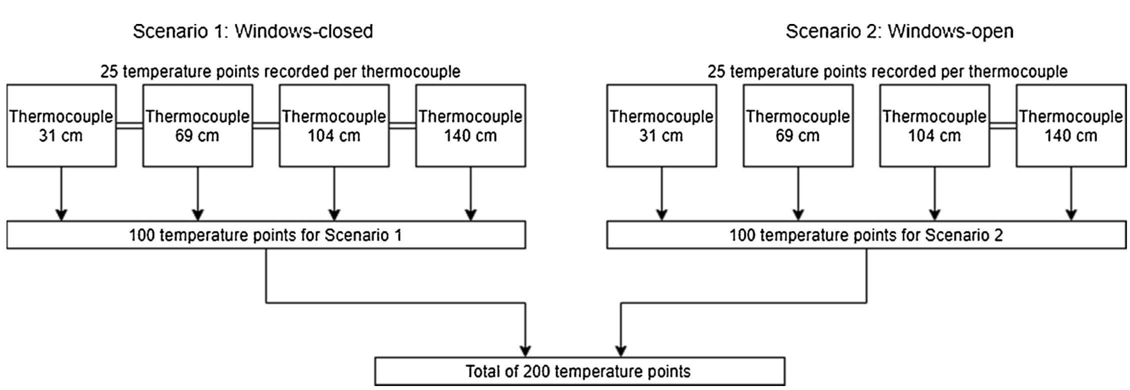

Fig. 4. Flow chart depicting sampling process and total numbers of samples taken for each scenario.

4. Discussion

4.1. Key findings

In the windows-open scenario, decreased temperature differentials were consistently observed between all thermocouple locations, while windows-closed scenario produced greater temperature differences between all thermocouple locations. The greatest differences (5 °C and 9.8 °C, respectively) were observed between thermocouple one (31 cm) and thermocouple four (140 cm). Closed windows indicated a temperature differential that would allow for greater smoke movement out of the breathable zone of the homestead. Although neither scenario demonstrated conditions that would be effective for smoke dispersal, the findings indicate that, in general, the addition of natural ventilation via windows in traditional Kenyan homesteads is not likely to improve smoke concentration for inhabitants.

4.2. Relationship to current literature

The findings of this study suggest that interventions beyond simple ventilation are needed to produce a sustainable impact on Kenyan indoor air pollution. They are in agreement with existing literature that emphasizes the importance of temperature and its relationship to smoke movement. The "draw effect" states that a greater temperature differential creates a more efficient movement of smoke, which is why the simple addition of windows does not create conditions favorable to reducing smoke concentration in Kenyan homesteads (Ma & Sun, 2016). These results are not applicable to all climates, but are so in Kenya, where ambient temperatures remain temperate year-round. A lesser temperature differential leads to smoke stratification, or smoke that, due to the loss of density and buoyancy, becomes a static layer in the air (*Why does hot air rise?*, 2013). Although there has been a multitude of studies related to traditional cooking practices and the associated exposures, this experimentation with natural ventilation (i.e. windows) is novel.

4.3. Confounding factors

The creation of the tower as a mode of simulating indoor cooking in rural Kenyan homesteads allowed the researchers to examine the efficiency of windows without markedly affecting actual households. Some confounding factors, including wind and temperature, were addressed by conducting the experiment under controlled laboratory conditions. Other potential confounders, such as those due to ventilation flows, were more difficult to control but remained constant throughout the entirety of sampling. The lab was under constant negative pressure, with the door to the lab open at all times.

Ideally, this study could have been performed in the Kenyan environment to better recreate the ambient weather conditions. Kenya's humidity levels range from high levels in coastal environments to low levels in arid, hot desert areas (Trading Economics, 2019). The impact of greater humidity levels on indoor air pollution has been extensively investigated. It could be argued that the increased number of water droplets from high humidity conditions could change the kinetics of the smoke. In other words, the droplets likely would create a nesting area for small particles to agglomerate, thus increasing the settling velocity as well as further stratifying the smoke layers. This can be seen in the concentration of smoke in Kenya's enclosed kitchen huts (Zona et al., 2015). An interesting follow- up study could involve the use of Stokes' law and wet deposition enhancements in highly humid environments. While performing the experiment indoors meant these variables could not be controlled for, it allowed the researchers to simplify the design of the study.

