# Performance Comparison and Indoor Air Quality Exposure Assessment of Fan-Powered Stove versus Charcoal-Fueled Stoves

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## Abstract

The Philippines still has struggled in energy distribution throughout the country that nearly 35% of Filipino households still make use of charcoal as their fuel for cooking especially in rural areas. Using the traditional way of cooking leads to some serious health problems as charcoal is not burned efficiently leading to produce harmful contaminants that affect the indoor air quality (IAQ). This is the reason why Chen et al. (2015) made a study about designing and fabricating three improved charcoal-fueled stoves that were efficient and produce lesser harmful contaminants than the traditional stove. These stoves have undergone testing to check their efficiency and performance by using the water boiling test (WBT) provided by the Global Alliance for Clean Cook Stoves. For this reason, it became the research interest of the authors to design and fabricate a fan-powered stove and compare its IAQ exposure and performance to the charcoal-fueled stove developed by Chen et al. Major contaminants which are carbon dioxide (CO2), carbon monoxide (CO), and particulate matter (PM), were recorded in the IAQ assessment, while other IAQ criteria, which are temperature, relative humidity, fuel consumption, firepower and thermal efficiency were also measured and evaluated in the study. Based on the results of the water boiling test, the fan-powered stove developed by the researchers was much better than the charcoal-fueled stove in terms of performance except on the firepower. Furthermore, the fan-powered stove was efficient enough to lower the parameters within standards except for the Particulate Matter (PM).

## Keywords
Indoor air quality, carbon monoxide, carbon dioxide, particulate matter, fan-powered cookstove

## 1. Introduction
According to Lawrence Berkeley National Laboratory, about three billion people around the world use wood-fired cookstoves to cook their meals because of its low-cost biomass fuels, such as wood or charcoal. However, these common cook stoves are not properly designed and regulated to limit the emission of air pollutants which can affect the indoor air quality (IAQ) in household areas leading to indoor air pollution. Around 25% of black carbon emission in global output comes from traditional cookstoves which is a major factor contributing to indoor air pollution and climate change (Bond et al. 2007; Bond et al. 2004). These are all produced by inefficient cookstoves with poor combustion of its biomass fuel. Indoor air pollution is produced by biomass fuel such as charcoal which can cause several pulmonary sicknesses (Fullerton et al. 2008). According to the World Health Organization, exposures to this indoor air pollution lead to an estimated 4.3 million people dying every year. This study is part of a series of studies aimed at replicating the methodology used in the previous studies, but with more trials per cookstove.

# 2. Methodology

## 2.1. Design and Fabrication of Cook Stove

The design of the cookstove was replicated by the researchers from the previous study of Chen et al. The Kool Kalan stove (Improved Stove no. 3) modified by Chen et al. was adopted by the researchers to improve its respective designs by performing multiple trials to the existing study. The design of the modified Kool-Kalan stove was sketched using CAD software which served as the basis for fabricating the stove. The design of the charcoal-fueled cookstove involved the use of a 12V DC fan and an 8x8 cm duct located at the front where the fan is placed. Stainless steel was used as the material for the outer casing, grate, and fan duct of the stove. The grate is a perforated plate with a hole diameter of 1 cm to avoid charcoal from falling through the stove. For the firebox, the material used was clay due to its low thermal storage which reduces heat transfer. The design layout of the fan-powered cook stove is shown in Figure 1.

