Field testing cookstove performance

in Uttar Pradesh and West Bengal, India

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ABBREVIATIONS

BA	Berkeley Air Monitoring Group
CO	Carbon monoxide
g	Gram
FDP	Forced-draft pellet stove
GIZ	Deutsche Gesellschaft fur Internationale Zusammenarbeit
HH	Household
ISO	International Organization for Standardization
IIT	Indian Institutes of Technology
IWA	International Workshop Agreement
IQR	interquartile range
kg	Kilograms
KPT	Kitchen Performance Test
MCE	Modified Combustion Efficiency
MJ	Mega joules
PM2.5	Particulate matter less than 2.5 microns in diameter
ppm	Parts per million
Rocket1 and 2	Rocket Stoves 1 and 2
person	Standard adult
SD	Standard deviation
TC	Traditional Chulha
TEG	Forced Draft TEG Stove
Top-Lit Updraft	Top Lit Up Draft Stove
TPM	Two Pot Mud Stove
UP	Uttar Pradesh
WB	West Bengal
WBT	Water Boiling Test

EXECUTIVE SUMMARY

Background: Clean and efficient cookstoves are being promoted in order to mitigate the health, environmental, and socioeconomic impacts of cooking with inefficient, traditional cookstoves in India. Such clean cookstoves are generally selected based on their performance during standardized laboratory tests. Field conditions, however, are different from laboratory: Fuel types and conditions vary between households and communities, as well as across seasons; there are a number of different food types cooked even within the same home; cooking vessels differ in their size, shape, and material; and how the users tend cook fires and operate stoves is highly variable. The variability in these factors, which can differ by region and sociocultural groups, means that characterizing real-world performance for the relevant target communities is critical to ensuring that only stoves which impart benefits under normal daily operating conditions, in homes, are promoted or targeted for scale-up activities.

Objective: This project was supported by GIZ (IGEN ACCESS) to address this need by carrying out a field study of several promising cookstoves in India. The specific objectives of this work were to demonstrate the importance of field testing by comparing stove performance tested under field conditions to those tested under laboratory conditions, and to provide an example for how field testing can be used to differentiate real-world performance of stoves targeted for potential scale-up.

Study summary: The study included testing of six cookstove models, as well as the traditional cookstove (called "chulha" in Hindi) for comparison, and assessed their performance during normal daily cooking events in homes. Field campaigns were carried out during 2014 and 2015 in Uttar Pradesh and West Bengal, during which 50-60 cooking events were sampled per stove type. The stoves were also tested in the laboratory, according to Bureau of Indian Standards protocols, to compare results with field performance results. The main performance indicators were fuel savings and emissions of particulate matter and carbon monoxide. Additionally, stove operation, including fuel, type of food prepared, fuel condition, cooking power, and other factors were analyzed to attempt to explain why stove performance varies from stove to stove and also from the field to the laboratory.

Key outcomes

- Comparisons of laboratory and field performance results indicate that the general trends in fuel efficiency (percentage fuel saving with respect to the traditional stove), were somewhat consistent between the lab and the field, but similar patterns in emissions performance were not evident. In general, the emissions were much higher in the field tests than the laboratory tests, a trend which has been reported in several previous studies.
- There were differences in performance between the two locations, likely due to differences in cooking demands and fuel conditions. While the differences were generally systematic (e.g. the same stoves

performed relatively better or worse compared to the traditional chulha), it was clear performance should not be generalized from one region to another. This underlines the importance of testing stoves in the field in each socio-geographic region where the deployment of improved stoves is envisioned. There are substantive differences in fuel consumption estimates (up to approximately 40% for some stove types) when charcoal is included or excluded from the calculation of the fuel consumption. . Therefore, care should be taken to use the most appropriate scenario for the local context. For this study, since the char is typically discarded, all fuel consumption metrics have been calculated using the "without char" scenario.

- The majority of the new stoves had significant fuel and emissions reductions relative to the traditional chulha, and there was a wide range of field performance results for various stove types. In both locations, four of the cookstove models saved more than 30% of fuel compared to the traditional chulha. All but one cookstove reduced emission rates of particulate matter, with reductions varying from twenty to ninety percent. The best performing cookstove, in terms of fuel efficiency and emissions performance, was a model with processed fuel pellets and a fan, which assisted in the combustion process. Overall, the results show that many of the cookstoves provide substantial performance improvements relative to the traditional chulha, suggesting that user adoption should play a key role in deciding which cookstove models are ultimately promoted.
- Analysis of operational conditions indicated that differences in stove performance were not strongly associated with changes in factors such as firepower, moisture content, and use of non-wood fuels. Why the associations were weaker than expected is not clear, although additional operational factors or alternative analysis approaches could yield additional insight.

Recommendations:

- The utility of informing decisions for technology selection with data such as that reported here is evident. The field testing approach was able to provide differentiation in performance from the traditional chulha and suggest which stoves were better or worse performers, as well as indicate how performance may differ between locations. The differences in performance between locations suggest it is important to conduct regional specific studies to select the best suited cookstoves. Hence similar studies may be conducted on additional technologies and/or in other regions where decisions on technology selection are needed.
- Complimenting field performance studies with user preference/affordability, durability, and ideally, direct measures of stove usage would indicate which stoves are most likely to have meaningful household-level impacts. Importantly, this study looked at stove performance for distinct cooking events, which only provide an indication of the emissions or fuel benefits accrued per meal. While these outcomes suggest the potential that different stoves may have, their overall benefit, at the household level, depend on the extent to which the improved stoves are adopted and displace the baseline technology (e.g. traditional chulhas). A user acceptance study can give insights about the probability of different stoves models being adopted by households and is necessary for selecting best suited stove models. Such a study was previously conducted by GIZ in India (https://www.giz.de/en/downloads/giz2014-en-kaleidoscope-of-cooking india.pdf).

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1. INTRODUCTION AND OBJECTIVES

According to WHO estimates, in 2012 there were close to 1.7 million premature deaths attributed to household air pollution from cooking in the South East Asia region with India shouldering the biggest burden. Indoor air pollution causes more than 1 million deaths in India annually and 4 million deaths worldwide (Lim et al., 2012). Almost 800 million people in India rely on solid fuels and traditional cook stoves for domestic cooking (India, 2011) despite their negative impact on peoples' health. Additional environmental strains result from unsustainable harvesting of biomass fuels and emission of pollutants which impact the climate, such as methane and black carbon (Bailis et al., 2015; Bond et al., 2013; Gustafsson et al., 2009; Smith et al., 2000a; Venkataraman, 2005).

Clean and efficient cookstoves are being promoted in order to mitigate the health, environmental, and socioeconomic impacts of cooking with inefficient, traditional cookstoves in India (Venkataraman et al., 2010). Such clean cookstoves are often selected in part due to their performance during standardized laboratory testing. It is well established, however, that stove performance measured in homes differs substantially from stove performance measured by standardized laboratory testing (Arora and Jain, 2016; Bailis et al., 2007; Johnson et al., 2010; Roden et al., 2009). The differences in performance arise as the field fuel types and conditions vary between households and communities, as well as across seasons; there are a number of different food types cooked even within the same home; cooking vessels differ in their size, shape, and material; and how the users tend cook fires and operate stoves is highly variable. As stoves are often not selected for promotion/dissemination based on the field performance and sometimes do not provide the benefits as advertised, this can result in user dissatisfaction and low adoption rates. Incorporation of field-performance testing into the technology selection, in combination with user acceptance and willingness to pay studies, should help to shift this paradigm.

GIZ's IGEN ACCESS programme is providing support to three strategic pillars, i.e. public support programmes, Private Sector Development and Innovation and Access to Finance. Under the IGEN ACCESS programme, GIZ is carrying out several activities to address these problems in India. This includes efforts to better understand the field performance of cookstoves and the different dimensions of household cooking experiences, such as consumer preferences and market based solutions for scaling up clean cooking solutions. To achieve this, identifying the right stove technology adapted to the respective socio-cultural and economic context, as well applicable to existing fuel types, is crucial to identifying suitable cookstove models for different user groups and geographical locations.

This report is part of the effort to demonstrate the importance of field testing by comparing performance of stoves being tested under field and laboratory conditions to determine which do not perform well in homes

IIT Delhi had initiated the research work on clean cookstoves as early as 1980. The work at IIT Delhi was at the back of the Government of India initiating the earlier National Program on Improved Cookstoves (NPIC). IIT Delhi was the first Technical Backup Unit to the program starting 1983, designed and developed the first few models of improved cookstoves under the program, trained many others for the purpose, setup a laboratory for testing and certification of improved cookstoves, carried out feedback studies in the field, and advised the Government, in various ways, on how to strengthen the program. IIT Delhi was called back into the program by the ministry when the new initiative was being planned in 2008, and prepared an action plan for development and deployment of cookstoves under the programme. The initiative stressed the implementation of state-of-the-art testing, certification, and monitoring facilities and called for a strengthening of current R&D programmes. One such Centre is located at IIT Delhi. Berkeley Air Monitoring Group (BA) is a for-profit social venture consultant in California, USA. Their mission is to support the advancement of cleaner energy solutions in less developed countries, for global health and climate benefits. They provide independent scientific field testing and monitoring services to a range of implementers and funders. BA provided technical training and oversight to build capacity for IIT Delhi in conducting this field performance study and to facilitate future studies.

and will clearly not provide the desired health and environmental improvements. It presents an analysis and summary of field tests conducted in Uttar Pradesh and West Bengal by GIZ India and carried out jointly by Indian Institute of Technology, Delhi) and Berkeley Air Monitoring Group (see the box below for more details on these organizations) Several stoves which have potential for broad consumer uptake were assessed for their emissions and fuel performance to help inform which would be promoted for scaling up activities. The study included testing of six cookstove models, as well as the traditional chulha for comparison, and assessed their performance during normal daily cooking events in homes.

Secondary aims of the study are as follows:

- Identify and apply the most accurate methodology for assessing performance of household cookstoves under field conditions, particularly how accounting for leftover char can impact results.
- Test and present performance outcomes of different stove technologies tested under real-world conditions in rural Indian homes and investigate impact of operational conditions on field performance.

The study was complimented with the development of a manual for conducting scientific measurement of the performance of cookstoves in the field to enable Institutions and organizations to replicate the field performance testing procedures.

Field campaigns of this study were carried out during 2014 and 2015 in Uttar Pradesh and West Bengal, during which 50-60 cooking events were sampled per stove type. The stoves were also tested in the laboratory, according to BIS protocols, to compare results with field performance results. The sample size in the laboratory was six. The main performance indicators were fuel savings and emissions of particulate matter and carbon monoxide. Additionally, stove operation, including fuel type and condition, cooking power, and other factors were analyzed to attempt to explain why stove performance varies from stove to stove and also from the field to the laboratory. There are several protocols adopted for field performance evaluation/measurements. The field-testing protocol selected for use in this this study was the Uncontrolled Cooking Test (UCT), as it provides a real-world indication of stove performance across a wide range of cooking conditions in homes.

The report has been organized in eight chapters including references and appendices. Following the introduction, section 2 describes the methods used including the test protocols, project stoves, study sites, sampling design, quality control and assurance. The report next presents the stove performance results in terms of fuel efficiency and emissions as well as impact of operational conditions (Section 3). Section 4 describes the impact on accounting for char on outcome metrics, followed by a comparison of field and laboratory tests (Chapter 5). The report finishes with conclusions and the recommendations (Chapter 6), which is followed by references and appendices.

2. METHOD

2.1 Stove selection

Selecting stoves to be field tested may be driven by several factors. Ideally, only stoves with reasonable potential for good performance and uptake in the targeted communities are field tested, which helps make the best use of available testing resources. Data to inform performance-related decisions may come from several sources. First, it is recommended that stove candidates for field testing have their laboratory performance evaluated, as stoves which do not perform well during the relatively idealized operating conditions of controlled laboratory testing are unlikely to perform well during normal uncontrolled conditions in homes. In many cases there may also be field performance data available for stove candidates. While this field data will often be from other areas, and contextual factors such as cuisine, fuel conditions, pot types, and others may limit direct comparability to the project site, stoves which have demonstrated strong field performance should be considered favorably. Finally, evidence from users' perceived performance captured systematically in a user acceptance study can assist in the stove selection process. Due to unreliability in users' perceived fuel savings or reductions in smoke levels, it is not recommended to rely solely on this data source, but it may provide anecdotal information to support the selection of a given stove. Consideration of stove uptake is equally important. Stoves which perform well, but are ultimately not adopted by consumers and/or do not displace use of traditional technologies will not result in meaningful impacts. However, compared to laboratory studies, field studies are typically expensive, time consuming, and can be logistically challenging. Specific considerations of the stove selection included the following:

Stove models and its design characteristics, requirements of the cooking practices of the users in the field, strengths and weaknesses offered by designs in terms of fuel use preparation, results from earlier studies, and the stove cost:

- Stove cost was not to exceed INR 4000, which is likely beyond the purchasing power of the target populations.
- One model with lower cost (INR 1000) was selected to see if a stove produced with inexpensive materials and manufacturing demands could provide meaningful performance benefits. Similarly, one model towards the higher end of the cost (INR 4000) with potential to provide large benefits in terms of efficiency, emission reductions, and ease of operation was selected.
- One model offering a two pot arrangement for cooking, which is believed to be an important factor for usability in some households.
- One model using processed fuel, which may offer several performance and ease-of use advantages.
- Two models offered at the lower end of the cost, easy to operate, and not needing any power or fan etc.
- Two natural draft rocket stoves, which are the most common non-traditional cookstoves sold in Indian and therefore important to assess.
- One model based on top lid updraft technology using almost all unprocessed fuel.

2.2 Test protocol

There are several protocols adopted for field performance evaluation/measurements. There are many types of field assessment approaches which are employed for studies on household energy. One common field assessment method is the Kitchen Performance Test (KPT), for which household-level fuel consumption is measured over a minimum of three days. While a good approach for measuring fuel consumption impacts, the KPT does not directly measure stove performance, as the fuel consumption is measured per household (e.g. kg wood/household/day) rather than per stove. Another method is Controlled Cooking test (CCT), during which a local cook, or cooks, perform(s) a specified task cooking task. The CCT is often used as a screening tool. The cook, the food cooked, and the fuel used remain controlled and standardized.

The protocol select for use in this study was the Uncontrolled Cooking Test (UCT), as it provides a real-world indication of stove performance across a wide range of cooking conditions in homes (Johnson et al., 2011a; Robinson et al.). No variables are controlled by the researchers during a UCT; rather they measure the performance and operating conditions of a normal stove use event. The test is conducted in homes, and the meal, fuel types/conditions, fuel tending practices, pots, and other operational conditions are entirely dictated by user. Along with obtaining the consent of the users for conducting the test and their participation, the following information was recorded:

- Stove type
- Stove condition
- Ambient temperature
- Pressure
- Pump flow rate
- Background $PM_{2.5}$ and CO concentration
- Initial fuel masses and conditions like shape and size
- Cooking pot shape, weight and dimensions
- Type of food to be cooked
- Cooking event like cooking start time, fuel use to start fire, how the fire was lit, sequence of events during cooking etc.
- Weight of fuel additions, if any
- Number of people meal cooked for
- Weight of pot with food cooked
- Cooking event end time
- Post cooking conditions such as temperature, pressure, and pump flow rate
- Post sampling background $PM_{2.5}$ and CO concentrations
- Remaining fuel mass
- Weight of char and ash produced

UCTs most fundamental measure of performance is fuel efficiency (mass or energy of fuel used per meal). Emissions can also be measured during UCTs, but are not a necessary component of the protocol. For this study, half of the samples included emissions measurements.

The field team conducting the UCTs was comprised of three teams of two technicians, who were supported by a field supervisor. Two of the teams measured emissions and fuel consumption performance, generally sampling two to three events per team, per day. The third team focused on fuel consumption events only, and was generally able to sample 4-6 events per day. The order of stoves sampled within the day was mixed, to mitigate against potential temporal bias in results associated with sampling specific stoves on any given day.