Another possible limitation of this study is that a cardboard tower cannot be analogous to the architecture of a traditional Kenyan homestead. This difficulty in reproducing conditions in typical Kenyan kitchens extended throughout the study process. Although this study's results are suggestive of how temperature differential conditions might affect smoke dispersal, there was difficulty in being able to create adequate smoke movement. Ideally, reproducible smoke would be utilized to identify in real time the movement of smoke. However, as the only available means of assessing smoke was a subjective measurement of smoke opacity, it was decided to focus on temperature differentials instead.

4.4. Potential and follow-on research

Future research could experiment with means of reproducing cookstove smoke, either via an actual biomass stove or by other means. One possible means of more accurately quantifying smoke dispersal would be through the use of lasers. Alternatively, future research might consider the use of computer simulation, which is an increasingly common technique among the fields of fire safety.

This study served as preliminary data for an innovative architectural design that could achieve effective ventilation without the need for expensive interventions. Dr. Uwe Reischl designed a prototype kitchen that implemented an external, but still protected and accessible, stove that encourages smoke to exit with little to no movement into the interior of the kitchen. This intervention should not create a financial hardship because kitchens can be retrofitted at minimal cost to the families (Reischl, Haggerty, & Salinas, 2019). See Fig. 6 for a visual schematic of Dr. Reischl's kitchen design. This, as well as other low-cost and environmentally-friendly solutions, would take advantage of this understanding of when natural ventilation alone does not sufficiently create conditions favorable to smoke dispersal.

5. Conclusion

Indoor air pollution is a significant health hazard for millions of people. In developing countries where traditional cooking practices are used (e.g., biomass fuels and 3-stone cookstoves, as in Kenya), exposure to smoke and other toxic byproducts is especially high. Much research has focused on how to reduce these exposures, including different fuel sources, stove designs, and the addition of chimneys, but few studies

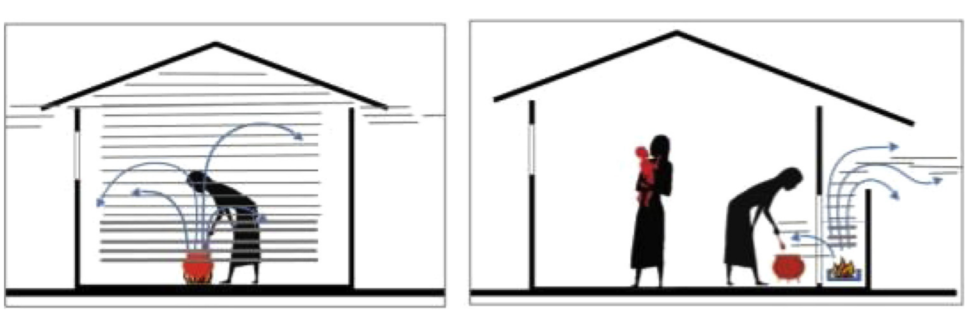

Fig. 6. A visual of Dr. Uwe Reischl's prototype kitchen, designed using the preliminary data from this study (Reischl et al., 2019).

have evaluated the thermodynamics of additional ventilation via windows.

This study suggests how the addition of windows to a Kenyan homestead does not create conditions favorable to reducing indoor air pollution. Windows decreased the temperature differential within the tower and cooled the smoke, which inhibited upward convection (buoyancy). Cooled smoke becomes stagnant and lingers inside the kitchen and breathing zone. Natural ventilation (i.e., windows), if not strategically placed, can exacerbate these tendencies and lead to greater concentrations of hazardous smoke and other pollutants. These findings suggest that alternative interventions, such as the use of an exterior stove, offer a more promising direction of study.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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