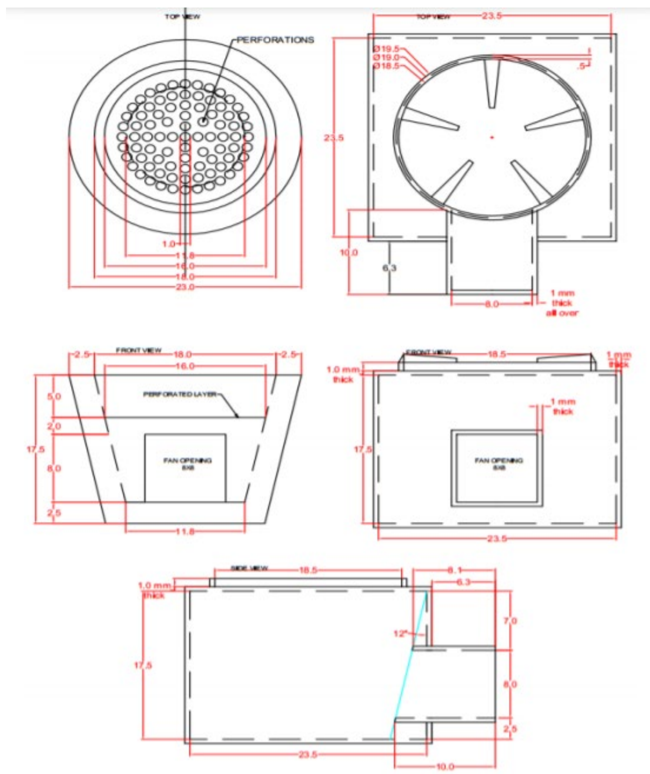


Figure 1. Design layout of fan-powered cook stove

## 2.2. Water Boiling Test

The procedures of the water boiling test (WBT) version 4.2.3 of the Global Alliance for Clean Cook Stoves was the basis to test the efficiency of the fabricated fan-powered cook stove. The WBT has three phases: the cold start, the hot start, and the simmering phase. For the cold start phase, 2.5 liters of water were boiled in which the stove temperature is initially at room temperature. For the hot start, the same amount of water was boiled with the stove temperature initially high. For the simmering phase, the remaining water from the hot start phase was simmered (temperature kept at least 97 °C) for 45 minutes. The measurements (initial conditions) that were taken before each phase were the initial water temperature, the initial weight of pot with the water, the initial weight of charcoal, and the starting time. While the measurements (final conditions) that were taken after each phase were the final water temperature, the weight of pot with remaining water, the final weight of the charcoal, the weight of ash, and the boiling time.

## 2.3. Experimental Set-Up

A modified set-up implemented by the previous research study of Chen et al. was used for the experiment set-up. The selected test area for the evaluation of tracer contaminants and stove performance was the ME foundry room which is located between the south building and canteen of Mapúa University. The test area was still accessible to the equipment and materials for data gathering and analysis. The test area's dimension is 3.75 meters by 6 meters, with its height from the floor to the ceiling approximately 3 meters. The cookstove was placed 195 centimeters away from the door and window. Tiles and rags were placed in between the stove and the table to avoid any damage that can be caused by heat. The IAQ materials for gathering data at the breathing zone level was placed on a table assembly at a height of 1.58 meters. The set of the IAQ equipment was placed 60 cm to the left of the cookstove assembly and one hygrometer was placed separately for the indoor condition.

### 2.4. Assessment and Evaluation of Contaminants

Table 1 shows the Indoor Air Quality Parameters that will be used to compare the performance of fan-powered cookstoves and the equipment that will be used for measurements.

Table 1. IAQ equipment and sampling protocol used

| IAQ Parameter | Equipment used | Equipment Description | Protocol |
|---|---|---|---|
| Carbon dioxide ($CO_2$) | Telaire 7001 | Digital, direct reading, passive | Every 3 minutes, taken at breathing zone and outdoor |
| Carbon monoxide (CO) | Honeywell Gas Detection Tubes | Colorimetric tubes with manual hand pump, passive | After cold and hot start phases, 15 and 45-minute mark of simmering phase, taken at breathing zone |
| Particulate matter, inhalable (PMi) and respirable (PMr) | SKC IOM sampler (25 mm, 0.8 um MCE filter; MultiDust Foam Discs) | Size-selective, Gravimetric, battery operated pump | All phases, time of sampling depends on time of phase or 30 minutes maximum, taken at breathing zone and outdoor |
| Temperature and relative humidity | TFA | Digital, direct reading, passive | Every 1 minute for breathing zone, foundry room,<br><br>Every 3 minutes for outdoor |

In addition, the researchers used the following limits to evaluate the indoor air quality parameters such as limit values and exposure duration adopted from different agencies as shown in Table 2.