Figure 1. Emissions sampling setup with a Traditional Chulha at the Uttar Pradesh project site location.

2.1.1. Fuel Use and Characteristics

Before the beginning of each sampling event, all fuels apportioned for the event were weighed separately. Upon completion of the sample, any unused fuel was weighed and a rapid assessment of the used fuel weight was accomplished by separating the ash from the char using a set of buckets. The top bucket had 3/16 inch steel mesh in the bottom, through which ash could fall. Fuel moisture content was measured by collecting small samples (5 to 10 grams) and analyzing them immediately with a Precisa Moisture Analyzer Balance (Model - XM 60-HR). Fuel energy contents and percent carbon were taken from the WBT 4.2.3 protocol[1].

Information on the type of event, amount of food cooked, and number of people being cooked for was also collected, to account for differences in energy demand between events. Before the start of the cooking events, all the weights of the empty pots (and lids) were measured. After the completion of the cooking event, the weight of food cooked, including the pot, were taken with the difference between these two weights providing the mass of cooked food. To normalize for the different energy demands for people of different ages and gender, they were weighted according to the standard adult convention[2] used in the Kitchen Performance Test Protocol (Bailis, 2007). Cooking events were weighted at 1 for preparing meals and 0.5 for preparing beverages, such as tea or warm milk. This normalization provided the metric of mass or energy of fuel used per person meal. A second metric of mass or energy of fuel used per kg of food was also calculated to explicitly account for the quantity of food cooked.

2.1.2. Emissions Sampling

The emissions species measured included carbon dioxide (CO_2), carbon monoxide (CO), and particulate matter ($PM_{2.5}$), which were collected directly above the stove using a three-pronged stainless steel sampling probe (Figure 1). A three-sided aluminum curtain was placed around the stove to minimize impacts from air currents. Real-time concentrations of CO_2 and CO were measured using a TSI IAQ-CALC 7545 (TSI Inc., USA), and gravimetric measurements were taken to quantify $PM_{2.5}$. Sample streams were drawn by constant flow SKC sampling pumps (SKC Inc., USA) through a

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[1] http://cleancookstoves.org/binary-data/DOCUMENT/file/000/000/406-1.xlsx

[2] "Standard adult" equivalence factors defined in terms of gender and age: child 0-14 years = 0.5; female over 14 years = 0.8; male 15-59 years = 1; and male over 59 years = 0.8.

BGI Triplex cyclone (BGI, USA) at 1.5 liters per minute to remove particles larger than 2.5 microns in diameter. $PM_{2.5}$ was determined gravimetrically by weighing the 47mm glass fiber sampling filters (Whatman, USA) before and after sampling on an electronic microbalance with 1µg resolution (Mettler Toledo, USA). Emission factors were determined using the carbon balance approach, as has been done in previous studies of stove emissions and is described in the WBT 4.2.2 protocol (Johnson et al., 2011a; Roden et al., 2006; Smith et al., 2000b). Flow rates and sample volumes were adjusted for temperature and pressure, which were recorded before and after each event.

2.1.3. Operational Conditions

Observations of stove condition and operational condition during the UCTs were recorded for analysis of how operating condition may potentially affect stove performance. Operational factors such as firepower, non-wood fuels, stick size, pot size, and accounting for char, on performance of the stove, were collected to determine if they could be used to predict fuel and emissions performance. Factors associated with biomass cooking, such as lighting technique, pot characteristics, fuel size/conditions, and others, as well as activities during the cooking event such as noting when pots were added and removed, changes in tending conditions (additions or subtractions of fuel), and others were also recorded for potential analysis of their impacts.

2.2. Project Stoves

The set of stoves selected covered a major spectrum of stoves available in India under the umbrella of clean cookstoves. Thus the study included six (five portable and one fixed) new stoves and a traditional baseline chulha at each site (Uttar Pradesh and West Bengal).

Figure 2: Typical picture of traditional chulhas in Uttar Pradesh (left) and West Bengal.

All cookstoves were the same for the both sites; however, the traditional cookstoves varied in construction and design but were primarily made of mud. The selected stoves included four natural draft stoves, one of them being the two pot mud stove without chimney using locally available mud and bricks for construction, another was a typical rocket stove, factory-made, using mostly stainless steel for fabrication, one more was a rocket stove, again factory–made, but using mild steel and hence lower in cost, and one Top Lid Up Draft (TLUD) stove, factory-made using stainless steel. The other two stoves selected were forced draft, one of them using pre -processed fuel, pellets, supplied by the manufacturer and the other a rocket design based stove using Thermo-electric Generator (TEG) to operate the fan, light a small LED light, and charge a mobile phone. Further description of six new cookstoves selected is provided below, as well as table with more detailed specifications (see Table 1).

- ***Two-Pot Mud:*** This stove is a fixed type, double pot, natural draft biomass cookstove constructed of locally available mud. Fuel is fed through a front opening in the primary combustion chamber, however, there is a provision of combustion gases to move in secondary pot chamber. The Two Pot Mud does not have provision of secondary air in primary combustion chamber because pot is tightly fit with wall of primary combustion chamber.

However, pan support has been provided on the top of secondary combustion chamber which can provide some ambient air for the combustion of fuel wood. A grate is present in the primary combustion chamber to provide necessary air for combustion.

- ***Rocket1:*** This stove is a single pot portable type natural draft rocket stove constructed of metal. Fuel is fed through front opening in combustion chamber. There is provision of secondary air through secondary air holes, however, primary air comes through only fuel feeding door.Pan support has been provided on the top of combustion chamber. Grate is present in the combustion chamber to provide necessary air for combustion.
- ***Rocket2***: This stove is a single pot portable type natural draft rocket stove constructed of metal. Fuel is fed through front opening in combustion chamber. There is provision of both primary and secondary holes through which air necessary for combustion comes. Pan support has been provided on the top of combustion chamber. Grate is present in combustion chamber to provide necessary air for combustion.
- ***Top-Lit Updraft:*** This natural draft cookstove is based on Top Lit Up Draft (Top-Lit Updraft) Gasifier stove, constructed of metal.Fuel is fed through top of combustion chamber. There is provision of both primary and secondary air necessary for combustion. Pan support has been provided on the top of combustion chamber. Grate is present in combustion chamber to provide necessary air for combustion.
- ***Forced-draft TEG:*** This forced draft cookstove is based on the thermo-electric generation principal, which converts waste heat into electricity, powering a fan and USB port. The combustion chamber of the TEG cookstove is constructed of refractory material and rest of body is made up of metal. Fuel is fed through a front opening in combustion chamber. A fan is provided for supply of air necessary for combustion. Primary air comes throughholes (diameters of 5 mm) present at lower part of the combustion chamber and secondary air comes through holes (diameter of 4 mm) present at upper part of the combustion chamber. Pan support has been provided on the top of combustion chamber. The stove comes with two lithium ion batteries. One of them is used to drive the fan to pump adequate air into the stove not only during combustion but even the initial phases of the ignition, while the other can be charged so that it can be exchanged with the other is discharged.
- ***Forced-draft pellet:*** This forced draft cookstove is based on Top Lit Updraft design and constructed of metal. Fuel pellets are loaded through the top of the combustion chamber. A fan is provided for supply of air necessary for combustion. Primary air comes through below the grate and secondary holes (diameter of 6 mm) are present in upper part of combustion chamber. Pan support has been provided on the top of combustion chamber. Grate is present in combustion chamber to provide necessary air for combustion.

Table 1. Detailed specifications of cookstoves

	Two Pot Mud	Rocket 1	Rocket 2	Top Lit Up Draft	Forced-draft TEG	Forced-draft pellet	Traditional Chulha at Uttar Pradesh	Traditional Chulha at West Bengal
Type	Natural Draft, Rocket stove , Fixed	Natural Rocket stove Draft, Portable	Natural Draft, Rocket stove, Portable	Natural Draft, TLUD (Top Lit up draft) Gasifier stove Portable	TEG based, Forced Draft Rocket stove, Portable	Forced Draft TLUD (Top Lit up draft) Gasifier stove Portable	Natural Draft, Fixed	Natural Draft, Fixed
Combustion chamber and No of Pot	Single combustion chamber with two pot Mud	Single combustion chamber with Single pot	Single combustion chamber with Single pot	Single combustion chamber with Single pot	Single combustion chamber with Single pot	Single combustion chamber with Single pot	Single combustion chamber with Single pot	Single combustion chamber with Single pot
Fuel Feeding mechanism	front fuel feeding	Front fuel feeding	Front fuel feeding	Top fuel feeding	front fuel feeding	Top Fuel Feeding	front fuel feeding	front fuel feeding
Provision for Primary air	Through Fuel feeding door & Below the grate	Through Fuel feeding door	Through Fuel feeding door	Single hole of 3 cm in in circular part of inner combustion chamber below grate	Through Fuel feeding door & 8nos of holes of dia= 0.5cm	Through the grate	Through Fuel feeding door	Through Fuel feeding door
Provision for Secondary air	No provision	40 holes of Dia= 1 cm	No provision	Single hole of 8 cm in in circular part of outer combustion chamber near base plate	40 nos of holes of dia=0 .4cm	18 nos of holes of Dia= 0.6 cm	Diffusion from the top of the stove	Diffusion from the top of the stove
Inner combustion diameter	ID1=18 cm, ID2=14cm	11 cm	10 cm	15cm	13.5 cm	10.5 cm	17 cm	20 cm
Height of combustion chamber & Material	10 cm & mud	24.2 cm & Mild Steel	17.5cm Mild Steel	21 cm Stainless Steel	17.5 cm & Refractory	21.5 cm & Refractory	22 cm	25 cm
Outer diameter of cookstove & Material	Not Applicable	19 cm & Mild Steel	26.2 cm Mild Steel	18.5cm Stainless Steel	26 cm	16.5 cm & Mild Steel	37 cm	40 cm
Height of cookstove	18.5 cm	28.2 cm	20 cm	31 cm	28 cm	29 cm	22 cm	12 cm
Grate	Present	Present	Present	Present	no	Present	no	no
Pan support height	No pan support	2.2 cm	1.5 cm	1.5 cm	2.5 cm	2 cm	2.5 cm	2.5 cm
Fuel feeding door (L x W)	14 cmX12.5 cm	12.5cmX12.5 cm	11cmX10.7cm	Not Applicable	9 cm X 9 cm	Not Applicable	22 cm x 17 cm	18 cm x 15 cm

2.3 Study Sites

GIZ had previously carried out a background survey in several different Indian states to understand the acceptance of new stoves by the users and the parameters which allowed them to be either accepted or rejected (Singh, 2014). This study was qualitative and provided context about the preference of users. To compliment the methodology for technology selection presented in this earlier study by GIZ, this study looked at field performance of the stoves. However, the earlier study was spread out in to three different states, Utter Pradesh, Bihar, and West Bengal of India. Due to time and resource limitation, two of these states, Uttar Pradesh and West Bengal, were selected to represent range of different cooking practices, food habits, fuels used, and other stove operating conditions. Utter Pradesh was selected to also reflect the state of Bihar in terms of stoves, food, and cooking practices, while West Bengal was selected to represent the socio-economic conditions of stoves, food and cooking practices in eastern India.

2.3.1 Uttar Pradesh

The study site in Uttar Pradesh was in the Khaga Block of District Fatehpur (Figure 3). Selected villages were Kripalpur, Bahlolpur, Meerpur, Maheshpur, Ekdala, Midanpur, and Dudhorpur. The primary fuel in this area was wood, with cow dung cake and agricultural residue also being used. Cow dung was used relatively more than agricultural residue. The traditional chulhas used at the site were mostly U-shaped with front loading, without grate, without chimney, made up of mud with varying dimensions (Detailed specifications in Table 2).

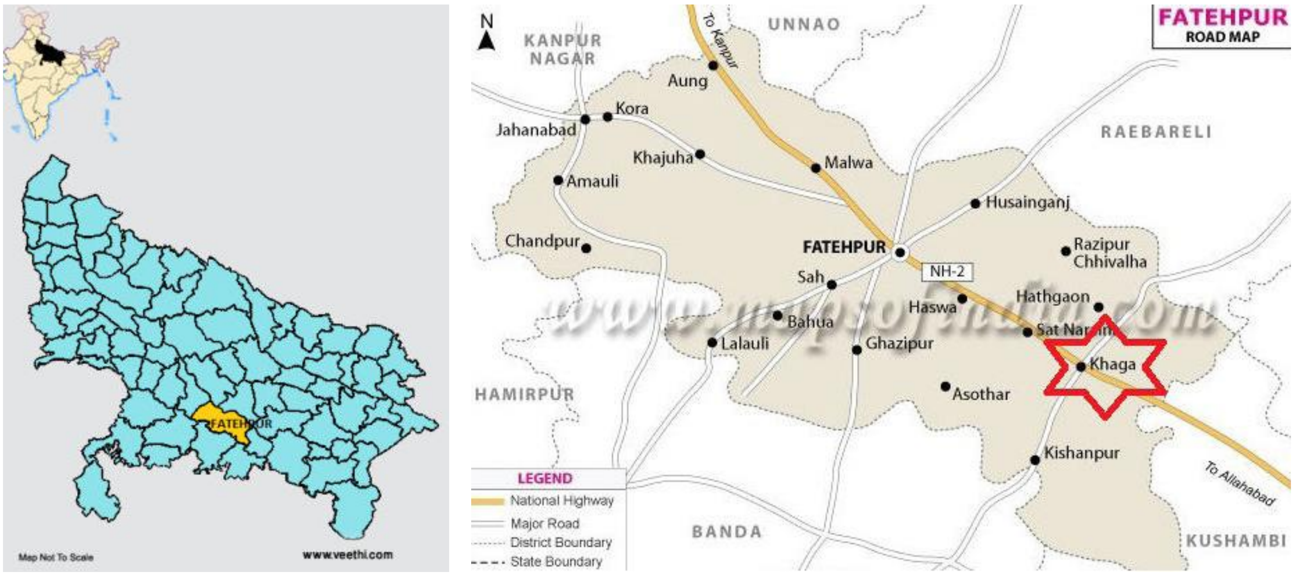

Figure 3: Map of Utter Pradesh with location of Fatehpur District (left) and project site location in Fatehpur District of Uttar Pradesh.

The monitoring campaign for all the stoves took place between the last week of November 2014 and first week of January 2015. Representatives from each stove manufacturing organization led a user-training on their respective stoves, approximately 15 days before the start of sampling.0

2.3.2 West Bengal

The study site in West Bengal was in the Bagnan Block of District Howrah (Figure 4). Selected villages were Bangalpur, Murgaberia, Harop,Joka and Kalikapur. The primary fuel in this area was agricultural residue, with mixed wood and cow dung cake also used. Cow dung was the lowest component for the fuel used. The traditional stove used at the site were mostly U-shaped with front loaded, some with grate and some without grate, without chimney, made up of mud with varying dimensions (Detailed specifications in Table 2).

