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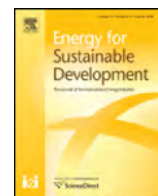
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Performance comparison of charcoal cookstoves for Haiti: Laboratory testing with Water Boiling and Controlled Cooking Tests



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ABSTRACT

Charcoal cooking accounts for a large portion of Haiti's energy usage and leads to severe economic, health, and environmental hardships. Organizations are hoping that fuel-efficient cookstoves can help solve the problem. In this study, four charcoal cookstoves intended for dissemination in Haiti were rigorously assessed and compared using Water Boiling and Controlled Cooking Tests.

Due to the poor thermal efficiency of the traditional stove, all improved stoves saved fuel on average over the traditional with the majority also reducing the total emissions released. However, the traditional stove could be difficult to replace because it had the fastest time-to-boil, an important consideration for end users. Through the testing, the number of trials conducted was found to be an important consideration for error analysis. Also, noticeable differences in stove performance were seen between the two protocols, supporting arguments by prior researchers of the necessity to use multiple test protocols for practically useful comparisons.

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Introduction

Approximately three billion people use biomass as fuel for cooking and heating worldwide, including most of the ten million people of Haiti (IEA, 2004). It is estimated that 70% of Haiti's annual energy use comes from the burning of solid biomass, primarily charcoal and wood (Nexant, Inc., 2010). Besides being a major human health concern, over the years the unsustainable harvesting of biomass has substantially contributed to rampant deforestation; in 1923, 60% of Haiti was forested, but by 2009 only 2% of the country was forested (Nexant, Inc., 2010; Lim et al., 2012). In cities, a marmite, or the amount of charcoal needed to cook roughly half a day's worth of food, costs 20–25 gourdes (roughly 0.50 USD). The gross national income per capita in Haiti is about 700 USD (UNICEF, 2013). Therefore, families spend a significant fraction of their income on cooking fuel. After the devastating earthquake in January 2010, many organizations, including USAID, the Women's Refugee Committee, and the World Food Program, called for a rapid deployment of fuel-efficient cookstoves to ease the physical and economic hardships in Haiti (Nexant, Inc., 2010; WRC, 2010).

However, cookstove distributors have little or no data on the performance of most charcoal cookstoves developed for Haiti. A few studies in peer-reviewed literature include Haitian stoves as part of a larger study (Bentson et al., 2013) but for the most part, studies evaluating cookstoves do not focus on Haitian stoves (Jetter and Kariher, 2009; MacCarty et al., 2010), except in the gray literature (Nexant, Inc., 2010). This leaves agencies seeking to distribute efficient cookstoves without knowledge of the potential impacts of different Haitian stoves.

We report results from two cookstove testing methods, the Water Boiling Test (WBT) and Controlled Cooking Test (CCT), performed on four charcoal cookstoves designed for use in Haiti. This study aimed to obtain baseline data on the performance of the cookstoves in terms of efficiency and emissions in order to inform the design and help selection of improved charcoal stoves for dissemination in Haiti under the post-earthquake emergency conditions. Results of this work were promptly made available to stove manufacturers, distributors, and funding agencies for use in the knowledgeable dissemination of stoves in Haiti.

Experimental system

Cookstoves tested

Cookstoves that were either readily available in Port-au-Prince or being considered for relief-operations distribution in Haiti were

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Fig. 1. Traditional Haitian stove: height: 27 cm; length/width: 11 cm; weight: 2.8 kg.

identified through a field visit by scientists from Lawrence Berkeley National Laboratory (LBNL). Typical traditional charcoal cookstoves were purchased in Port-au-Prince and manufacturers of improved cookstoves were contacted to obtain cookstove units for testing. Based upon their timely availability, the following four stoves were included in both WBT and CCT evaluations.

Traditional Haitian

Haitians typically use simple stoves made locally from scrap sheet metal. These stoves are widely available and have either a square or circular charcoal chamber. The stove tested in this study has a square charcoal chamber with evenly distributed holes along the sides and bottom (Fig. 1). The pot sits directly on the charcoal bed, and ash falls through to a tray underneath which is emptied by turning the stove over.

EcoRecho

The EcoRecho, shown in Fig. 2, is a metal stove with a ceramic liner made in Haiti by D&E Green Enterprises. The pot sits above the charcoal bed on three triangular metal rod supports. A door on the front of the stove can be operated to control airflow and remove ash.