Table 2. Limits used to evaluate the indoor air quality parameters

| Parameters | Limit values | Exposure Duration | Agency |
|---|---|---|---|
| $CO_2$ | 5000 ppm | 8-h TWA | ACGIH |
| CO | 90 ppm | 15-min TWA | WHO |
| PMi | 10,000 μg/m$^3$ | Ceiling | ACGIH |
| PMr | 3,000 μg/m$^3$ | Ceiling | ACGIH |

## 3. Results and Discussion

### 3.1.1. Carbon Dioxide Level

The results for the carbon dioxide concentration (ppm) at the breathing zone, room, and outdoor are discussed for each trial. The carbon dioxide concentrations at the breathing zone were recorded every 5 minutes while the carbon dioxide concentrations for the outdoor were recorded after 3 carbon dioxide readings for the breathing zone. For Trial 1, the carbon dioxide levels at the breathing zone during the background phase ranged from 659 ppm to 917 ppm. The carbon dioxide concentrations from the cold start ranged from 1,136 ppm to 1,657 ppm while the hot start ranged from 1,121 ppm to 2,024 ppm. The carbon dioxide concentrations at the simmer phase ranged from 1,239ppm to 1486ppm. The carbon dioxide concentrations at the breathing zone during the cold start increased concerning time. At the simmer phase, the concentration increased first then decreased at the end. For Trial 2, the carbon dioxide levels at the breathing zone during the background phase ranged from 530 ppm to 644 ppm. The carbon dioxide concentrations from the cold start ranged from 720 ppm to 778 ppm while the hot start ranged from 692 ppm to 755 ppm. The carbon dioxide concentrations at the simmer phase ranged from 620ppm to 836ppm. The outdoor carbon dioxide concentrations obtained were quite near to each other ranging from 565 ppm to 692 ppm. For Trial 3, the carbon dioxide levels at the breathing zone during the background phase ranged from 580 ppm to 715 ppm. The carbon dioxide concentrations from the cold start ranged from 704 ppm to 1317 ppm while the hot start ranged from 1143 ppm to 1343 ppm. The carbon dioxide concentrations during the simmer phase range from 932 ppm to 1786 ppm. The outdoor carbon dioxide concentrations obtained were quite near to each other ranging from 551 ppm to 602 ppm. The carbon dioxide concentrations at the breathing zone during the cold start and hot start increased with respect to time. At the simmer phase, the carbon dioxide concentration decreased. The summary of results in shown in Table 3.

Table 3. Statistical summary of carbon dioxide concentrations in the breathing

| Breathing Zone | | | | | | |
|---|---|---|---|---|---|---|
| Trial | Water Boiling Phase | Mean | SD | Min | Max | 8-hr TWA |
| 1 | Background | 816 | 80.87 | 659 | 917 | 623.31 |
| | Cold Start | 1420.4 | 251.23 | 1136 | 1657 | |
| | Hot Start | 1373.333 | 124.91 | 1239 | 1486 | |
| | Simmering | 1873.25 | 292.29 | 825 | 1138 | |
| 2 | Background | 605.21 | 29.57 | 530 | 644 | 628.55 |
| | Cold Start | 746 | 23.605 | 720 | 778 | |
| | Hot Start | 727.8333 | 24.85 | 692 | 755 | |
| | Simmering | 710.4166 | 64.219 | 620 | 836 | |
| 3 | Background | 644.4583 | 38.12 | 580 | 718 | 668.42 |
| | Cold Start | 973.8333 | 234.13 | 704 | 1317 | |
| | Hot Start | 1204.666 | 79.35 | 1143 | 1343 | |
| | Simmering | 1362.666 | 368.77 | 932 | 1818 | |

## 3.2. Carbon Monoxide Level

The carbon monoxide gathered during the water boiling phases for each trial is also obtained in the study. Based on the results as shown in Table 4, there was no carbon monoxide reading throughout the background phase for all trials. It was also observed that the highest average recorded CO concentration was during the hot start phase and decreases on the next water boiling procedure. The CO concentration is lowest at the end of the simmering phase. Comparing the CO concentrations to standard limits, it can be seen that the values fall within the WHO standard (which is 90 ppm).

Table 4. Carbon monoxide levels for each trial during the different WBT phases

| Water Boiling Phase | Trial 1 | Trial 2 | Trial 3 | Average |
|---|---|---|---|---|
| Background | 0 | 0 | 0 | 0 |
| Cold Start | 14 | 22 | 32 | 22.67 |
| Hot Start | 56 | 52 | 73 | 60.33 |
| Simmering (15 min) | 50 | 52 | 62 | 54.67 |
| Simmering (45 min) | 0 | 0 | 14 | 4.67 |

## 3.3. Particulate Matter

Table 5 and Table 6 show the summary of results of particulate matter levels for both inhalable and respirable PM levels.