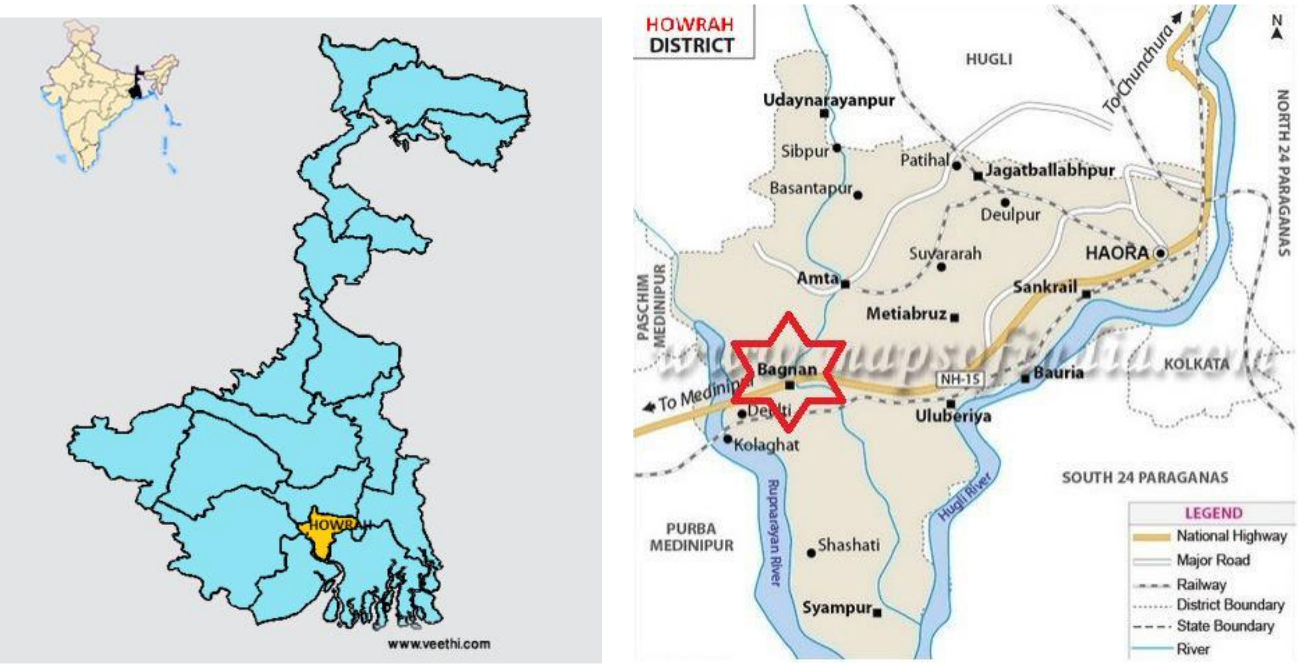

Figure 4: Map of West Bengal with location of Howrah District (left) and the project site location in Howrah District of West Bengal.

The monitoring campaign for all the stoves took place between the third week of January, 2015 and second week of February, 2015. Representatives from each stove manufacturing organization led a user training on their respective stoves approximately 15 days before the start of sampling.

2.3.3 Community and Participant Selection

Dharma life, New Delhi in Uttar Pradesh and Bagnan Gramin Mahila Sammilan, Bagnan in West Bengal Organizations provided critical assistance with accessing the study communities. These organizations were well established and respected in the study community, and were familiar with the region's culture and geography. They had also been field partners of GIZ for the earlier qualitative study, mentioned above.

The local organizations helped identify the necessary permissions required to carry out the fieldwork within the study location. They then initiated a dialogue with all required organizations including local government and other community heads, as appropriate. They were also instrumental in locating suitable participants, as guided by the project manager, and engaged the selected households to determine their interest in participating. A guide from the local organization helped direct the field team during fact-finding sessions, while collecting selection criteria, and, finally sampling. They also advised on identifying a culturally appropriate participant gift, given to each participant as compensation for their time and willingness to take part in the study. Feedback from these groups also aided survey development by incorporating specific fuel types used, foods cooked, and cooking techniques in the given study location.

Selection criteria was used to identify study participants that had representative cooking and fuel use patterns the target population of interest and would be suitable for sampling. The target population was households using traditional stoves with biomass fuel available in the area such as wood, agricultural residue, and cow dung. The criteria include considerations for the presence of commercial cooking in homes, number of people cooked for, and cooking for festivals or celebrations, which could result in extreme fuel demands that do not represent typical household cooking.

For households which met the screening criteria and indicated an interest in participating in the study, the next step was to obtain informed consent to enter their home and carry out the study. The consent form contained a detailed description of all procedures including time demands and all possible risks to the participant and their family members. The risks for UCTs are minimal and the main potential barrier to consent is inconvenience and interruption in the household for the duration of the cooking event in addition to approximately 30 minutes before and after to allow for the set up and take down of the equipment.

2.4 Sampling design

Sampling was conducted at two field sites (described in section 2.3), and was based on a cross-sectional design, for which the stove events were assumed to be independent of one another (e.g. different households). To calculate samples sizes, we targeted being able to detect a 30% reduction in fuel consumption relative to the Traditional Chulha, and assumed that the variability would be 50% as measured by the coefficient of variation[3]. Table 2 shows the samples sizes required to detect a significant different based on the combination of the expected difference and coefficient of variation. With a fuel savings target of 30% and a coefficient of variation of 50%, the required sample size would be 44. We therefore conservatively planned to conduct 50 samples per stove type in each location.

Table 2: Sample size table for cross-sectional study design.

		Coefficient of Variation												
		10%	20%	30%	40%	50%	60%	70%	80%	90%	100%	110%	120%	130%
Difference in means	5%	63	251	565	1005	1570	2261	3077	4019	5086	6279	7598	9042	10612
	10%	16	63	142	251	393	565	769	1005	1272	1570	1900	2261	2653
	15%	7	28	63	112	175	251	342	447	565	698	844	1005	1179
	20%	4	16	36	63	98	142	193	251	318	393	475	565	663
	25%	3	10	23	40	63	91	123	161	204	251	304	362	425
	30%	2	7	16	28	44	63	86	112	142	175	211	251	295
	35%	2	5	12	21	32	46	63	82	104	128	155	185	217
	40%	1	4	9	16	25	36	48	63	80	98	119	142	166
	45%	1	3	7	13	20	28	38	50	63	78	94	112	131
	50%	1	3	6	10	16	23	31	40	51	63	76	91	106
	55%	1	2	5	9	13	19	26	33	42	52	63	75	88
	60%	1	2	4	7	11	16	22	28	36	44	53	63	74
	65%	1	2	4	6	10	14	18	24	30	37	45	54	63
	70%	1	2	3	5	8	12	16	21	26	32	39	46	54
	75%	1	1	3	5	7	10	14	18	23	28	34	40	47
	80%	0	1	2	4	6	9	12	16	20	25	30	36	42
	85%	0	1	2	4	6	8	11	14	18	22	27	32	37
	90%	0	1	2	3	5	7	10	13	16	20	24	28	33
	95%	0	1	2	3	5	7	9	11	14	18	21	25	30
	100%	0	1	2	3	4	6	8	10	13	16	19	23	27

Adapted from (Edwards et al., 2007)

2.5 Quality Control and Assurance

2.5.1 Equipment Checks and Calibration

Weekly checks of instrumentation were done to ensure accurate data collection. A quality assurance checklist and data entry sheet was filled out by the local field team with specifications about the instrument functionality to record performance over time. These checks included:

- Testing fuel scale accuracy against a pre-weighed standard weight.
- Calibrating the TSI Indoor Air Quality Monitor.

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[3] Coefficient of variation is a relative measure of variability, defined as the ratio of the standard deviation to the mean for a given sample (CoV = SD/mean). For example, if the standard deviation of a set of fuel consumption measurements was 100 grams and the mean was 400 grams, then the CoV would be 25%. The larger the CoV, the larger the sample size will need to be to detect a significant difference.

- Checking the pressure of compressed calibration gases.
- Ensuring that supplies inventory is sufficient.
- Cleaning equipment.

The TSI Indoor Air Quality Monitor was calibrated weekly with NPL/NIST/NMI traceable gas calibration standards from Alchemie Gases & Chemicals Pvt. Ltd., Mumbai, India (4000 PPM CO_2 in a nitrogen balance, and 400 PPM CO in a nitrogen balance, as well as zero grade nitrogen). Post calibration, a correction adjustment was entered into the instrument per the manufacturer's instructions. Rotameters, for measuring sample line flows, were calibrated on site at the beginning of each project with a TSI Primary Calibrator 4146.

2.5.2 Quality Control of Data

To ensure a high level of data quality, team members from Berkeley Air remotely screened the uploaded data as it became available. The field team uploaded the data from a cellular device on a daily basis during the monitoring campaign. Each data set was then checked for consistency, accuracy, and completeness. Any problems that could potentially compromise the data quality and completeness were immediately communicated to the field team, who in turn, checked the data against written records and made any edits necessary. This expeditious process of data entry, review, and editing allowed for efficient, effective data cleaning while the sampling event was still current.

3. STOVE PERFORMANCE RESULTS

Key stove performance outcomes

- Most of the stoves were found to reduce fuel consumption and emissions relative to the traditional chulha; however, there was a wide range of stove performance observed during this study. The Two-Pot Mud stove had the lowest performance of the new stoves, and the Forced-Draft Pellet stove performed the best, reducing emissions by up to ~90% and the fuel consumption by ~45%.
- There were meaningful, and apparently, systematic differences in stove performance between the two study locations, indicating the importance of region-specific field testing of cookstoves.

3.1. Sampling overview

A total of 633 events were successfully sampled across the two locations (4), with up to 50 samples acquired per stove. Approximately half of the samples included emissions measurements. 20 samples were removed from the database due to source data either not passing quality assurance thresholds (e.g. gas concentrations either being too low or exceeding instrumentation limits), or being incomplete or incorrect. Note that the removal of these samples was unlikely to impact outcomes since the sample size was relatively large to guard against some loss. Also, samples for which the gas concentrations were too low or high were due to placement of the probe, too low or air currents moving the emissions plume away from the probe, and are not a reflection of the stoves performance. The following subsections summarize the main performance results. Given the large number of stoves and quantity of collected data, detailed tabular results have been provided in Appendices A and B.

Table 3: Number of samples collected across location for each stove type. Samples with emissions data also had fuel consumption measured, and are therefore a subset of the fuel samples.

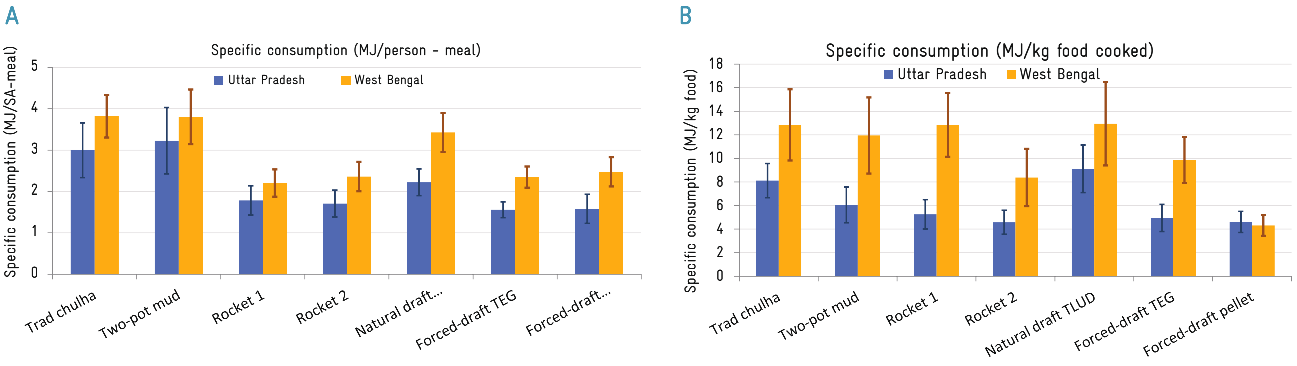
Stove	Uttar Pradesh		West Bengal	
	Fuel	Emissions	Fuel	Emissions
Trad chulha	41	20	41	21
Two-pot mud	45	17	46	23
Rocket 1	44	22	47	22
Rocket 2	44	23	46	22
Natural draft Top-Lit Updraft	50	25	47	23
Forced-draft TEG	44	23	46	23
Forced-draft pellet	47	22	45	22
Total	315	152	318	156

3.2. Fuel Efficiency Performance

Aside from the Two-Pot Mud stove, most new stoves were more fuel efficient (used less fuel per cooking event with respect to the traditional stove), especially when the MJ/person-meal metric was used (see 5A). In Uttar Pradesh, the Forced-Draft TEG, Forced-Draft Pellet and Rocket stoves saved the most fuel energy per meal (40-48%) compared to traditional chulha, while the Two-Pot Mud stove was the only stove which did not save fuel. The Natural Draft gasifier based TLUD stove saved 26% fuel relative to the traditional chulha. All differences in the fuel energy savings per person-meal, with the exception of the two-pot mud stove, were statistically significant at the $p<0.05$ level using the Student's t-test. In West Bengal, the fuel savings were not as large compare to in Uttar Pradesh, although the Forced-Draft TEG, Forced-Draft Pellet and Rocket stoves again performed well, saving 38-42% compared to the traditional chulha ($p<0.01$), while again, the two-pot mud stove was the only stove which did not save fuel. The natural draft gasifier based TLUD stove saved only 10% fuel relative to the traditional chulha, but these were not statistically significant reductions.

Figure 5 shows there are distinct differences in stove performance between the regions, with systematically higher fuel consumption per event in West Bengal. Reasons for the higher fuel consumption in West Bengal may be due different wood species and use of agricultural leaves for fuel (less than 1% of fuel mass in Uttar Pradesh was agricultural residues compared to ~5% in West Bengal). Perhaps most importantly, West Bengal households cooked meals for fewer people, averaging 3.1 persons per meal compared to 4.2 persons per meal in Uttar Pradesh. The specific energy needs for the types of food cooked may have also impacted the results as there are differences in cuisines between the two regions. More detail on the specific foods cooked is provided below.

The fuel efficiency results using the metric of energy used per mass food cooked (MJ/kg food) are shown in Figure 5B, which we had hoped would reduce variability between the cooking events compared to when measured as energy used per person per meal (MJ/person-meal), since including a direct measure of the mass of food cooked in the output metric would seem to be more closely related to the amount of energy required for the task. Unfortunately, this metric did not reduce variability in our estimates, especially for West Bengal (note the large 95% confidence intervals in 5B). Some specific differences in cooking behavior were observed which may explain why this was the case. While cooking tasks in Uttar Pradesh were relatively consistent in terms of food quantities, in West Bengal households regularly cook three or four different type of vegetables in small amounts over the course of the day, as well as use their stove for preparing larger amounts of food. Such variability in the amount of foods cooked may have increased the variability in the MJ/kg food cooked estimates in West Bengal.



Notes: Error bars represent ±95% confidence intervals.

Figure 5A, B: Mean specific fuel consumption estimates normalized by A) the number of people (MJ/person-meal) and B) the quantity of food cooked (MJ/kg food cooked).

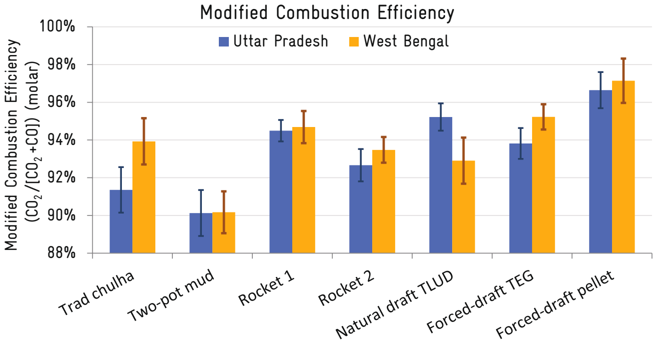
3.3 Emissions Performance

A fundamental measure for emission performance is combustion efficiency, which indicates how fully the fuel carbon is combusted (converted to carbon dioxide). Here we use modified combustion efficiency (MCE)[4] as a proxy for true combustion efficiency, as it is much more practical to measure. Complete combustion would result in CO_2 as the only combustion product. Any presence of CO means reduced combustion efficiency. Aside from Two-Pot Mud stove, all new stoves in Uttar Pradesh had statistically significant higher combustion efficiencies (see Figure 6). The Forced-Draft Pellet stove was had the best combustion efficiency for both (MCEs from 96-98%) indicating that it was best at fully combusting the fuel carbon. The Two-Pot-Mud stove performed poorly at both locations (MCEs of ~90%), which was lower than the Traditional Chulha.

In Uttar Pradesh, the Rocket 1 displayed combustion efficiencies within the range of 94-95%. In contrast, the Rocket 2 stove had slightly lower combustion efficiencies (MCEs of 92- 94%). The gasifier based Top-Lit-Up-Draft stove performed similar to the Rocket 1 stove (MCEs of 94-96%). The Forced-Draft TEG stove had combustion efficiencies from 93-95%, indicating it did not provide much improvement relative to rockets style stoves. It is important to note that the fan was not working properly in some homes (with full speed) due to the discharged batteries. The traditional chulha had with higher variability than the other stove types and generally low combustion efficiency (MCEs of ~90-95%).