Prakti Rouj

The Prakti Rouj, shown in Fig. 3, is a ceramic-insulated metal stove with a small circular charcoal chamber. The pot sits on raised metal wedges above the charcoal bed and a door on the front of the stove can be adjusted to control airflow. A tray can be removed through the door to empty ash.



Fig. 2. EcoRecho stove: height: 22 cm; diameter: 27.5 cm; weight: 6.2 kg.



Fig. 3. Prakti rouj stove: height: 20.5 cm; diameter: 25.5 cm; weight: 4.6 kg.

Mirak (copy)

The Mirak copy, shown in Fig. 4, is a locally-made, scrap metal stove copied from the Mirak stove designed by the humanitarian agency CARE. It is widely available in Port-au-Prince. The charcoal chamber is hemispherical, and the pot sits directly on the charcoal bed. An opening in the side of the stove allows airflow, but there is no door for airflow control. The charcoal chamber rests on top of the stove body and can be removed to dump out the ashes.

Instructions on using the stoves were not provided by the manufacturers, but several practice tests were conducted with each stove prior to the official tests used for measuring performance. Using the experience gained from these tests, each stove was operated in order to maximize combustion efficiency by adjusting airflow if possible. The cooking pots used for testing were common, traditional Haitian pots purchased in Port-au-Prince, as those would be the same pots used by cooks in the field.

Experimental setup

The test system consisted of a stove platform under an extraction hood which drew gases upward through an aluminum duct (15 cm diameter) using two blowers, shown in Fig. 5. Prior to reaching these blowers, the gases were mixed along a long stretch of duct with stationary fan blades and subsequently sampled for gas analysis. All testing was performed in a well-monitored indoor space at LBNL with initial temperature and humidity data recorded.



Fig. 4. Mirak stove: height: 32 cm; diameter: 30.5 cm; weight: 2.8 kg.

Carbon monoxide (CO) and carbon dioxide (CO₂) concentrations in the exhaust duct were continuously measured (1 Hz) with a California Analytical Instruments 600-series gas analyzer. In addition, the weight of the charcoal added to the stove and the temperature of the food or water were continuously measured and recorded in real time.

Fuel

The fuel for the tests was Grillmark© all-natural lump charcoal, as procuring adequate quantities of Haitian charcoal for all testing activities was impractical. The all-natural lump charcoal is produced in a fashion similar to Haitian charcoal, unlike charcoal briquettes which can have additives such as sand. The rectangular lump charcoal was broken into pieces similar in size to Haitian charcoal (no larger than 8 cm × 5 cm × 2.5 cm). Charcoal samples, analyzed using standard oven-drying procedures, were found to have a moisture content of 5.9%.

Because some of the cookstoves were not designed to accommodate the large initial amount of charcoal used in the traditional stove, the initial amount of charcoal used in each stove was adjusted for the fuel bed size of that stove. The initial amounts of charcoal were: 280 g for the EcoRecho, 450 g for the Mirak, 200 g for the Prakti, and 475 g for the traditional. Additional pieces of charcoal were added as needed to maintain a steady, hot fire. The total fuel consumed was calculated as the total mass of charcoal added minus the mass of charcoal left over at the end of the test.

Experimental protocols

Two separate testing protocols were used for these tests, a Water Boiling Test (WBT) and a Controlled Cooking Test (CCT).

Water Boiling Test protocol

A WBT, as the name implies, is a standard method for evaluating cookstove performance based on boiling water. A modified version of the Shell Foundation Household Energy Project Water Boiling

Test version 3.0 was used to evaluate the stoves (Bailis et al., 2007). It is an internationally known and well-defined protocol that can be used to test and compare any cookstove in the field or in the lab. This allows WBT results from any lab to be compared with those from other labs using other stoves. However, the WBT has the disadvantage of being narrowly defined to a specific task, namely boiling water, which may not be relevant to the actual cooking activities conducted in the field.

As the WBT 3.0 was originally designed for wood-burning stoves, minor modifications were made to accommodate charcoal stoves. These modifications were reported previously in Booker et al. (2011), which is included in the Supplemental Information.