Table 5. Inhalable particulate matter levels for each trial during different WBT phases

| Water Boiling Phase | Trial 1 (ug/m$^3$) | Trial 2 (ug/m$^3$) | Trial 3 (ug/m$^3$) |
|---|---|---|---|
| Background | 0 | 555.55556 | 55.56 |
| Cold Start | 11904.76 | 10416.667 | 11111.111 |
| Hot Start | 13888.89 | 13703.7037 | 10416.667 |
| Simmering | 1666.67 | 555.55556 | 3333.33 |

Table 6. Respirable particulate matter levels for each trial during the different WBT phases

| Water Boiling Phase | Trial 1 (ug/m$^3$) | Trial 2 (ug/m$^3$) | Trial 3 (ug/m$^3$) |
|---|---|---|---|
| Background | 555.56 | 555.55556 | 0 |
| Cold Start | 8333.33 | 5555.5556 | 5555.5556 |
| Hot Start | 1666.67 | 3703.7037 | 4166.6667 |
| Simmering | 7142.85 | 5555.56 | 5555.5556 |

## 3.4. Air Change Rate

The comparison between the actual and derived CO2 decay in the test area caused by setting a flame the charcoal in the cookstove in the test area were also gathered in the study. The $CO_2$ concentration starts from 4198 ppm and exponentially decaying with respect to time until it stabilizes. The value of 698 ppm was considered as the background concentration. The air change rate (ACR) was obtained every 30 seconds. The ACR is also the ventilation rate in the room.

## 3.5. Stove Performance

The parameters compared were the time to boil, the specific fuel consumption, the thermal efficiency, and the firepower.

### 3.5.1. Boiling Time

Based on the data obtained, the fastest time reached to boil 2.5 L of water recorded was around 5.01 minutes which was done during the hot start phase. The slowest time to boil 2.5 L of water was 8.0 minutes during the cold start. The average time of the three trials to boil 2.5 L of water was at 7.62 minutes while the average boiling time under the previous study for the high powered phase was at 9.0 minutes. The results of water boiling test for three (3) trials are shown on Table 7-9.

Table 7. Water Boiling Testing Results for Trial 1

| Cold Start | | Cold Start | | Hot Start | | Simmer Phase | |
|---|---|---|---|---|---|---|---|
| Calculation Results | Units | Data | Label | Data | Label | Data | Label |
| Fuel consumed (moist) | g | 150 | $f_{cm}$ | 146 | $f_{hm}$ | 41 | $f_{sm}$ |
| Net change in char during test | g | 50 | $\Delta_{cc}$ | 54 | $\Delta_{ch}$ | 43 | $\Delta_{cs}$ |
| Equivalent dry fuel consumed | g | 80 | $f_{cd}$ | 72.80036 | $f_{ht}$ | 79 | $f_{hs}$ |
| Water vaporized from all pots | g | 27 | $w_{cv}$ | 24 | $w_{hv}$ | 256 | $W_{sv}$ |
| Effective mass of water boiled | g | 2473 | $w_{cm}$ | 2476 | $w_{hm}$ | - | |
| Water remaining at end – all pots | g | - | - | - | - | 2220 | $w_{st}$ |
| Time to boil Pot # 1 | min | 7 | $\Delta_{tc}$ | 5 | $\Delta_{th}$ | - | - |
| Time-corrsp time to boil at Pot # 1 | min | 7 | $\Delta_t{}^T{}_c$ | 5 | $\Delta_t{}^T{}_h$ | - | - |
| Time to simmer (45 mins) | min | - | - | - | - | 45 | $\Delta_{ts}$ |
| Thermal efficiency | % | 35 | $h_c$ | 38 | $h_h$ | 30 | $H_s$ |
| Burning rate | g/min | 11.5 | $r_{cb}$ | 14.6 | $r_{hb}$ | 1.7 | $r_{sb}$ |
| Specific fuel consumption | g/L boiled | 32 | $SC_c$ | 29.39845 | $SC_h$ | 35.4 | $SC_s$ |
| Temp-corrsp consumption | g/L | 32.8945 | $SC^T{}_c$ | 30.03929 | $SC^T{}_h$ | - | - |
| Temp-corrsp energy consumption | KJ/L | 980 | $SE^T{}_c$ | 985 | $SE^T{}_h$ | - | - |
| Firepower | watts | 5696 | $FP_c$ | 7232 | $FP_h$ | 868 | $FP_s$ |
| Turn down ratio | - | - | - | - | - | 6.56 | TDR |
| Specific energy consumption | KJ/L | - | - | - | - | 10.55 | $SE_s$ |