In West Bengal, the combustion efficiency performance was similar to in Uttar Pradesh for four of the new stoves: Two-Pot Mud, Rocket 1, Rocket 2 and the Forced-Draft Pellet. However, the Top-Lit-Updraft stove had lower combustion efficiency (MCE ~93%) compared to when used in Uttar Pradesh (MCE ~95%), and the Forced-Draft TEG Stove had higher combustion efficiency (MCEs of 95-96%) compared to when used in Uttar Pradesh (MCE of ~94%). The Traditional Chulha also had much higher combustion efficiency in West Bengal compared to in Uttar Pradesh, which may have been due to difference in chulha design. Traditional Chulha's in West Bengal were typically larger and sunk into the ground, which allowed for higher fuel feeding rates and hence higher fire power as compared to those in Uttar Pradesh. Also, the dung use was much higher in Uttar Pradesh (270 grams per meal) compared to West Bengal (0.05 grams per meal).

Emission rates, the quantity of pollutants emitted over time, for $PM_{2.5}$ and CO are shown in Figure 7. The World Health Organization has provided emission rate targets that are estimated result in meeting air quality guidelines. For $PM_{2.5}$ the initial target is 1.75 mg/min and for CO its 0.35 g/min (WHO, 2014). Although all the stoves except for the Two-Pot Mud stove performed better than the baseline Traditional Chulha, none of the stoves were able to achieve these levels for $PM_{2.5}$, with the Forced-Draft Pellet stove coming the closest (medians of 22 mg/min in Uttar Pradesh and 38 mg/min in West Bengal). The Forced-Draft Pellet stove did have lower median emission rates for CO than the guideline (0.30 g/min in both locations).



Notes: Error bars represent ±95% confidence intervals.

Figure 6: Mean combustion efficiency estimates, measured as modified combustion efficiency (molar ratio of (CO_2/CO_2+CO) during the stove use events.

In Utter Pradesh, the Two-Pot Mud stove had relatively higher emissions of both $PM_{2.5}$ and CO, with medians of 161 mg/min and 1.44 g/min, respectively. The median $PM_{2.5}$ and CO emission rates from the Forced Draft Pellet Stove were 22 mg/min and 0.30 g/min, respectively, reducing the emissions $PM_{2.5}$ by 88% and CO by 77% in respect to the Traditional Chulha. The Forced-Draft TEG stove performed well too, with relatively low emissions of both $PM_{2.5}$ and CO (medians of 37 mg/min and 0.45 g/min, respectively), reducing particulate matter and CO by 79% and 65%

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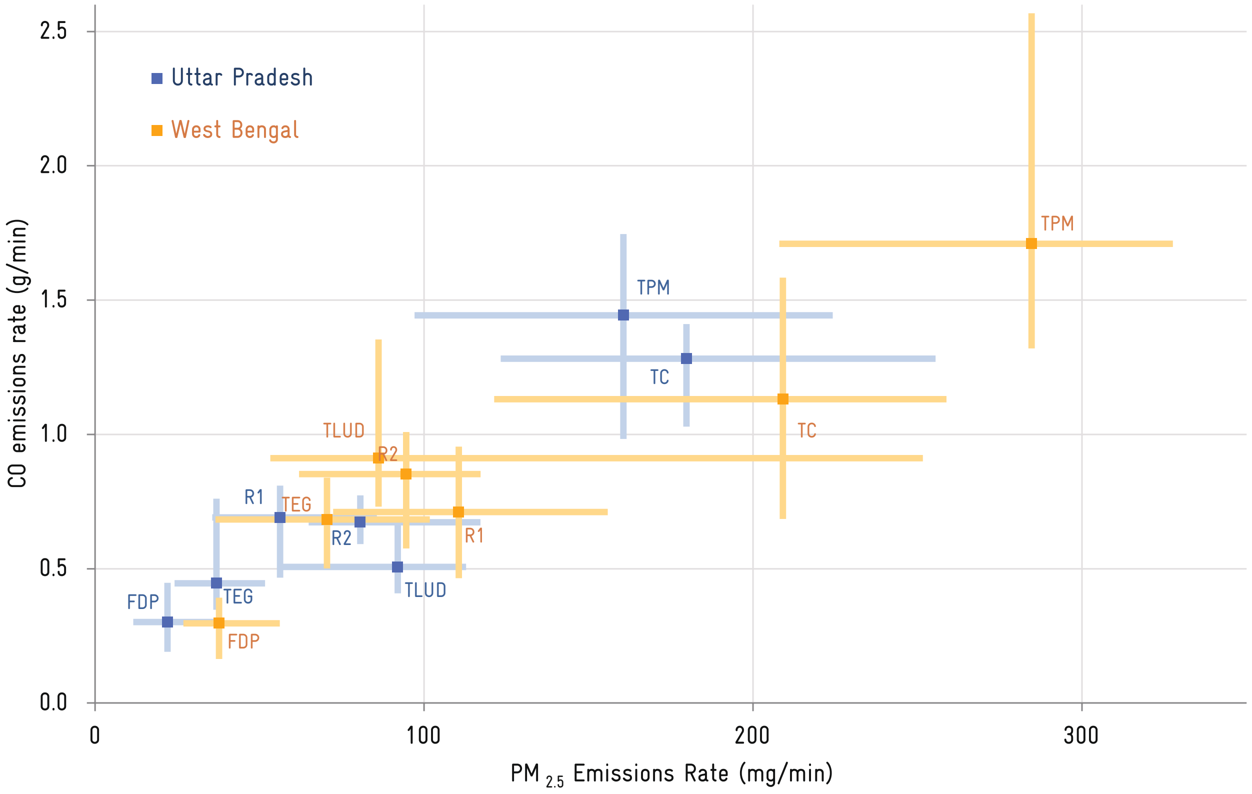
[4] Modified combustion efficiency is the ratio of carbon dioxide to carbon dioxide plus carbon monoxide, as a molar ratio: (CO_2/[CO_2+CO]).

respectively as compared to Traditional Chulha. The rocket stoves have also performed relatively well, with Rocket 1 producing slightly less particulate emissions, reducing PM$_{2.5}$ and CO by 68% and 46%, respectively, compared to the Traditional Chulha. The gasifier based Top-Lit Up-Draft stove produced more particulate matter but less CO emissions than the rocket stoves, reducing the emissions of PM$_{2.5}$ by 48% and CO by 60% as compared to the Traditional Chulha.

In West Bengal, the emission rates were generally higher. The Two-Pot Mud had the highest emission rates, higher than Traditional Chulha. The Traditional Chulhas in West Bengal generated more PM$_{2.5}$ compared to those in Uttar Pradesh, possibly due to differences in design and use of more agricultural residue. The median PM$_{2.5}$ and CO emission rates from the Forced-Draft Pellet stove was again the lowest, reducing the emissions of PM$_{2.5}$ by 90% and CO by 83% relative to the Traditional Chulha. The Force-Draft TEG stove also performed well, with emission rates just slightly higher than the Forced Draft Pellet Stove. Rocket 2 was slightly better in producing lower PM emissions in respect to Rocket 1. The gasifier based Top-Lit Updraft stove produced slightly more PM$_{2.5}$ and substantially higher CO compared to in Uttar Pradesh.



Notes: Error bars represent the 25th and 75th percentiles of the respective distributions.

Figure 7: PM$_{2.5}$ emission rates per minute are presented along the X-axis and CO along the y-axis, with the best performing stoves in the bottom left-hand corner and poorest performers in the upper right. Median emission rates – the midpoint at which half of the samples for a given stove are higher or lower – are shown as square markers. The bars extend on either side of the markers to include the middle 50% of the samples for each stove, which provides an indication of the variability in their emissions performance. TC = Traditional Chulha; TPM = Two-Pot Mud; R1 = Rocket1; R2 = Rocket 2; Top-Lit Updraft = Top-Lit Updraft; TEG = Forced-Draft TEG; FDP = Forced-Draft Pellet.

Emissions of PM$_{2.5}$ and CO per kg of food cooked are shown in Figure 8. This metric indicates overall emissions performance by combining how cleanly a stove burns with how efficiently it cooks food. Stoves which emit less pollutants per kilogram fuel and use less fuel to cook will have the lowest emissions and vice versa. Similar to the emissions rates shown in Figure , all the stoves except the Two-Pot Mud performed better than the Traditional Chulha, while the best performer was the Forced-Draft Pellet. Note that the variability, indicated by the bars, was relatively high for this metric as variability of both emissions and fuel consumption contribute to the overall variability.

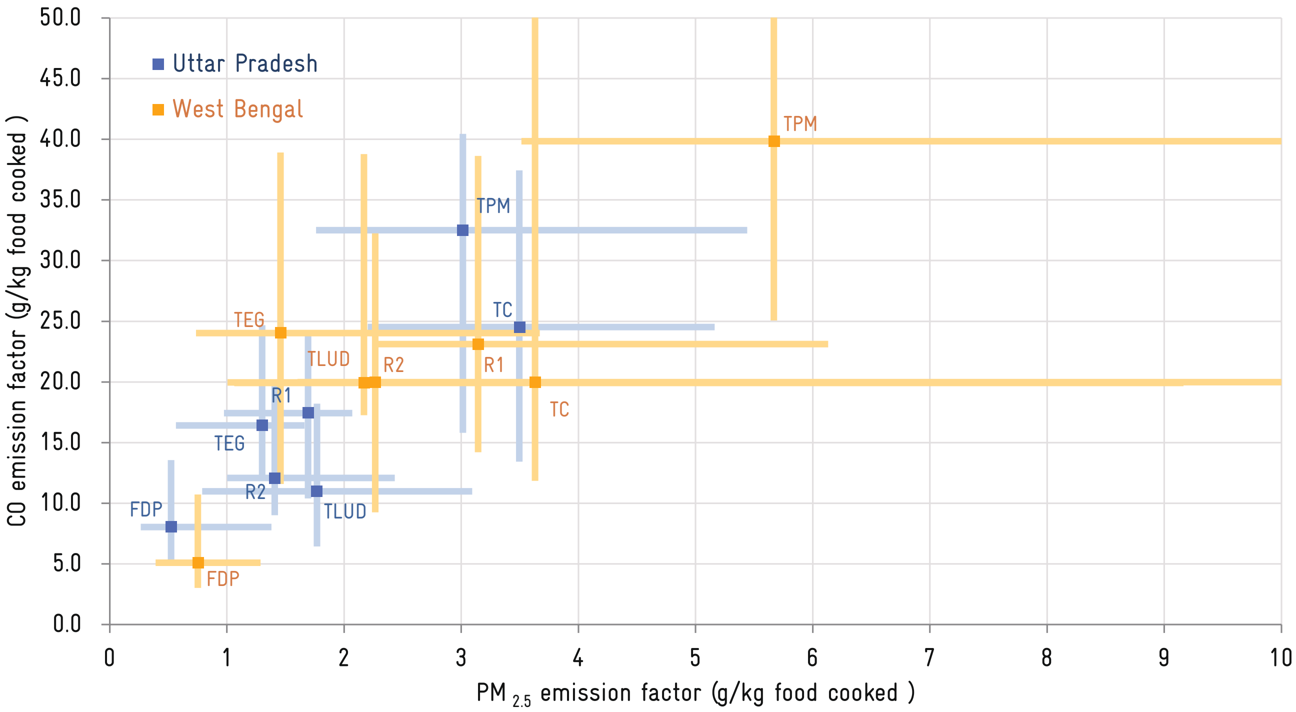


Figure 8. $PM_{2.5}$ emissions per kg food cooked are presented along the X-axis and CO along the y-axis, with the best performing stoves in the bottom left-hand corner and poorest performers in the upper right. Median emission factors – the midpoint at which half of the samples for a given stove are higher or lower – are shown as square markers. The bars extend on either side of the markers to include the middle 50% of the samples for each stove, which provides an indication of the variability in their emissions performance. TC = Traditional Chulha; TPM = Two-Pot Mud; R1 = Rocket1; R2 = Rocket 2; Top-Lit Updraft = Top-Lit Updraft; TEG = Forced-Draft TEG; FDP = Forced-Draft Pellet.

4. IMPACT ON ACCOUNTING FOR CHAR ON OUTCOME METRICS

Key char accounting outcomes:

- Subtracting the remaining char energy in the calculation of fuel efficiency can result in substantially different estimates of the energy required to prepare a meal, and therefore how the stove is rated in terms of fuel efficiency. As this char is not typically re-used by Indian households, it is recommended that the char energy not be accounted for, as was done in this study.

It has been observed in the field, that households generally dispose of post-fire char rather than reusing it. Thus, utilizing the available energy, the specific consumption results are presented in two conditions: the 'with char' case, for which the energy content value (calorific value) of left over char has not been accounted in final calculation of total fuel energy value; and the 'without char' case, for which the energy content value of left over char has been accounted in final calculation of total fuel energy value. Hence, the 'with char' case is the more real world fuel consumption pattern in representing the technical performance of the cookstove in India. The results are presented in figure 10. The results show that if char is accounted for, stoves which produce more char will appear to perform relatively better as this char energy is assumed to go towards cooking.

In determination of thermal efficiency of biomass cookstoves according to Indian Bureau Standards (IS 13152: Part 1- Portable Solid Bio-Mass Cookstove [Chulha], First revision 2013), char energy is not accounted at the end of test (with char), which results in a lower thermal efficiency of the same biomass cookstove when the char energy is included in the calculation of the amount of available energy (without char).

From 10 it can be seen that results of specific consumption at both Uttar Pradesh and West Bengal, that the 'without char' scenario results in lower estimates of specific fuel consumption compared to the 'with char' estimates. This is due to subtraction of char energy content value from results. The Two-Pot Mud and Natural-draft gasifier based TLUD have the largest difference in 'with char' and 'without char' scenarios because they produced the largest relative amounts of char. The Forced-Draft Pellet and Forced Draft TEG cookstoves produce negligible amounts of char and therefore there are almost no differences between the cases.

Importantly, there are substantive differences in between with char and without char scenarios, up to approximately 40% for some stove types. Therefore, care should be taken use the most appropriate scenario for the local context. For this study, since the char is not typically used, all fuel consumption metrics have been calculated using the "with char" scenario.

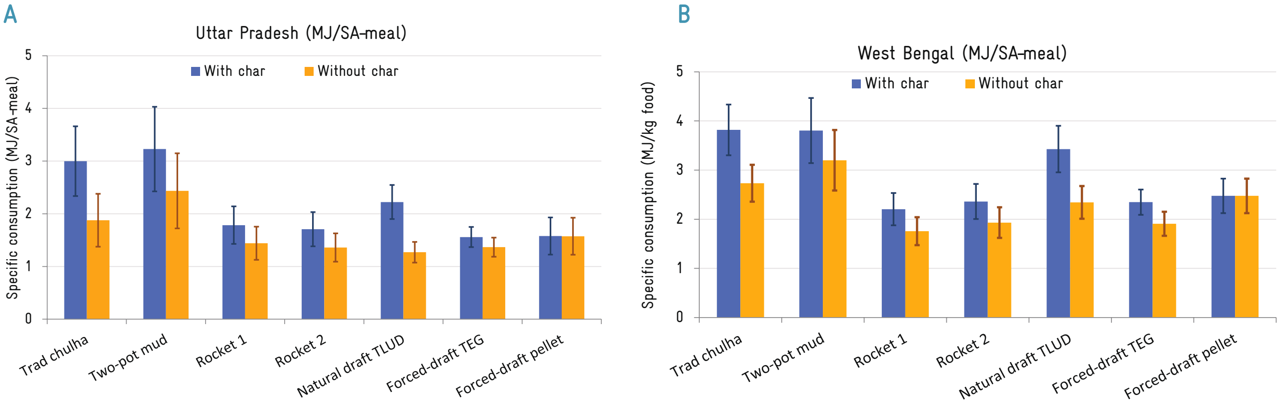


Figure 10 A, B: Specific fuel consumption (MJ/SA-meal) with char and without char at A) Uttar Pradesh and B) West Bengal.