The WBT consists of three phases: cold start, hot start, and simmer. Performance and emissions data were collected for all three test phases. For stoves with a door to control air supply, the door was kept open for the high power tests (cold and hot start phases) and 50–60% open during the low power test (simmer phase).

Controlled Cooking Test protocol

Because of the limitations of WBT results when assessing field performance, we also developed a unique, laboratory-based CCT protocol for testing Haitian charcoal stoves. A CCT mirrors specific, culturally-relevant cooking tasks from the intended region of dissemination, standardizing the cooking tasks into a scientifically valid and repeatable protocol.

The CCT protocol was developed by LBNL researchers based on notes from Haitian cooks, brief cooking trials conducted in Haiti by the LBNL observation team, and consultations with Nexant staff, who had conducted cooking field trials in Haiti (Nexant, Inc., 2010). The protocol was designed to create a standardized procedure for laboratory testing that closely follows the cooking practices in Haiti for the staple Haitian dish of *diri kole ak pwa* (rice with red beans and vegetables). The CCT protocol is divided into three main cooking tasks: Bean phase, Vegetable phase, and Rice phase. These phases are primarily time-controlled tests; however if the food was not cooked to the protocol's definition by the end time for each phase, cooking was continued for additional time as



Fig. 5. The stove testing system at LBNL. The exhaust hood and ductwork is seen on the right-hand portion of the photo; the instrumentation is on the left.

needed. An in-depth description of the CCT protocol was presented by Lask et al. (2011), included in the Supplemental Information.

We chose to use a CCT because this type of test can provide a more accurate portrayal of cookstove performance in the field. However unlike the WBT, a customized CCT protocol must be developed for each cultural cooking style, making it meaningless to use a CCT protocol to compare stoves developed for different cultures; this is where the WBT results are more useful.

Analysis of data

This section presents the background of the data analysis performed for the main areas of the WBTs and CCTs: performance-based metrics (time-to-boil, specific fuel consumption, and thermal efficiency) and emission-based metrics (emissions of carbon monoxide and modified combustion efficiency).

Performance-based metrics

The time-to-boil is the amount of time it takes 2.5 L of water to reach the local boiling point. The time-to-boil in this WBT was recorded from when the charcoal was considered lit until the water started boiling. The charcoal was qualitatively determined to be lit when enough charcoal was burning such that the fire would not die out with the addition of a pot being set on it to heat. Time-to-boil is only presented for the WBT, as the CCT is primarily a time-based test.

Thermal efficiency was calculated for the WBTs as defined in the WBT 3.0 protocol (Bailis et al., 2007).

For both the WBT and CCT, the amount of charcoal required to produce a specific amount of boiled water or cooked food is called the specific fuel consumption. The specific fuel consumption as defined by the WBT 3.0 protocol (Bailis et al., 2007) is calculated as:

$$\text{Specific fuel consumption} = \frac{\text{equivalent dry fuel consumed (g)}}{\text{total weight of product produced (kg)}} \quad (1)$$

where the product produced is boiled water for the WBT and cooked food for the CCT.

The equivalent dry fuel consumed was calculated as follows:

$$F_d = F_m \times (1 - 1.08 \times m). \quad (2)$$

Here, F_d is the equivalent dry fuel consumed, F_m is the actual fuel consumed, and m is the moisture content of the fuel (Booker et al., 2011).

Emission-based metrics

CO and CO₂ concentrations in the duct were measured (1 Hz), recorded, and summed for the entirety of each test with the background CO and CO₂ levels removed. The concentrations were originally recorded in parts per million (ppm) and converted to g/m³. A general equation for the flow rate through the system was developed experimentally and used to convert the integrated concentrations from g/m³ to g.

The emission factor for a given species of emitted pollutant is defined as the grams of that species emitted per kilogram of fuel consumed. This can be used to extrapolate the mass of emissions released for a specific stove solely by knowing the fuel consumption, which is useful in field testing where emissions sampling is difficult. In this study, we examine the CO emission factor, calculated as:

$$EF_{CO} = \frac{\Sigma CO}{F_d}. \quad (3)$$

Similarly, the emission rate for a given species of emitted pollutant is defined as the grams of that species emitted per minute. This can be used to extrapolate the amount of emissions released for a specific

stove solely by knowing the length of the test, which is also useful in field measurements. The CO emission rate with units of grams per minute is calculated as:

$$ER_{CO} = \frac{\Sigma CO}{\text{Length of test}}. \quad (4)$$

Modified combustion efficiency evaluates the amount of CO₂ released from a fire in comparison to the total gaseous carbon emissions. The total gaseous carbon emissions are estimated as the summation of the two major carbon-based combustion products, CO₂ and CO.