Table 8. Water Boiling Testing Results for Trial 2

| Cold Start | | Cold Start | | Hot Start | | Simmer Phase | |
|---|---|---|---|---|---|---|---|
| Calculation Results | Units | Data | Label | Data | Label | Data | Label |
| Fuel consumed (moist) | g | 153 | $f_{cm}$ | 138 | $f_{hm}$ | 49 | $f_{sm}$ |
| Net change in char during test | g | 46 | $\Delta_{cc}$ | 62 | $\Delta_{ch}$ | 33 | $\Delta_{cs}$ |
| Equivalent dry fuel consumed | g | 86 | $f_{cd}$ | 57.85239 | $f_{ht}$ | 76 | $f_{hs}$ |
| Water vaporized from all pots | g | 55 | $w_{cv}$ | 66 | $w_{hv}$ | 217 | $W_{sv}$ |
| Effective mass of water boiled | g | 2445 | $w_{cm}$ | 2433 | $w_{hm}$ | - | |
| Water remaining at end – all pots | g | - | - | - | - | 2215 | $w_{st}$ |
| Time to boil Pot # 1 | min | 7 | $\Delta_{tc}$ | 7 | $\Delta_{th}$ | - | - |
| Time-corrsp time to boil at Pot # 1 | min | 7 | $\Delta_t{}^T{}_c$ | 7 | $\Delta_t{}^T{}_h$ | - | - |
| Time to simmer (45 mins) | min | - | - | - | - | 45 | $\Delta_{ts}$ |
| Thermal efficiency | % | 35 | $h_c$ | 53 | $h_h$ | 28 | $H_s$ |
| Burning rate | g/min | 12.3 | $r_{cb}$ | 8.3 | $r_{hb}$ | 1.7 | $r_{sb}$ |
| Specific fuel consumption | g/L boiled | 35 | $SC_c$ | 23.78147 | $SC_h$ | 34.3 | $SC_s$ |
| Temp-corrsp consumption | g/L | 36.052873 | $SC^T{}_c$ | 24.43302 | $SC^T{}_h$ | - | - |
| Temp-corrsp energy consumption | KJ/L | 1074 | $SE^T{}_c$ | 728 | $SE^T{}_h$ | - | - |
| Firepower | watts | 6120 | $FP_c$ | 4105 | $FP_h$ | 838 | $FP_s$ |
| Turn down ratio | - | - | - | - | - | 7.31 | TDR |
| Specific energy consumption | KJ/L | - | - | - | - | 1021 | $SE_s$ |

Table 9. Water Boiling Testing Results for Trial 3

| Cold Start | | Cold Start | | Hot Start | | Simmer Phase | |
|---|---|---|---|---|---|---|---|
| Calculation Results | Units | Data | Label | Data | Label | Data | Label |
| Fuel consumed (moist) | g | 148 | $f_{cm}$ | 144 | $f_{hm}$ | 44 | $f_{sm}$ |
| Net change in char during test | g | 52 | $\Delta_{cc}$ | 56 | $\Delta_{ch}$ | 39 | $\Delta_{cs}$ |
| Equivalent dry fuel consumed | g | 77 | $f_{cd}$ | 68.4405 | $f_{ht}$ | 77 | $f_{hs}$ |
| Water vaporized from all pots | g | 23 | $w_{cv}$ | 13 | $w_{hv}$ | 77 | $W_{sv}$ |
| Effective mass of water boiled | g | 2477 | $w_{cm}$ | 2487 | $w_{hm}$ | - | |
| Water remaining at end – all pots | g | - | - | - | - | 2239 | $w_{st}$ |
| Time to boil Pot # 1 | min | 7 | $\Delta_{tc}$ | 6 | $\Delta_{th}$ | - | - |
| Time-corrsp time to boil at Pot # 1 | min | 7 | $\Delta_t{}^T{}_c$ | 6 | $\Delta_t{}^T{}_h$ | - | - |
| Time to simmer (45 mins) | min | - | - | - | - | 45 | $\Delta_{ts}$ |
| Thermal efficiency | % | 36 | $h_c$ | 39 | $h_h$ | 23 | $H_s$ |
| Burning rate | g/min | 10.9 | $r_{cb}$ | 11.4 | $r_{hb}$ | 1.7 | $r_{sb}$ |
| Specific fuel consumption | g/L boiled | 31 | $SC_c$ | 27.523 | $SC_h$ | 34.5 | $SC_s$ |
| Temp-corrsp consumption | g/L | 31.440015 | $SC^T{}_c$ | 28.2771 | $SC^T{}_h$ | - | - |
| Temp-corrsp energy consumption | KJ/L | 937 | $SE^T{}_c$ | 843 | $SE^T{}_h$ | - | - |
| Firepower | watts | 5431 | $FP_c$ | 5665 | $FP_h$ | 853 | $FP_s$ |
| Turn down ratio | - | - | - | - | - | 6.37 | TDR |
| Specific energy consumption | KJ/L | - | - | - | - | 1028 | $SE_s$ |