5. COMPARISON OF FIELD AND LABORATORY TEST RESULTS

Key field and laboratory comparisons:

- Stoves were systematically run at a higher firepower in the laboratory compared to in the field, indicating a fundamentally different way that real-world users operated their stoves compared to during controlled testing.
- The modified combustion efficiency, as expected, is generally higher in the laboratory than in the field. Emissions performance was substantially worse in the field compared to the laboratory for all stoves.
- Fuel efficiency in the laboratory and the field generally agreed across stove types, with the caveat that there were several stoves which performed better in the field than the lab. This may be because there is generally a correlation between the firepower at which the stove is operated and the fuel efficiency of the stove. As stoves are operated at lower fire power in the field, this may lead to higher fuel efficiency compared to the laboratory for all stoves.

A comparison of laboratory and field results was made by conducting a series of controlled water boiling tests on the same stoves at the Biomass Cookstove laboratory at IIT Delhi. The sample size for each stove in the laboratory was six. The number of samples was worked out by the same methodology as for the field. These tested were done according to Indian Bureau Standards (BIS) (IS 13152: Part 1- Portable Solid Bio-Mass Cookstove (Chulha), First revision 2013.). Firepower, which is a function of the rate of feeding of the stove is presented as a fundamental characteristic of stove operation. In the BIS protocol, the first step is determination of the burning rate (amount of fuel used by stove per unit time), for every biomass cookstove. Once the burning rate has been determined, the cookstove is tested at that fixed burning rate for one hour, which results in a consistent amount of biomass being used for each test cycle. The BIS test estimates are the means of the six tests carried out on the same stove in the laboratory. The reported values are the means calculated for the six tests. Means are one statistical way to represent the distribution of results obtained in the number of replicates of tests conducted on the same stove. Means are also used as the representative estimates for the field-based data.

Figure 11 A, B, and C show the comparisons of field and laboratory performance. As a fundamental measure of operation, Figure 11A shows the mean firepower. The mean firepower was systematically higher for all stoves when tested in the laboratory, indicating that the laboratory tests were not reflecting the fuel feed rate used in homes. The fuel savings shown in Figure 11C, indicate that the general trend of which stoves saved more or less was relatively consistent. The Two-Pot Mud stove had the lowest fuel efficiency and the forced draft stoves had the best fuel efficiency, for both the laboratory and the field. Interestingly, many of the stoves had relatively greater fuel savings per event in the field compared to the lab, particularly for the two rocket stoves. This difference may be due to the rocket stoves being operated at a lower firepower in the field, which generally allows for more heat to transfer from the combustion gases as they are travelling more slowly over the pot during lower firepower. Except for the Traditional Chulha in West Bengal and natural draft TLUP in Uttar Pradesh, all new cookstoves had combustion efficiencies substantially higher in the laboratory compared to the field (Figure 11B), which substantiates the observation that emissions are much higher in field compared to the lab, and is consistent with previous studies (Berkeley Air, 2012; Johnson et al., 2011b; Roden et al., 2009). The higher combustion efficiency is not surprising given that the laboratory tests were done in a controlled environment with idealized operational conditions.

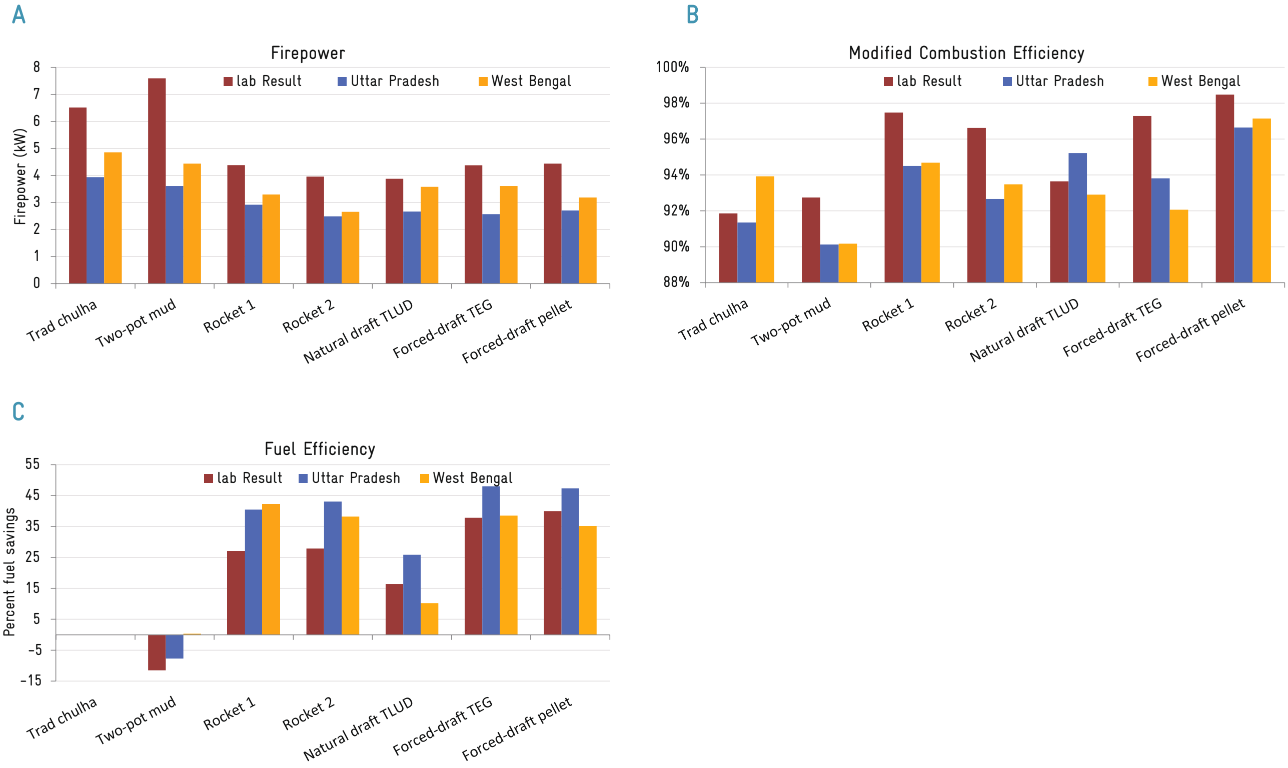


Figure 11. Comparison of laboratory and field performance. Each bar represents a mean result. The firepower graph shows of how much fuel energy is used per unit time, measured by dividing the fuel energy used by the cooking event time. The modified combustion efficiency plot shows the percent of combusted fuel that is converted to carbon dioxide, which is an indicator of how clean the emissions are. The fuel efficiency graph shows the relative fuel savings, either per controlled laboratory test or per person per cooking event during field-testing in both of the states.

6. IMPACT OF OPERATIONAL CONDITIONS

Key operational condition outcomes:

- It was hoped that analysis of operational conditions on stove performance would help explain why stove performance varies both between cooking events and between the laboratory and field. However, this analysis did not result in the ability to substantively explain differences in stove performance based on operational factors. Overall, there were no consistent patterns in which factors caused differences, with non-wood use, moisture content, and pot diameter all providing some predictive capacity for different stoves types.

Given the varied conditions under which stoves are used during normal use in homes, an analysis was conducted to determine if changes in operating conditions could explain the differences between laboratory and field performance. Being able to partially explain why performance varies could help better link laboratory and field performance, as well as inform strategies which can help users optimize the performance of their stoves.

As a first step to help understand the changes in operational conditions, graphs showing how key factors differed were plotted for each stove type (Figure 9). These graphs provide a visual indication of how firepower, moisture content, percent-non woodfuel (dung and crop residues), stick size, and pot size varied for each stove type, and plotting them together shows how they differ between stove types. The boxplots show how the data for each of the factors is distributed, with the middle line representing the median and the boxes encompassing the middle 50% of the data. All of these variables have been shown to impact stove performance (Habib et al., 2008; Johnson et al., 2010; L'Orange et al., 2012a, 2012b; Yuntenwi et al., 2008). Firepower reflects basic tending practices, specifically the extent to which users are adding fuel. Higher proportions of fuel moisture content, use of larger sticks, and lower quality, non-wood fuel use are generally associated with lower stove performance. Larger pots can help increase thermal transfer efficiency, but may also reduce combustion efficiency if they cool the fire or restrict airflow.

Firepower and non-wood fuel use were greatest, and had the most variability, for the Traditional Chulha and the Two-Pot Mud stove, which is not surprising given that these stoves are the most flexible in terms of user operation. The higher firepower reflects their need to burn more fuel per unit time to transfer the same fuel energy to the pot as the other, more fuel-efficient stoves. The Forced-Draft Pellet stove had the narrowest distributions for firepower, non-wood fuel use, moisture content, and stick (pellet) circumference, due to its uniform fuel and restrictive fuel loading regime. Moisture content varied across stove type, and was highest for the Traditional Chulha and the natural draft gasifier based Top-Lit Updraft stove. The natural draft gasifier based Top-Lit Updraft stove also had the highest median stick diameter; however the stick length was limited by the stove height. Pot diameters and stick size distributions (aside from the pellets) were similar across stove type. Overall, the operational factors generally differed substantially between cooking events for the different stove types, which suggests that those changes could be responsible for changes in stove performance.

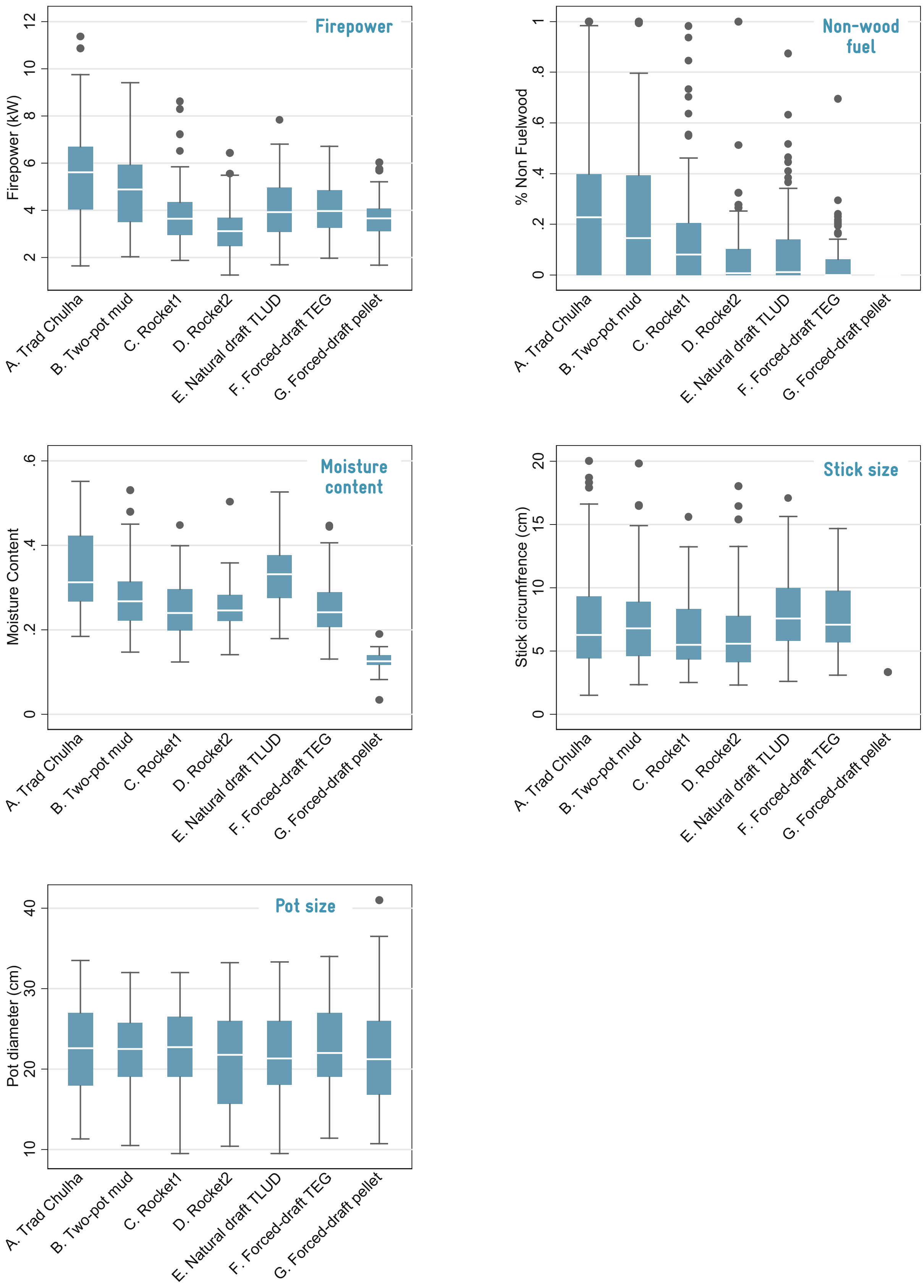


Figure 9. Box plots showing how operational factors varied for the different stove types. The boxplots illustrate how the data is distributed for each factor that may impact stove performance, with the middle line representing the median and the end of the boxes span encompass the middle 50% of the data. The whiskers extend to 1.5 times the middle 50% and the dots are all values outside the whiskers.

To investigate which factors might be causing changes in stove performance, a model[5] was used to see if differences in firepower, moisture content, non-wood fuel use (dung or crop residues), and/or moisture content could predict fuel efficiency and combustion efficiency. The model also included location as the final potential predictor of stove performance to see if variables other than those in the model, but potentially associated with location, may have impacted stove performance.

Table 5 shows that there were very few instances where changes in operational factors were able to explain differences in stove performance. The best prediction of combustion efficiency (r-squared of ~ 0.3) was for the Traditional Chulha, suggesting that at most, 30% of the variability in combustion efficiency could be explained by differences in operational conditions. For fuel efficiency, the best prediction was only about 20%, for the Two-Pot Mud and Rocket1 (r-squared = 0.2). Although firepower was expected to impact fuel performance, it was only a significant predictor for the Two-Pot Mud stove.

For this investigation we selected what were thought to be the most promising operational factors, but further analysis may show stronger associations with different variables such as kerosene use, wood species, ambient temperature or others. The analysis also did not include how tending practices, such as how often fuel or pots were adjusted/added/removed impacted performance, which could also explain some of the differences in fuel and/or combustion efficiency (note that firepower is a reflection of fuel feeding rate). There is also the possibility that other analysis approaches could work better, and it is also likely that there are limits to capturing and accurately quantifying some of the potential predictors of stove performance.

Table 5. Summary of predictive performance of regression models and statistically significant predictors. The R-squared statistic is a measure of how close the data are to the fitted regression line. It is also known as the coefficient of determination, or the coefficient of multiple determination for multiple regression. 0% indicates that the model explains none of the variability of the response data around its mean. If the model has an r-squared value of 0.5, this means that 50% of the differences in fuel efficiency or combustion efficiency can be attributed to changes in operational factors such as firepower and moisture content.

Stove	Modified Combustion Efficiency		MJ/person-meal	
	r-squared	Significant predictors	r-squared	Significant predictors
Traditional chulha	0.31	Non-wood use	0.02	
Two-Pot Mud	0		0.22	Firepower
Rocket 1	0		0.22	Non-wood use
				Moisture content
				Location
Rocket 2	0		0.11	Location
Top-Lit Updraft	0.17	Moisture content	0.18	Non-wood use
		Location		Location
Forced-Draft TEG	0.20	Pot diameter	0.12	Pot diameter
		Location		Location
Forced-Draft pellet	0.04		0.05	Location

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[5] The model used was an ordinary least squares regression model. The model's ability to predict fuel efficiency or combustion efficiency is indicated by the r-squared statistic. If the model has an r-squared value of 0.5, this means that 50% of the differences in fuel efficiency or combustion efficiency can be attributed to changes in operational factors such as firepower and moisture content. The level of significance for each operational factor is also provided by the model, with those that have p-values less than 0.05 being considered statistically significant. The model was run for each stove type. Full output from the models can be found Appendix B.

7. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Informing decisions on stove selection: The main objective of this study was to demonstrate the importance of field testing when determining which cooking technologies to promote based on stove performance. All stoves, except for the Two-Pot Mud stove, performed better than the baseline Traditional Chulha, with significantly lower median emission rates. The best performance at both locations was the Forced-Draft Pellet stove, which comes closest of the stoves tested to the WHO guidelines. Only the forced-draft pellet stoves' CO emissions achieved the WHO emission rate targets.

Field performance varied widely for the different stove types. This study illustrated the potential for reductions in emissions and fuel consumption by these stoves in a real-world situation. There were substantial differences in relative stove performance between Uttar Pradesh and West Bengal, indicating the importance of conducting regionally-specific tests. Informing technology selection decisions based on real-world data, such as that reported herein, is important, as stoves which perform better in real-world situations have the greatest potential for imparting benefits.

Accounting for leftover char: If remaining char is re-used, then the energy in the char can be subtracted from the total fuel energy that was used. However, this will impact the fuel efficiency, making it appear to be better than if the char is not re-used. When the user discards the char, the char energy is lost and should be included in the energy requirement for determining fuel efficiency. Stoves which more completely convert fuel into combustion gases, leaving less char behind, generally perform more efficiently and their fuel efficiency estimates do not change much depending on whether the calculation is made to include or exclude char. As it is more typical for users to discard their char in India, technical performance assessments of the cookstoves in India should not include the leftover energy in their calculations.

Comparing laboratory and field performance: All stoves had poorer emissions performance in the field than in the lab, which is an expected trend. Fuel savings, however, were similar and several of the stove types even had relatively better fuel savings in the field when comparing fuel use against the traditional chulha. Although the analysis conducted here did not show strong patterns between operational conditions and stove performance (see below), there were important differences between how they were operated in the laboratory and the field. Perhaps most importantly, stoves were systematically run at a higher firepower in the laboratory compared to in the field, indicating users did not require the same energy demands as required to conduct the laboratory test.

Impact of operational condition on stove performance in the field: No consistent patterns were observed between operational conditions and stove performance. The analysis indicated that differences in performance were not strongly associated with changes in operational factors such as firepower, moisture content, and use of non-wood fuels. Additional or different analysis may reveal potential relationships not uncovered here by looking at additional factors such as kerosene use, wood species, ambient temperature or others.

Recommendations

User acceptance studies: This study assessed stove performance for distinct cooking events, which only provides an indication of the emissions or fuel benefits accrued per meal. While these outcomes suggest the potential that different stoves may have, their overall benefits at the household level depend on the extent to which the new stoves displace the baseline technology (e.g. traditional chulhas). Complimenting field performance studies with user preferences/ affordability, and ideally, direct measures of stove usage would indicate which stoves would be most likely to have meaningful household level impacts.

Climate implications: This study focused on fuel efficiency and emissions of health-damaging pollutants, which are priorities for India. Climate impacts, especially from black carbon, are also of interest to many stakeholders. GIZ has permitted Berkeley Air Monitoring Group to carry out additional tests of particulate samples to estimate the black carbon emissions (funded by the Global Alliance for Clean Cookstoves). IIT Delhi has transferred all the particulate samples collected for the study to Berkeley Air Monitoring Group. The results should complement this work when available.

Linking laboratory and field performance: A better understanding of laboratory and field performance would provide better prediction of field performance based on lab testing. More predictive laboratory testing would help to both guide stove development towards better field performance and reduce the need for expensive and logistically challenging field testing. Since operational conditions must ultimately be responsible for the differences in performance, it is recommended to continue to determine what combinations of factors are impacting performance, especially those which differ between the laboratory and field.

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9. APPENDICES

A. Detailed Stove Performance Results – Uttar Pradesh

Significant differences from Traditional Chulha are shaded and bolded.

		MCE	CO2 g/kg	CO g/kg	PM2.5g/kg	CO2 g/MJ	CO g/MJ	PM2.5 g/MJ	CO2 g/kg food cooked	CO g/kg food cooked	PM2.5 g/kg food cooked	CO2 g/min
Trad chulha	Mean	91.4%	1169	68.6	10.1	111.1	7.0	1.1	473	27.4	3.8	50.9
	Median	91.7%	1199	66.2	10.3	102.0	6.1	0.9	397	24.5	3.5	41.4
	Standard Deviation	2.7%	217	19.8	4.5	21.9	3.8	0.8	305	18.6	2.3	33.6
	Standard Error	0.6%	49	4.4	1.0	4.9	0.8	0.2	68	4.2	0.5	7.5
	CoV	3%	19%	29%	45%	20%	54%	77%	65%	68%	61%	66%
	Upper 95% CI	92.6%	1264	77.3	12.1	120.7	8.6	1.5	607	35.6	4.8	65.6
	Lower 95% CI	90.2%	1074	59.9	8.1	101.5	5.3	0.7	339	19.3	2.7	36.2
	25th percentile	89.7%	1049	55.0	6.4	97.2	4.5	0.5	261	13.4	2.2	31.4
	75th percentile	93.3%	1302	78.4	11.3	111.6	8.5	1.2	673	37.4	5.1	57.2
	N	20	20	20	20	20	20	20	20	20	20	20
	Mean Difference	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	P-value	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Two-pot mud	Mean	90.1%	1215	84.0	10.1	100.3	7.0	0.8	430	29.3	3.6	41.2
	Median	90.1%	1190	84.5	10.1	99.3	6.8	0.9	391	32.5	3.0	41.5
	Standard Deviation	2.6%	155	21.2	4.9	12.8	1.9	0.4	226	14.8	2.5	23.4
	Standard Error	0.6%	38	5.1	1.2	3.1	0.5	0.1	55	3.6	0.6	5.7
	CoV	3%	13%	25%	48%	13%	27%	46%	53%	51%	70%	57%
	Upper 95% CI	91.3%	1289	94.1	12.4	106.4	7.8	1.0	538	36.4	4.8	52.3
	Lower 95% CI	88.9%	1141	73.9	7.7	94.2	6.1	0.6	323	22.3	2.4	30.1
	25th percentile	88.1%	1121	68.5	6.4	97.1	5.7	0.7	229	15.8	1.8	19.8
	75th percentile	92.0%	1313	102.7	12.3	103.2	8.1	1.0	517	40.5	5.4	63.6
	N	17	17	17	17	17	17	17	17	17	17	17
	Mean Difference	-1%	4%	22%	-1%	-10%	0%	-25%	-9%	7%	-4%	-19%
	P-value	0.200	0.624	0.070	0.937	0.079	0.983	0.212	0.478	0.997	0.699	0.368
Rocket 1	Mean	94.5%	1444	53.9	5.9	104.0	3.9	0.4	485	18.2	1.8	62.1
	Median	94.7%	1488	52.2	4.6	103.1	4.1	0.3	436	17.4	1.7	54.3
	Standard Deviation	1.4%	179	16.1	3.1	6.8	1.0	0.2	289	10.1	1.2	36.5
	Standard Error	0.3%	38	3.4	0.7	1.4	0.2	0.1	62	2.2	0.3	7.8
	CoV	1%	12%	30%	52%	7%	25%	54%	60%	56%	66%	59%
	Upper 95% CI	95.1%	1518	60.6	7.1	106.8	4.3	0.5	606	22.4	2.3	77.3
	Lower 95% CI	93.9%	1369	47.1	4.6	101.2	3.5	0.3	364	14.0	1.3	46.8
	25th percentile	93.3%	1374	40.3	3.6	100.5	3.2	0.3	281	10.4	1.0	34.1
	75th percentile	95.4%	1536	69.3	7.9	105.9	4.6	0.6	592	24.3	2.0	87.7
	N	22	22	22	22	22	22	22	22	22	22	22
	Mean Difference	3%	23%	-21%	-42%	-6%	-45%	-61%	3%	-34%	-52%	22%
	P-value	**0.000**	**0.000**	**0.003**	**0.000**	0.206	**0.000**	**0.001**	0.964	**0.017**	**0.000**	0.221
Rocket 2	Mean	92.7%	1417	70.8	8.9	99.1	5.0	0.6	320	15.6	1.8	48.1
	Median	93.1%	1426	66.7	9.2	98.6	4.6	0.6	265	12.1	1.4	46.4
	Standard Deviation	2.1%	123	19.1	4.7	3.3	1.5	0.4	205	10.8	1.1	19.2
	Standard Error	0.4%	26	4.0	1.0	0.7	0.3	0.1	43	2.3	0.2	4.0
	CoV	2%	9%	27%	52%	3%	29%	56%	64%	70%	64%	40%
	Upper 95% CI	93.5%	1467	78.6	10.8	100.4	5.6	0.8	404	20.0	2.3	56.0
	Lower 95% CI	91.8%	1367	63.0	7.0	97.7	4.4	0.5	236	11.1	1.3	40.2

CO g/min	PM2.5 mg/min	Power (kW)	Fuel Consumption Per Event (g)	Fuel Consumption Per Event (MJ)	Standard Adults	Event Weight	Fuel Consumption Per SA-meal (g)	Fuel consumption per SA-Meal (MJ)	Mass of Food Cooked Per Meal (kg)	Fuel Consumption per mass food cooked (g fuel/kg food)	Fuel Consumption per mass food cooked (MJ fuel/kg food)
1.5	211	3.94	900	10.75	4.4	1.2	251	3.0	1.7	666	8.1
1.3	180	3.59	865	9.40	4.1	1.0	194	2.2	1.5	524	5.9
0.9	135	1.98	466	5.52	2.2	0.5	187	2.2	1.1	377	4.7
0.2	30	0.31	73	0.86	0.3	0.1	29	0.3	0.2	59	0.7
61%	64%	50%	52%	51%	49%	43%	74%	72%	63%	57%	58%
1.8	270	4.55	1043	12.44	5.1	1.4	308	3.7	2.0	782	9.6
1.1	152	3.33	757	9.05	3.8	1.1	194	2.3	1.4	551	6.7
1.0	124	2.54	543	6.64	3.3	1.0	110	1.4	0.9	355	4.4
1.4	254	4.81	1144	12.93	5.0	1.0	338	3.9	2.4	995	11.2
20	20	41	41	41	41	41	41	41	41	41	41
0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.5	170	3.61	929	11.67	4.6	1.3	255	3.2	2.7	491	6.1
1.4	161	3.35	814	9.88	4.1	1.0	209	2.5	2.5	319	4.0
0.6	97	1.26	463	6.48	2.2	0.5	202	2.7	1.6	429	5.2
0.2	24	0.19	69	0.97	0.3	0.1	30	0.4	0.2	64	0.8
43%	57%	35%	50%	56%	47%	40%	79%	85%	60%	87%	86%
1.8	216	3.98	1064	13.57	5.2	1.5	314	4.0	3.2	617	7.6
1.2	124	3.24	793	9.78	4.0	1.2	196	2.4	2.3	366	4.5
1.0	98	2.70	641	7.82	3.3	1.0	121	1.6	1.3	213	2.6
1.7	223	4.36	1126	13.28	5.6	2.0	269	3.7	3.9	563	7.0
17	17	45	45	45	45	45	45	45	45	45	45
1%	-20%	-8%	3%	9%	4%	7%	1%	8%	60%	-26%	-25%
0.834	0.218	0.194	0.971	0.672	0.720	0.273	0.966	0.709	0.001	0.034	0.037
0.7	74	2.92	475	6.52	4.2	1.1	130	1.8	1.5	389	5.3
0.7	56	2.64	390	5.34	4.0	1.0	91	1.4	1.4	322	4.0
0.2	49	1.10	307	4.20	1.9	0.4	90	1.2	0.9	310	4.2
0.1	10	0.17	46	0.63	0.3	0.1	14	0.2	0.1	47	0.6
37%	67%	38%	65%	64%	44%	37%	69%	67%	57%	80%	81%
0.8	94	3.25	566	7.76	4.8	1.3	157	2.1	1.7	480	6.5
0.6	53	2.60	385	5.27	3.7	1.0	104	1.4	1.2	297	4.0
0.5	37	2.11	226	3.24	3.3	1.0	53	0.8	0.8	209	3.0
0.8	85	3.44	661	8.43	4.9	1.0	215	2.8	2.0	452	6.4
22	22	44	44	44	44	44	44	44	44	44	44
-55%	-65%	-26%	-47%	-39%	-5%	-7%	-48%	-40%	-13%	-42%	-35%
0.000	0.000	0.001	0.000	0.000	0.595	0.603	0.000	0.001	0.251	0.000	0.002
0.7	89	2.49	475	6.74	4.4	1.2	120	1.7	2.1	326	4.6
0.7	81	2.28	444	5.88	4.4	1.0	106	1.4	1.8	250	3.3
0.2	45	0.81	230	3.35	1.3	0.5	76	1.1	1.4	242	3.4
0.0	9	0.12	35	0.50	0.2	0.1	11	0.2	0.2	36	0.5
33%	51%	32%	48%	50%	30%	43%	63%	64%	66%	74%	75%
0.8	108	2.72	543	7.72	4.7	1.3	142	2.0	2.5	397	5.6
0.6	71	2.25	407	5.75	4.0	1.0	97	1.4	1.7	254	3.6

		MCE	CO2 g/kg	CO g/kg	PM2.5g/kg	CO2 g/MJ	CO g/MJ	PM2.5 g/MJ	CO2 g/kg food cooked	CO g/kg food cooked	PM2.5 g/kg food cooked	CO2 g/min
	25th percentile	91.8%	1356	59.2	6.3	96.5	4.1	0.4	199	9.0	1.0	36.1
	75th percentile	93.9%	1506	81.5	9.8	100.9	5.7	0.8	380	19.8	2.4	59.7
	N	23	23	23	23	23	23	23	23	23	23	23
	Mean Difference	1%	21%	3%	-12%	-11%	-28%	-43%	-32%	-43%	-52%	-5%
	P-value	0.045	0.000	0.921	0.334	0.021	0.019	0.023	0.028	0.004	0.000	0.882
Natural draft Top Lit Updraft	Mean	95.2%	1265	39.5	7.7	96.6	3.1	0.6	438	12.9	2.5	56.4
	Median	95.5%	1234	39.2	5.9	97.4	3.0	0.4	369	11.0	1.8	52.2
	Standard Deviation	1.8%	193	14.3	6.8	9.3	1.3	0.5	365	8.7	2.6	25.0
	Standard Error	0.4%	39	2.9	1.4	1.9	0.3	0.1	73	1.7	0.5	5.0
	CoV	2%	15%	36%	87%	10%	42%	86%	83%	67%	104%	44%
	Upper 95% CI	95.9%	1341	45.0	10.4	100.2	3.6	0.8	581	16.3	3.5	66.2
	Lower 95% CI	94.5%	1189	33.9	5.1	92.9	2.6	0.4	294	9.5	1.5	46.6
	25th percentile	93.7%	1132	28.1	4.6	92.2	2.1	0.3	256	6.4	0.8	42.2
	75th percentile	96.2%	1381	47.8	8.9	104.2	4.4	0.8	477	18.2	3.1	55.8
	N	25	25	25	25	25	25	25	25	25	25	25
	Mean Difference	4%	8%	-42%	-23%	-13%	-55%	-45%	-7%	-53%	-34%	11%
	P-value	0.000	0.184	0.000	0.140	0.008	0.000	0.026	0.591	0.001	0.046	0.404
Forced-draft TEG	Mean	93.8%	1522	63.8	4.3	96.2	4.0	0.3	561	23.5	1.5	46.7
	Median	93.7%	1514	64.7	4.3	96.8	4.0	0.3	423	16.4	1.3	42.8
	Standard Deviation	2.0%	104	21.3	2.4	7.9	1.3	0.1	433	18.7	1.3	27.2
	Standard Error	0.4%	22	4.4	0.5	1.6	0.3	0.0	90	3.9	0.3	5.7
	CoV	2%	7%	33%	55%	8%	33%	55%	77%	80%	85%	58%
	Upper 95% CI	94.6%	1565	72.5	5.3	99.4	4.6	0.3	738	31.1	2.1	57.8
	Lower 95% CI	93.0%	1480	55.1	3.3	93.0	3.5	0.2	384	15.8	1.0	35.6
	25th percentile	92.3%	1469	52.7	2.7	92.1	3.1	0.2	320	12.0	0.6	26.6
	75th percentile	94.9%	1578	78.6	5.7	99.8	5.2	0.4	610	24.7	1.6	55.1
	N	23	23	23	23	23	23	23	23	23	23	23
	Mean Difference	3%	30%	-7%	-57%	-13%	-42%	-75%	19%	-14%	-59%	-8%
	P-value	0.001	0.000	0.233	0.000	0.006	0.001	0.000	0.511	0.293	0.000	0.771
Forced-draft pellet	Mean	96.6%	1721	38.1	3.5	112.7	2.5	0.2	545	11.5	1.2	59.1
	Median	97.3%	1708	30.2	2.1	113.0	2.0	0.1	401	8.0	0.5	57.1
	Standard Deviation	2.3%	88	26.0	3.6	5.8	1.7	0.2	371	12.7	1.6	18.4
	Standard Error	0.5%	19	5.5	0.8	1.2	0.4	0.1	79	2.7	0.3	3.9
	CoV	2%	5%	68%	103%	5%	69%	102%	68%	111%	135%	31%
	Upper 95% CI	97.6%	1758	49.0	5.1	115.1	3.2	0.3	700	16.8	1.9	66.8
	Lower 95% CI	95.7%	1684	27.2	2.0	110.2	1.8	0.1	390	6.2	0.5	51.4
	25th percentile	96.2%	1684	19.1	1.2	110.4	1.2	0.1	284	4.9	0.3	44.5
	75th percentile	98.3%	1745	49.3	3.7	116.0	2.8	0.3	681	13.6	1.4	73.7
	N	22	22	22	22	22	22	22	22	22	22	22
	Mean Difference	6%	47%	-44%	-65%	1%	-64%	-79%	15%	-58%	-68%	16%
	P-value	0.000	0.000	0.000	0.000	0.538	0.000	0.000	0.575	0.001	0.000	0.218