$$MCE = \frac{\Sigma CO_2}{\Sigma CO + \Sigma CO_2}. \quad (5)$$

For all metrics, statistical analysis was conducted using Student's t-distribution to look for statistically significant outcomes. When presenting results for each performance metric, error bars represent $\pm 95\%$ confidence intervals calculated using Student's t-distribution. Further explanation of the statistics background of these results is explained by Lask et al. (2011).

Results

We present results using six metrics relevant to efficient cookstove design and dissemination: time-to-boil, specific fuel consumption, thermal efficiency, CO emission factor, CO emission rate, and modified combustion efficiency. From interviews with women in the field, the time-to-boil was found to be extremely important from the user perspective, as women are unlikely to use a stove that lengthens their usual cooking time. Specific fuel consumption indicates if fuel savings occur, which is important to both the users and environmental agencies. Thermal and modified combustion efficiencies are relevant to stove designers, while the emissions data provides information on the release of pollutants to the environment, important information for funding and public health agencies, governments, and policy makers.

Time-to-boil

As can be seen in Fig. 6, for the cold start phase, the traditional stove brought water to boil at least 15 minutes faster than any of the other stoves on average, while the other stoves performed fairly similarly to one another. The amount of time necessary to cook is extremely

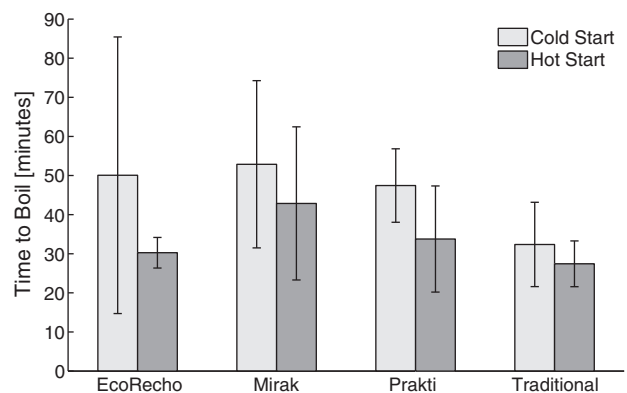


Fig. 6. The time to boil 2.5 L of water, reported in minutes, for both cold and hot starts. For cold starts, the traditional stove was noticeably faster on average than any other stove, but for hot starts, the EcoRecho and Prakti stoves were similar to the traditional one. Error bars represent 95% confidence intervals.

Table 1

The weight of each stove (kg) and the percent difference between their cold and hot start times-to-boil. As the weight increases, so does the percent difference, indicating the importance of even modest differences in thermal mass for stove performance comparisons.

	Weight of stove (kg)	Percent difference (%)
Traditional	2.8	17
Mirak	3.0	21
Prakti	4.6	32
EcoRecho	6.2	50

important to end users per discussions with women and organizations in the field. Therefore, our results indicate a potential barrier to the adoption of these improved cookstoves in the field. For the hot start phase, the traditional stove also had the fastest time-to-boil; however, the EcoRecho and Prakti were only marginally slower than the traditional.

A trend can be noticed in the average times-to-boil for the cold and hot start phases due to the differences in the thermal masses of the stoves. During a hot start, the Prakti and EcoRecho stoves, which are insulated and retain heat, are comparable in time-to-boil with the traditional stove, while during the cold start they take a longer time. The percent difference between the cold and hot start times-to-boil for each stove and their weight are presented in Table 1. For this comparison, weight is held as a proxy for thermal mass; it overestimates the relative thermal mass for the two lighter, all-metal stoves (traditional and Mirak) and underestimates it for the two heavier stoves made of metal and insulation (Prakti and EcoRecho) but this would only increase the resulting trend seen in Table 1. It is seen that as the weight of the stove increases, so does the percent difference between the cold and hot start times-to-boil.

One would expect a large, thermally-massive stove to have a larger difference in times-to-boil between hot and cold starts than a thermally-light stove. However, none of the stoves in this test are considered particularly large and thermally-massive, so the trend shown in Table 1 suggests thermal mass is an important consideration even for small, thermally-light stoves.