### 3.5.2. Specific Fuel Consumption

Overall, the average specific fuel consumption of the stove was 31.51 g/L boiled while the average specific fuel consumption under the previous study was 40.50 g/L boiled. In each of the water boiling phase, the simmering phase has the highest value for specific fuel consumption ranging from 29.398 to 35.4 g/L boiled. In the hot start phase, the values of specific fuel consumption recorded for each trial were the lowest among the three water boiling test phases.

### 3.5.3. Thermal Efficiency

The thermal efficiency recorded in each trial for the cold start and hot start phase ranged from 35% to 53%. While during the hot start phase of all the trials, where the stove has its highest thermal efficiency, its peak value was recorded to be 53%. Overall, the stove average thermal efficiency was about 35% while the average thermal efficiency under the previous study was 29%.

### 3.5.4. Firepower

Overall, the average firepower for the high-powered phase, low-powered phase, and turn-down ratio of the fan-powered stove were 5708.17 W, 853 W, and 6.7433, respectively. While the results under the previous study for the high-powered phase, the low-powered phase, and turn-down ratio were 5949.50 W, 803 W, and 6.51, respectively. The summary of performance of the improved cook stove is shown in Table 10.

Table 10. Summary of performance of the improved cookstove

| Parameters | Cold start | Hot start | Simmer | Average | Chen et al. |
|---|---|---|---|---|---|
| Time to boil (mins) | 7.28 | 6.36 | n/a | 6.82 | 9.00 |
| Specific fuel consumption (g of fuel/L boiled) | 32.67 | 27.12 | 34.73 | 31.51 | 40.50 |
| Firepower (W) | 5,749 | 5,667.33 | 853 | 5708.17 | 5,949.5 |
| Thermal efficiency (%) | 35.33 | 43.33 | 27.00 | 35.22 | 29 |

3.5.5. IWA Performance Matrices

Table 11 shows the tier for high power thermal efficiency and low power specific consumption per trial and their average. Based on the data gathered, the high power thermal efficiency falls under tier 3 with an average of 39% while the low power specific consumption falls under tier 3 with an average of 0.023MJ/min/L.

Table 11. IWA-11:2012 tiers for efficiency and fuel use

| Tier | High Power Thermal Efficiency (%) | Low Power Specific Consumption (MJ/min/L) |
|---|---|---|
| Tier 0 | < 15 | > 0.050 |
| Tier 1 | ≥ 15 | ≤ 0.050 |
| Tier 2 | ≥ 25 | ≤ 0.039 |
| **Tier 3** | **≥ 35** | **≤ 0.028** |
| Tier 4 | ≥ 45 | ≤ 0.017 |

## 4. Conclusion

The water boiling test results of the fan powered cook stove were much higher than the study of Chen et al. (2015) due to better design and fabrication of the stove. In terms of stove performance, the charcoal-fueled cookstove had less time to boil, lower specific fuel consumption, higher thermal efficiency, high turn-down ratio but lower firepower compared to the results of the previous study. Based on the results of the IAQ assessment, it can be concluded that improving the design of the cookstove can lower the contaminants emitted. However, stove design improvement alone is not enough to lower the contaminants within standards. It was observed that cooking using charcoal-fueled cookstoves slightly affected the temperature and relative humidity at the breathing zone. However, the results obtained for the indoor temperature and relative humidity were not within standards which may be due to the heat from cooking.

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