CO g/min	PM2.5 mg/min	Power (kW)	Fuel Consumption Per Event (g)	Fuel Consumption Per Event (MJ)	Standard Adults	Event Weight	Fuel Consumption Per SA-meal (g)	Fuel consumption per SA-Meal (MJ)	Mass of Food Cooked Per Meal (kg)	Fuel Consumption per mass food cooked (g fuel/kg food)	Fuel Consumption per mass food cooked (MJ fuel/kg food)
0.6	66	2.03	343	4.65	3.4	1.0	77	1.0	1.1	172	2.5
0.8	116	2.88	558	8.28	5.1	1.6	141	2.1	2.7	443	6.1
23	23	44	44	44	44	44	44	44	44	44	44
-51%	-58%	-37%	-47%	-37%	-2%	-3%	-52%	-43%	21%	-51%	-44%
0.000	0.000	0.000	0.000	0.000	0.803	0.950	0.000	0.000	0.198	0.000	0.000
0.5	102	2.67	651	8.31	4.3	1.0	177	2.2	1.2	709	9.1
0.5	92	2.66	561	7.59	4.0	1.0	152	1.9	1.0	568	7.3
0.2	74	0.99	271	3.23	1.7	0.4	112	1.2	0.7	560	7.3
0.0	15	0.14	38	0.46	0.2	0.1	16	0.2	0.1	79	1.0
42%	72%	37%	42%	39%	39%	40%	63%	53%	58%	79%	80%
0.6	130	2.95	726	9.20	4.8	1.1	208	2.5	1.4	864	11.1
0.5	73	2.39	576	7.42	3.8	0.9	146	1.9	1.0	553	7.1
0.4	57	1.90	481	6.04	3.1	1.0	116	1.6	0.8	381	5.1
0.7	112	3.26	799	10.01	5.4	1.0	221	2.7	1.5	715	9.8
25	25	50	50	50	50	50	50	50	50	50	50
-63%	-52%	-32%	-28%	-23%	-3%	-21%	-30%	-26%	-28%	6%	12%
0.000	0.001	0.000	0.001	0.004	0.702	0.017	0.017	0.025	0.013	0.717	0.496
0.5	35	2.57	358	5.33	3.8	1.2	104	1.6	1.4	328	4.9
0.4	37	2.33	325	4.95	3.6	1.0	98	1.5	1.2	254	3.8
0.3	19	1.17	134	2.00	1.4	0.5	43	0.6	0.8	243	3.9
0.1	4	0.18	20	0.30	0.2	0.1	6	0.1	0.1	37	0.6
48%	52%	45%	37%	38%	37%	40%	41%	41%	58%	74%	79%
0.7	43	2.91	397	5.92	4.2	1.4	117	1.7	1.6	400	6.1
0.4	28	2.22	318	4.74	3.4	1.1	92	1.4	1.2	256	3.8
0.3	25	1.80	263	3.91	2.8	1.0	72	1.1	1.0	201	2.9
0.8	51	3.04	458	6.73	4.8	1.0	134	2.0	1.6	326	5.0
23	23	44	44	44	44	44	44	44	44	44	44
-62%	-83%	-35%	-60%	-50%	-14%	-1%	-58%	-48%	-18%	-51%	-39%
0.000	0.000	0.000	0.000	0.000	0.090	0.881	0.000	0.000	0.115	0.000	0.000
0.4	36	2.71	329	4.87	3.8	1.0	106	1.6	1.4	313	4.6
0.3	22	2.82	299	4.60	3.6	1.0	85	1.2	1.2	233	3.7
0.2	38	0.62	129	1.78	1.6	0.2	84	1.2	0.9	221	3.1
0.0	8	0.09	19	0.26	0.2	0.0	12	0.2	0.1	32	0.5
64%	105%	23%	39%	37%	42%	21%	79%	78%	63%	70%	68%
0.5	51	2.88	366	5.38	4.2	1.1	130	1.9	1.7	377	5.5
0.3	20	2.53	292	4.36	3.3	1.0	82	1.2	1.2	250	3.7
0.2	13	2.25	242	3.57	2.8	1.0	66	1.0	0.9	161	2.5
0.4	38	3.08	392	5.67	4.7	1.0	116	1.7	1.5	370	5.3
22	22	47	47	47	47	47	47	47	47	47	47
-75%	-83%	-31%	-63%	-55%	-15%	-16%	-58%	-47%	-18%	-53%	-43%
0.000	0.000	0.000	0.000	0.000	0.087	0.048	0.000	0.000	0.127	0.000	0.000

B. Detailed Stove Performance Results – West Bengal

Significant differences from Traditional Chulha are shaded and bolded.

		MCE	CO2 g/kg	CO g/kg	PM2.5g/kg	CO2 g/MJ	CO g/MJ	PM2.5 g/ MJ	CO2 g/ kg food cooked	CO g/ kg food cooked	PM2.5 g/ kg food cooked	CO2 g/min
Trad chulha	Mean	93.9%	1365	55.3	9.5	96.6	4.0	0.7	867	37.1	6.7	59.0
	Median	94.5%	1321	48.1	7.8	97.5	3.6	0.6	686	20.0	3.6	55.4
	Standard Deviation	2.9%	159	24.3	5.7	14.6	2.2	0.4	639	36.0	7.0	23.3
	Standard Error	0.6%	35	5.3	1.3	3.2	0.5	0.1	140	7.9	1.5	5.1
	CoV	3%	12%	44%	60%	15%	54%	61%	74%	97%	104%	40%
	Upper 95% CI	95.2%	1433	65.7	12.0	102.9	5.0	0.9	1140	52.5	9.7	69.0
	Lower 95% CI	92.7%	1297	44.9	7.1	90.4	3.1	0.5	593	21.6	3.7	49.1
	25th percentile	93.4%	1264	40.9	6.4	85.9	2.4	0.4	287	11.8	1.6	50.4
	75th percentile	95.7%	1451	59.6	11.2	103.3	4.6	0.8	1324	59.4	10.1	63.2
	N	21	21	21	21	21	21	21	21	21	21	21
	Mean Difference	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
	P-value	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Two-pot mud	Mean	90.2%	1470	101.3	16.1	103.1	7.1	1.1	1021	66.0	11.5	57.2
	Median	90.9%	1471	94.7	14.4	103.1	6.4	1.0	578	39.8	5.7	44.7
	Standard Deviation	2.7%	103	24.8	6.8	6.7	1.9	0.5	1013	60.9	12.5	25.4
	Standard Error	0.6%	22	5.2	1.4	1.4	0.4	0.1	211	12.7	2.6	5.3
	CoV	3%	7%	25%	42%	7%	27%	44%	99%	92%	108%	44%
	Upper 95% CI	91.3%	1513	111.5	18.9	105.8	7.9	1.3	1435	90.9	16.6	67.6
	Lower 95% CI	89.1%	1428	91.2	13.3	100.3	6.4	0.9	607	41.1	6.4	46.8
	25th percentile	88.8%	1415	87.2	11.7	99.2	6.1	0.8	324	25.1	3.5	39.0
	75th percentile	91.7%	1548	115.2	16.4	106.0	8.3	1.2	1446	78.9	13.9	82.4
	N	23	23	23	23	23	23	23	23	23	23	23
	Mean Difference	-4%	8%	83%	69%	7%	76%	66%	18%	78%	72%	-3%
	P-value	0.000	0.015	0.000	0.001	0.075	0.000	0.002	0.546	0.061	0.117	0.803
Rocket 1	Mean	94.7%	1470	52.1	8.9	104.8	3.8	0.6	924	33.4	5.6	75.8
	Median	94.8%	1513	47.9	7.1	105.5	3.5	0.6	702	23.1	3.1	75.1
	Standard Deviation	2.0%	176	20.9	6.0	5.8	1.5	0.5	632	35.3	5.6	24.1
	Standard Error	0.4%	38	4.5	1.3	1.2	0.3	0.1	135	7.5	1.2	5.1
	CoV	2%	12%	40%	67%	6%	40%	71%	68%	106%	99%	32%
	Upper 95% CI	95.5%	1544	60.8	11.4	107.3	4.4	0.8	1188	48.2	8.0	85.9
	Lower 95% CI	93.8%	1396	43.3	6.4	102.4	3.1	0.5	660	18.6	3.3	65.7
	25th percentile	93.5%	1310	41.5	6.3	101.5	2.8	0.4	461	14.2	2.3	57.8
	75th percentile	96.2%	1588	57.0	9.9	108.8	4.6	0.7	1315	38.6	6.1	100.1
	N	22	22	22	22	22	22	22	22	22	22	22
	Mean Difference	1%	8%	-6%	-6%	9%	-7%	-6%	7%	-10%	-16%	28%
	P-value	0.326	0.047	0.643	0.738	0.024	0.614	0.772	0.769	0.739	0.587	0.026
Rocket 2	Mean	93.5%	1498	66.5	7.9	105.5	4.7	0.6	595	27.4	3.8	65.1
	Median	93.6%	1484	63.6	7.2	105.0	4.7	0.5	383	20.0	2.3	55.9
	Standard Deviation	1.6%	124	17.3	3.4	6.0	1.2	0.2	464	28.1	4.6	28.3
	Standard Error	0.3%	26	3.7	0.7	1.3	0.3	0.1	99	6.0	1.0	6.0
	CoV	2%	8%	26%	43%	6%	26%	42%	78%	102%	120%	43%
	Upper 95% CI	94.2%	1550	73.7	9.4	108.0	5.2	0.7	789	39.1	5.7	76.9
	Lower 95% CI	92.8%	1446	59.2	6.5	103.0	4.2	0.5	401	15.7	1.9	53.3
	25th percentile	92.5%	1437	53.1	5.3	102.5	3.5	0.4	235	9.3	1.0	45.7
	75th percentile	94.7%	1608	75.4	9.4	107.5	5.4	0.7	795	32.2	4.4	80.2

CO g/min	PM2.5 mg/min	Power (kW)	Fuel Consumption Per Event (g)	Fuel Consumption Per Event (MJ)	Standard Adults	Event Weight	Fuel Consumption Per SA-meal (g)	Fuel consumption per SA-Meal (MJ)	Mass of Food Cooked Per Meal (kg)	Fuel Consumption per mass food cooked (g fuel/kg food)	Fuel Consumption per mass food cooked (MJ fuel/kg food)
1.3	218	4.86	889	11.58	3.2	1.0	297	3.8	1.7	1014	12.8
1.1	209	5.03	883	11.18	2.9	1.0	275	3.7	1.1	781	9.7
0.7	141	1.58	354	4.97	1.1	0.1	139	1.7	1.6	788	9.9
0.2	31	0.25	55	0.78	0.2	0.0	22	0.3	0.3	123	1.5
56%	64%	32%	40%	43%	34%	8%	47%	44%	93%	78%	77%
1.6	279	5.35	997	13.11	3.5	1.0	340	4.3	2.2	1255	15.9
1.0	158	4.38	781	10.06	2.9	1.0	255	3.3	1.2	772	9.8
0.7	121	3.80	653	8.48	2.4	1.0	188	2.4	0.5	447	5.6
1.6	259	5.99	1126	14.38	3.4	1.0	390	5.0	2.5	1394	17.7
21	21	41	41	41	41	41	41	41	41	41	41
0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
1.9	292	4.44	715	9.98	2.8	1.0	274	3.8	1.7	866	11.9
1.7	285	4.40	610	8.47	2.6	1.0	256	3.5	1.4	519	7.4
0.7	110	1.47	455	6.42	1.2	0.1	166	2.3	1.4	804	11.2
0.2	23	0.22	67	0.95	0.2	0.0	25	0.3	0.2	119	1.6
38%	38%	33%	64%	64%	43%	14%	61%	60%	81%	93%	94%
2.2	337	4.86	847	11.84	3.1	1.1	322	4.5	2.1	1098	15.2
1.6	247	4.02	584	8.12	2.4	1.0	226	3.1	1.3	633	8.7
1.3	208	3.30	349	4.92	2.3	1.0	148	1.9	0.4	288	4.0
2.6	328	5.48	904	12.49	3.1	1.0	335	4.9	2.5	1219	15.9
23	23	46	46	46	46	46	46	46	46	46	46
49%	34%	-9%	-20%	-14%	-14%	6%	-8%	0%	-2%	-15%	-7%
0.006	0.064	0.199	0.049	0.194	0.068	0.025	0.470	0.974	0.907	0.390	0.691
0.8	129	3.30	424	5.75	3.0	1.0	162	2.2	1.0	946	12.8
0.7	111	3.09	390	5.40	2.8	1.0	136	1.9	0.6	752	9.9
0.4	85	1.04	181	2.36	1.6	0.1	92	1.2	1.3	728	9.5
0.1	18	0.15	26	0.34	0.2	0.0	13	0.2	0.2	106	1.4
48%	66%	32%	43%	41%	54%	13%	56%	52%	132%	77%	74%
0.9	164	3.59	475	6.43	3.4	1.0	189	2.5	1.4	1154	15.5
0.6	93	3.00	372	5.08	2.5	1.0	136	1.9	0.6	738	10.1
0.5	72	2.68	282	3.87	2.2	1.0	118	1.6	0.3	491	6.8
1.0	156	3.70	510	7.03	3.5	1.0	171	2.4	1.0	1183	17.3
22	22	47	47	47	47	47	47	47	47	47	47
-41%	-41%	-32%	-52%	-50%	-8%	0%	-45%	-42%	-43%	-7%	0%
0.005	0.017	0.000	0.000	0.000	0.384	0.944	0.000	0.000	0.022	0.678	0.999
0.8	98	2.66	445	6.22	2.9	1.0	169	2.4	1.4	607	8.4
0.9	95	2.68	461	6.40	2.7	1.0	148	2.1	1.0	382	5.5
0.3	49	0.79	186	2.64	1.1	0.1	87	1.2	1.2	615	8.4
0.1	10	0.12	27	0.39	0.2	0.0	13	0.2	0.2	91	1.2
35%	50%	30%	42%	42%	39%	15%	51%	52%	81%	101%	101%
0.9	118	2.89	498	6.98	3.2	1.0	194	2.7	1.8	784	10.8
0.7	78	2.43	391	5.46	2.5	0.9	144	2.0	1.1	429	5.9
0.6	62	2.21	294	4.07	2.3	1.0	124	1.7	0.4	213	3.0
1.0	117	3.06	594	8.29	3.6	1.0	206	2.8	2.3	806	10.9