Thermal efficiency

The average thermal efficiency results for the three improved stoves were better than that of the traditional stove (Fig. 7). The Prakti and EcoRecho were the most efficient and the traditional and Mirak were the least efficient. In making comparisons between stoves and assessing whether differences between stoves were significant, we found the Prakti and traditional stoves to be significantly different from each other at $p = 0.05$.

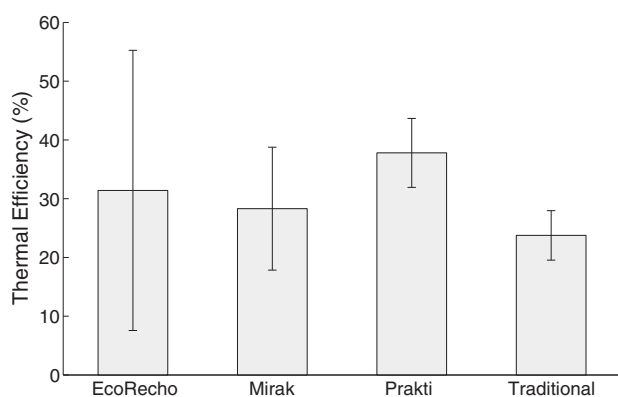


Fig. 7. Average thermal efficiency for the WBTs. All improved stoves had on average a higher thermal efficiency than the traditional one with the Prakti stove having a statistically significantly better thermal efficiency ($p = 0.05$). Error bars represent 95% confidence intervals.

Specific fuel consumption

All improved stoves reduced fuel use compared to the traditional, as seen in Fig. 8, and in the case of the CCTs, improved stoves had a statistically significant ($p = 0.05$) lower specific fuel consumption than the traditional stove.

These results demonstrate that the stoves dubbed to be “fuel-efficient” actually do save fuel under laboratory settings, both in the strict settings of the WBT and the potentially more realistic settings of the CCT. The results lead to the hope that if cooks in the field have correct training and operate stoves optimally, they will save fuel when cooking, an important consideration for deforested Haiti.

CO emission factors and emission rates

The CO emission factor (grams of CO per kilogram of equivalent dry fuel consumed) is shown in Fig. 9. For the WBT, the Mirak and traditional stoves have a lower emission factor than the Prakti and EcoRecho. For the CCT, this trend changes, with the Mirak and Prakti stoves having the lower emission factors.

A lower CO emission factor could indicate more complete combustion because in complete combustion, zero grams of CO will be emitted per kilogram of fuel. However when considering total emissions from a stove, it is important to compare the emission factor with the specific fuel consumption. For example, although the traditional stove has a comparable or better emission factor than the improved stoves, it consumes more fuel to complete the same task and therefore, releases more CO than the other stoves. This is confirmed by examining the total CO emitted from the stoves for each test, shown in Table 2. We report the CO emission factor here as it is helpful to estimate CO emissions in the field, where it is difficult to directly measure CO emitted but possible to weigh fuel consumed.

The average CO emission rates (grams of CO emitted per minute) for the stoves tested are listed in Table 3. The World Health Organization currently recommends a CO emission rate target for stoves of 0.16 g/min if the stove is not vented to the outdoors (WHO, 2014). For the WBT, we find the CO emission rates for all tested stoves to be well above the indoor target. Similarly, the CO emission rates for the CCTs for all stoves are above the target. However, the CCT CO emission rates for improved stoves are lower on average than the traditional stove, indicating they are better for human health from a CO emission standpoint than the traditional one.

Modified combustion efficiency

All stoves had MCEs in a range of 0.89–0.92 for the WBT and 0.915–0.93 for the CCT (Fig. 10). Studies have found these MCE values indicate smoldering to mixed combustion (Urbanski, 2013; Ward and Radke, 1993). For the WBT, the EcoRecho and Prakti appear to have lower combustion efficiencies than the Mirak and traditional. This would indicate the EcoRecho and Prakti stoves are burning with a less intense smoldering fire than the others. For the CCT, the standard deviation between the average MCEs of the stoves is less than 0.6%, indicating the efficiencies are comparable.

Discussion

Upon examining the data from the WBTs and CCTs, a few key points emerge and are discussed below.

WBT vs. CCT data

The first conclusion is the discrepancy between the stoves' performance per WBT and CCT data. While the WBT protocol is the universal standard for testing any cookstove in a laboratory setting,

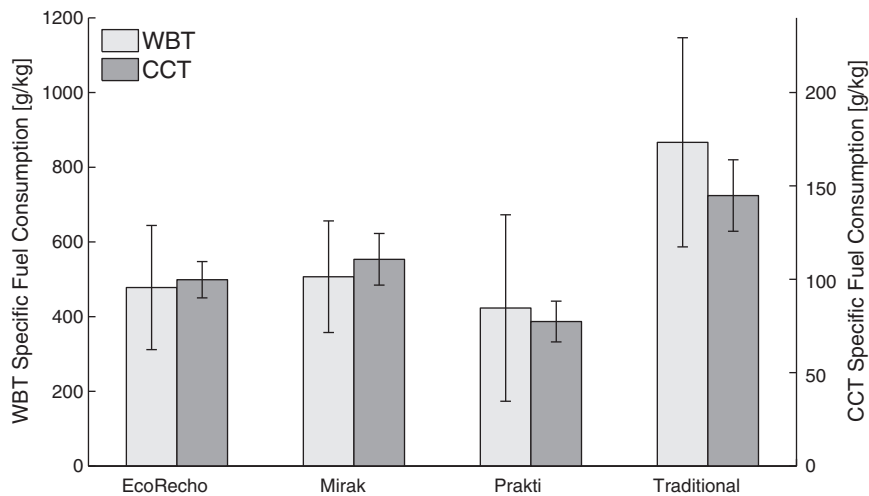


Fig. 8. Average specific fuel consumption [g/kg] during the WBTs and the CCTs. All improved stoves saved fuel compared to the traditional for both the WBTs (on average) and the CCTs (statistically significantly). Error bars represent 95% confidence intervals.

the CCT more closely mimics real-world cooking practices and may better indicate true stove performance in the field (Dutt and Ravindranath, 1993; Johnson et al., 2008; Smith et al., 2007). For this reason, differences in stove performance between the WBT and CCT could be quite meaningful as they would indicate the necessity of using multiple protocols for scientific comparisons in the lab when estimating field performance.

There is a significant difference between the magnitude of thermal power needed to complete a WBT versus a CCT. In this study, the thermal power as a function of time was estimated using the CO₂ released as a function of time, which was converted to power using the energy content of carbon. Example thermal power cycles for the WBT and CCT in the traditional stove are shown in Figs. 11 and 12, respectively, with the different transition events of the tests numbered sequentially.

In Fig. 11 prior to “1”, the increasing thermal power as the fire spreads in the charcoal bed can be seen. When the pot is placed on the fire at “1”, thermal power first drops, and then increases again until it becomes stable and plateaus until the water boils at “2”, ending the cold start portion of the WBT. At this point, the charcoal is emptied between the end of the cold start (“2”) and the beginning of the hot start (“3”). The power drops to zero in this interval as the fuel is replaced. A similar rise and plateau in thermal power is seen during the hot start

from “4” to “5” as was seen during the cold start from “1” to “2”. The hot start uses slightly less power as the stove is already warm. From “5” to “6”, there is a dip in power between the end of the hot start and beginning of the simmer, as the pot is quickly removed for weighing. After the simmer phase begins at “6”, the power decreases except when the fire is fed with fresh charcoal at about 7100 seconds.

In Fig. 12 we again see the rise in thermal power prior to “1” as the fire lights. At “1”, the bean pot is placed on the fire and a large amount of power is necessary to heat up the pot. By “2”, the beans are simmering and the power decreases as the charcoal burns down until the bean phase ends at “3”. Between “3” and “4”, the fire is fed and at “4” the vegetable pot is put on. Power increases as charcoal pieces catch on fire, heating up the vegetable pot, which doesn't quite reach simmering before stopping the test at “5”. At “6”, the bean pot is placed on the stove again, but heat from the first boiling is still retained so it does not need much power to regain a simmer and then the power decreases. The rice is added at “7” and is quickly brought back to a simmer at “8”. From there, the simmer continues until the end of the test, and the power decreases accordingly.

Although there are some similarities between the two cycles, there are several key differences between them, such as the large amount of energy needed for the hot start ignition in the WBT that does not exist in the CCT. On average over the test duration, a WBT uses approximately 2.3 kW and a CCT uses approximately 1.6 kW, with peak powers of approximately 4.7 kW and 3.0 kW, respectively. The differences between the WBT and CCT in the total amount of thermal energy used as well as fluctuations in the power can result in producing different amounts of emissions, different thermal efficiencies, and consuming different amounts of fuel between the two protocols.

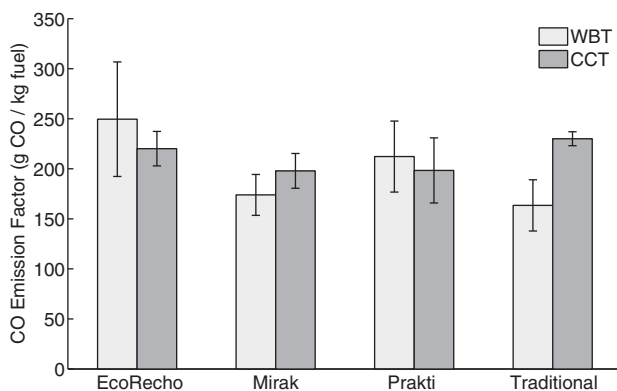


Fig. 9. The CO emission factors [g CO/kg fuel_{dry} consumed] for each stove. For the WBTs, the Mirak and traditional stoves had lower emission factors, while for the CCTs, the Mirak and Prakti stoves had lower values. However, it is important to note that the traditional stove uses more fuel than the others to complete each test and emits more CO. Error bars represent 95% confidence intervals.

Table 2

The total CO emitted per stove for each test. Note that the Prakti and Mirak stoves have lower emissions than the traditional for the WBT and all three improved stoves have reduced emissions for the CCT. Error represents a 95% confidence interval.

	Total CO[g] WBT	Total CO[g] CCT
EcoRecho	178.6 ± 23.1	92.7 ± 16.7
Mirak	131.4 ± 25.0	98.9 ± 22.9
Prakti	123.5 ± 30.3	69.0 ± 20.4
Traditional	150.5 ± 30.0	127.6 ± 15.5

Table 3

The CO emission rates (grams of CO emitted per minute) per stove for each test. None of the stoves meet the recommended WHO target of 0.16 g/min for unvented stoves. Error represents a 95% confidence interval.

	CO[g]/min WBT	CO[g]/min CCT
EcoRecho	1.37 ± 0.46	0.73 ± 0.28
Mirak	0.92 ± 0.21	0.76 ± 0.20
Prakti	0.97 ± 0.23	0.60 ± 0.21
Traditional	1.29 ± 0.31	1.08 ± 0.18

Sample size

The second conclusion drawn from these comparison tests is the need for attention to sample size, which could be a contributing factor to the differences between the WBT and CCT results. As observed by prior researchers (e.g., Wang et al., 2014), an appropriately large number of replicate tests must be conducted to obtain useful results with reasonable confidence intervals. Due to the nature of the Student's t-distribution, smaller numbers of replicate tests lead to larger confidence intervals. This is apparent throughout the test data when comparing the amount of error in the WBT and CCT results, as the magnitude of inherent variability was initially underestimated when conducting the WBTs, so the number of replicate tests was increased to obtain tighter confidence intervals for the CCT results.

To illustrate the impact sample size has on error, we highlight the specific fuel consumption results for the EcoRecho stove. Sample sizes for the average specific fuel consumption of the WBT simmer, WBT cold/hot starts, and the CCT were 3, 4, and 8 respectively. When comparing the amount of error to the average result, the percent errors for these trials are 60%, 30%, and 10% respectively. The data for the other stoves show similar results and trends, emphasizing the need for adequate replicate tests to reduce large statistical error.

Conclusions

There were three key findings in this comparison study. First, all improved stoves saved fuel on average over the traditional Haitian stove, accomplishing the goal of the disseminating entities. However, it is crucial to note the traditional stove boiled water fastest, which is very important from a users' viewpoint and therefore a potential barrier to user adoption if unaccounted for in improved stove design. Second, the improved stoves reduced the amounts of pollutants emitted overall, owing to their higher thermal efficiencies, despite having similar

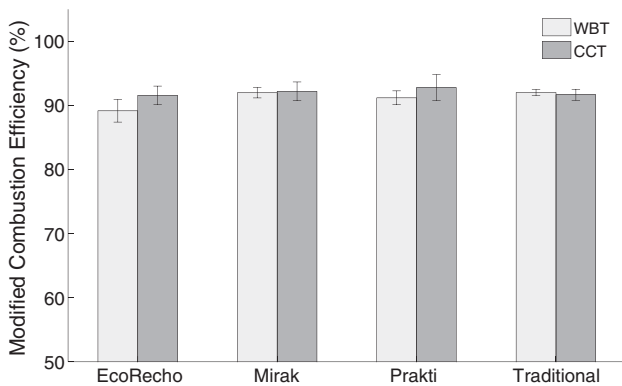


Fig. 10. The modified combustion efficiency for both the WBTs and CCTs; error bars represent 95% confidence intervals. Overall, the MCEs are comparable across the stoves, with a deviation between stoves of less than 3.3% for the WBTs and 0.6% for the CCTs. The values range from 89% to 93% indicating smoldering to mixed combustion, which is as expected for charcoal combustion.

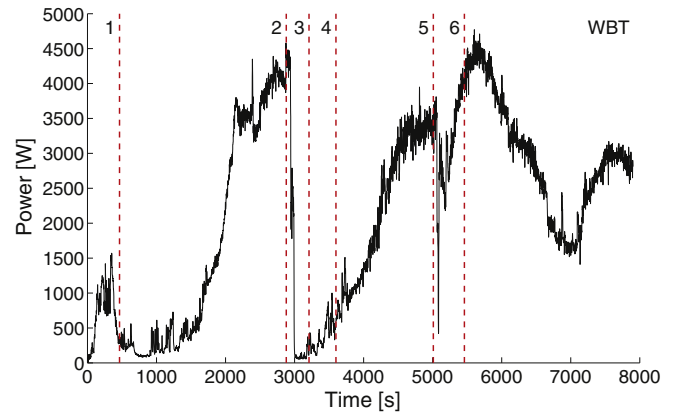


Fig. 11. Typical power cycle for a WBT of the traditional stove. Vertical numbered lines represent transitions in the test: 1. Pot on for the cold start; 2. End cold start; 3. Begin hot start; 4. Pot on for the hot start; 5. End hot start; 6. Begin simmer.

modified combustion efficiencies to the traditional stove. Third, stove performance rankings using the WBT and CCT were not identical. This emphasizes how the current dominant practice of solely using the WBT may be providing misleading results for in-field performance.

One interesting observation during the trials was the effect of modest differences in thermal mass for stoves not considered to be thermally-massive; even the relatively minor differences in mass affected the ratio of time-to-boil for the cold and hot starts. Additionally some results were obscured by sizeable statistical errors (i.e., large confidence intervals around mean reportable values), revealing the need for a greater number of replicate tests when evaluating cookstoves to avoid inconclusive results.

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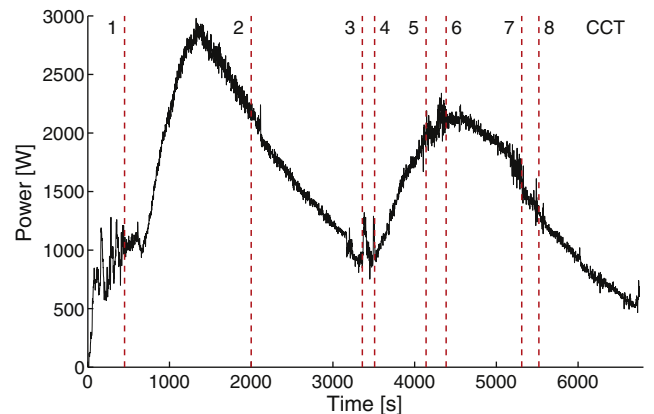


Fig. 12. Typical power cycle for a CCT of the traditional stove. Vertical numbered lines represent transitions in the test: 1. Bean Pot on; 2. Bean Pot simmering begins; 3. End Bean phase; 4. Vegetable Pot on; 5. Vegetable Pot off; 6. Bean Pot on again; 7. Rice added; 8. Rice and bean mixture simmering begins.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <http://dx.doi.org/10.1016/j.esd.2015.02.002>.

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