		MCE	CO2 g/kg	CO g/kg	PM2.5g/kg	CO2 g/MJ	CO g/MJ	PM2.5 g/MJ	CO2 g/kg food cooked	CO g/kg food cooked	PM2.5 g/kg food cooked	CO2 g/min
	N	22	22	22	22	22	22	22	22	22	22	22
	Mean Difference	0%	10%	20%	-17%	9%	16%	-19%	-31%	-26%	-43%	10%
	P-value	0.533	0.004	0.093	0.277	0.016	0.243	0.229	0.120	0.334	0.118	0.448
Natural draft Top Lit Updraft	Mean	92.9%	1361	66.0	12.8	101.4	4.9	1.0	837	50.5	15.2	46.0
	Median	94.2%	1390	53.4	5.1	102.0	4.1	0.4	533	19.9	2.2	45.7
	Standard Deviation	3.0%	132	28.1	15.8	6.8	2.0	1.2	743	74.2	38.6	14.6
	Standard Error	0.6%	28	5.9	3.3	1.4	0.4	0.3	155	15.5	8.1	3.0
	CoV	3%	10%	43%	123%	7%	40%	126%	89%	147%	253%	32%
	Upper 95% CI	94.1%	1415	77.5	19.3	104.2	5.7	1.5	1140	80.8	31.0	52.0
	Lower 95% CI	91.7%	1307	54.5	6.4	98.6	4.1	0.5	533	20.2	-0.5	40.1
	25th percentile	91.0%	1300	47.1	3.5	97.4	3.6	0.3	393	17.3	1.1	33.6
	75th percentile	94.8%	1452	82.3	16.5	106.9	5.8	1.0	903	38.8	9.2	54.1
	N	23	23	23	23	23	23	23	23	23	23	23
	Mean Difference	-1%	0%	19%	35%	5%	21%	43%	-3%	36%	128%	-22%
	P-value	0.254	0.916	0.184	0.356	0.185	0.188	0.291	0.885	0.444	0.307	0.035
Forced-draft TEG	Mean	95.2%	1477	47.2	5.1	104.9	3.3	0.4	866	29.0	2.9	58.1
	Median	95.5%	1483	45.6	4.8	105.6	3.2	0.3	832	24.0	1.5	54.9
	Standard Deviation	1.6%	120	17.6	3.5	4.4	1.1	0.2	557	23.9	3.1	19.8
	Standard Error	0.3%	25	3.7	0.7	0.9	0.2	0.1	116	5.0	0.6	4.1
	CoV	2%	8%	37%	68%	4%	34%	67%	64%	82%	106%	34%
	Upper 95% CI	95.9%	1526	54.4	6.5	106.7	3.8	0.5	1094	38.7	4.2	66.2
	Lower 95% CI	94.6%	1428	40.0	3.7	103.1	2.9	0.3	638	19.2	1.7	50.0
	25th percentile	94.1%	1421	33.7	2.9	102.3	2.6	0.2	431	11.6	0.7	45.7
	75th percentile	96.1%	1564	57.1	6.4	108.1	4.1	0.4	1121	38.9	3.7	67.9
	N	23	23	23	23	23	23	23	23	23	23	23
	Mean Difference	1%	8%	-15%	-47%	9%	-17%	-48%	0%	-22%	-56%	-2%
	P-value	0.077	0.013	0.219	0.004	0.020	0.192	0.004	0.997	0.392	0.030	0.892
Forced-draft pellet	Mean	97.1%	1718	32.4	3.3	115.7	2.1	0.2	559	9.0	1.3	73.6
	Median	97.9%	1714	23.0	2.7	118.7	1.6	0.2	448	5.1	0.8	67.2
	Standard Deviation	2.8%	74	31.8	2.6	7.4	2.1	0.1	377	8.9	1.9	31.5
	Standard Error	0.6%	16	6.8	0.6	1.6	0.5	0.0	80	1.9	0.4	6.7
	CoV	3%	4%	98%	79%	6%	100%	64%	67%	99%	150%	43%
	Upper 95% CI	98.3%	1748	45.7	4.4	118.8	3.0	0.3	716	12.7	2.1	86.7
	Lower 95% CI	96.0%	1687	19.1	2.2	112.6	1.2	0.2	402	5.3	0.5	60.4
	25th percentile	97.0%	1692	11.6	2.0	112.4	0.8	0.1	308	3.0	0.4	54.9
	75th percentile	98.9%	1726	33.9	3.7	121.0	2.1	0.2	689	10.7	1.3	90.0
	N	22	22	22	22	22	22	22	22	22	22	22
	Mean Difference	3%	26%	-41%	-65%	20%	-47%	-69%	-36%	-76%	-81%	25%
	P-value	0.001	0.000	0.011	0.000	0.000	0.006	0.000	0.065	0.002	0.002	0.093

CO g/min	PM2.5 mg/min	Power (kW)	Fuel Consumption Per Event (g)	Fuel Consumption Per Event (MJ)	Standard Adults	Event Weight	Fuel Consumption Per SA-meal (g)	Fuel consumption per SA-Meal (MJ)	Mass of Food Cooked Per Meal (kg)	Fuel Consumption per mass food cooked (g fuel/kg food)	Fuel Consumption per mass food cooked (MJ fuel/kg food)
22	22	46	46	46	46	46	46	46	46	46	46
-37%	-55%	-45%	-50%	-46%	-10%	-1%	-43%	-38%	-18%	-40%	-35%
0.009	0.001	0.000	0.000	0.000	0.166	0.703	0.000	0.000	0.296	0.009	0.027
1.1	227	3.58	756	10.46	3.4	1.0	249	3.4	1.5	939	12.9
0.9	86	3.73	691	9.90	3.4	1.0	216	3.0	1.3	559	7.5
0.6	308	0.87	278	3.93	1.3	0.1	123	1.7	1.3	903	12.4
0.1	64	0.13	41	0.57	0.2	0.0	18	0.2	0.2	132	1.8
51%	136%	24%	37%	38%	38%	7%	49%	48%	86%	96%	96%
1.4	353	3.83	836	11.59	3.8	1.0	284	3.9	1.9	1197	16.5
0.9	101	3.33	677	9.34	3.0	1.0	214	3.0	1.2	681	9.4
0.7	53	2.86	570	7.78	2.5	1.0	162	2.3	0.7	387	5.2
1.4	252	4.15	865	11.60	4.1	1.0	276	3.8	2.1	1173	15.9
23	23	47	47	47	47	47	47	47	47	47	47
-13%	4%	-26%	-15%	-10%	6%	0%	-16%	-10%	-12%	-7%	1%
0.388	0.905	0.000	0.056	0.249	0.447	0.924	0.090	0.276	0.518	0.681	0.967
0.7	77	3.61	631	8.96	4.0	1.0	166	2.3	1.6	703	9.9
0.7	71	3.58	608	8.51	3.7	1.0	140	1.9	1.1	610	8.7
0.3	54	0.80	193	2.91	1.2	0.1	61	0.9	1.4	492	6.8
0.1	11	0.12	29	0.43	0.2	0.0	9	0.1	0.2	73	1.0
39%	70%	22%	31%	32%	29%	13%	37%	38%	86%	70%	69%
0.8	100	3.84	687	9.80	4.4	1.0	183	2.6	2.0	846	11.8
0.6	55	3.38	575	8.12	3.7	0.9	148	2.1	1.2	561	7.9
0.5	37	3.09	501	7.12	3.3	1.0	123	1.7	0.6	314	4.6
0.8	102	4.05	725	10.74	4.5	1.0	210	3.0	2.4	954	13.6
23	23	46	46	46	46	46	46	46	46	46	46
-46%	-65%	-26%	-29%	-23%	25%	-2%	-44%	-39%	-10%	-31%	-23%
0.001	0.000	0.000	0.000	0.004	0.001	0.358	0.000	0.000	0.597	0.034	0.108
0.4	44	3.19	472	6.72	3.0	1.0	173	2.5	2.2	299	4.3
0.3	38	3.12	432	6.06	2.8	1.0	155	2.2	2.2	213	3.2
0.5	25	0.75	185	2.52	1.1	0.2	83	1.2	1.4	207	3.0
0.1	5	0.11	28	0.38	0.2	0.0	12	0.2	0.2	31	0.4
106%	57%	24%	39%	37%	35%	19%	48%	49%	63%	69%	70%
0.6	55	3.41	526	7.46	3.3	1.0	198	2.8	2.6	359	5.2
0.2	34	2.97	418	5.98	2.7	0.9	149	2.1	1.8	238	3.4
0.2	27	2.72	370	5.16	2.3	1.0	114	1.6	1.1	161	2.4
0.4	56	3.60	531	7.53	3.6	1.0	207	3.0	2.9	343	4.8
22	22	45	45	45	45	45	45	45	45	45	45
-66%	-80%	-34%	-47%	-42%	-6%	-1%	-42%	-35%	28%	-71%	-66%
0.000	0.000	0.000	0.000	0.000	0.417	0.739	0.000	0.000	0.141	0.000	0.000

C. Detailed regression analysis results relating operational conditions and stove performance.

Operational conditions and combustion efficiency

```
-> Stovename = A. Trad Chulha

      Source |       SS       df       MS              Number of obs =      42
-------------+------------------------------           F(  6,    35) =    4.10
       Model |  .015704807     6  .002617468           Prob > F      =  0.0032
    Residual |  .022323757    35  .000637822           R-squared     =  0.4130
-------------+------------------------------           Adj R-squared =  0.3123
       Total |  .038028565    41  .000927526           Root MSE      =  .02526

---------------------------------------------------------------------------------
modifiedcombu~y |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------+----------------------------------------------------------------
     FirepowerkW |  -.0030964   .0028263   -1.10   0.281     -.008834    .0026413
         Nonwood |  -.0792986   .0258187   -3.07   0.004    -.1317133   -.026884
Moisturecontent |  -.0323787   .0801747   -0.40   0.689     -.195142    .1303847
       sticksize |  -.0004139   .0010037   -0.41   0.683    -.0024516    .0016238
     potdiameter |   .0003427   .0007007    0.49   0.628    -.0010797    .0017652
        Location |   .0164641   .0127869    1.29   0.206    -.0094946    .0424229
           _cons |   .9408632   .0359551   26.17   0.000     .8678705    1.013856
---------------------------------------------------------------------------------

-----------------------------------------------------------------------------------
-> Stovename = B. Two-pot mud

      Source |       SS       df       MS              Number of obs =      38
-------------+------------------------------           F(  6,    31) =    0.87
       Model |  .003869133     6  .000644855           Prob > F      =  0.5307
    Residual |   .02308877    31  .000744799           R-squared     =  0.1435
-------------+------------------------------           Adj R-squared = -0.0222
       Total |  .026957903    37  .000728592           Root MSE      =  .02729

---------------------------------------------------------------------------------
modifiedcombu~y |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------+----------------------------------------------------------------
     FirepowerkW |  -.0020892   .0033643   -0.62   0.539    -.0089507    .0047722
         Nonwood |   -.013942   .0259346   -0.54   0.595    -.0668359     .038952
Moisturecontent |  -.1624883   .1313053   -1.24   0.225    -.4302873    .1053107
       sticksize |   .0010671   .0013876    0.77   0.448     -.001763    .0038972
     potdiameter |   .0016005   .0010363    1.54   0.133    -.0005131    .0037142
        Location |  -.0101901   .0132068   -0.77   0.446    -.0371256    .0167454
           _cons |   .9219167   .0500975   18.40   0.000     .8197422    1.024091
---------------------------------------------------------------------------------

-----------------------------------------------------------------------------------
-> Stovename = C. Rocket1

      Source |       SS       df       MS              Number of obs =      44
-------------+------------------------------           F(  6,    37) =    0.71
       Model |  .001363245     6  .000227207           Prob > F      =  0.6443
    Residual |   .01185494    37  .000320404           R-squared     =  0.1031
-------------+------------------------------           Adj R-squared = -0.0423
       Total |  .013218184    43    .0003074           Root MSE      =   .0179

---------------------------------------------------------------------------------
modifiedcombu~y |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------+----------------------------------------------------------------
     FirepowerkW |   .0004453   .0031825    0.14   0.889     -.006003    .0068936
         Nonwood |    -.01292   .0243603   -0.53   0.599    -.0622787    .0364388
Moisturecontent |   .0164822   .0643708    0.26   0.799    -.1139454    .1469099
       sticksize |   .0019951   .0010594    1.88   0.068    -.0001515    .0041416
     potdiameter |  -.0003265   .0006844   -0.48   0.636    -.0017132    .0010603
        Location |  -.0011181   .0086098   -0.13   0.897    -.0185632     .016327
           _cons |    .936897   .0215384   43.50   0.000     .8932559     .980538
---------------------------------------------------------------------------------
```

```
────────────────────────────────────────────────────────────────────────────────────
-> Stovename = D. Rocket2

      Source │       SS       df       MS              Number of obs =      44
─────────────┼──────────────────────────────           F(  6,    37) =    1.05
       Model │  .002317104     6  .000386184           Prob > F      =  0.4083
    Residual │  .013580619    37  .000367044           R-squared     =  0.1458
─────────────┼──────────────────────────────           Adj R-squared =  0.0072
       Total │  .015897723    43  .000369714           Root MSE      =  .01916

───────────────┬────────────────────────────────────────────────────────────────
modifiedcombu~y│      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
───────────────┼────────────────────────────────────────────────────────────────
    FirepowerkW│    .001286   .0046619     0.28   0.784      -.00816    .0107319
        Nonwood│  -.0378349   .0306154    -1.24   0.224    -.0998676    .0241978
Moisturecontent│  -.0822783   .1050966    -0.78   0.439    -.2952243    .1306676
      sticksize│   .0002513   .0009318     0.27   0.789    -.0016366    .0021392
    potdiameter│   .0003092   .0005838     0.53   0.599    -.0008737    .0014922
       Location│   .0035467   .0068511     0.52   0.608     -.010335    .0174285
          _cons│   .9336361   .0354256    26.35   0.000      .861857    1.005415
───────────────┴────────────────────────────────────────────────────────────────

────────────────────────────────────────────────────────────────────────────────────
-> Stovename = E. Natural draft TLUD

      Source │       SS       df       MS              Number of obs =      48
─────────────┼──────────────────────────────           F(  6,    41) =    2.64
       Model │  .009894095     6  .001649016           Prob > F      =  0.0295
    Residual │  .025630902    41  .000625144           R-squared     =  0.2785
─────────────┼──────────────────────────────           Adj R-squared =  0.1729
       Total │  .035524998    47  .000755851           Root MSE      =    .025

───────────────┬────────────────────────────────────────────────────────────────
modifiedcombu~y│      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
───────────────┼────────────────────────────────────────────────────────────────
    FirepowerkW│  -.0041813   .0035097    -1.19   0.240    -.0112693    .0029067
        Nonwood│  -.0208309   .0424756    -0.49   0.626    -.1066121    .0649503
Moisturecontent│  -.2189171   .1041895    -2.10   0.042    -.4293322    -.008502
      sticksize│  -.0012397   .0017634    -0.70   0.486     -.004801    .0023215
    potdiameter│   4.85e-06   .0006688     0.01   0.994    -.0013457    .0013554
       Location│  -.0315332    .012918    -2.44   0.019    -.0576216   -.0054447
          _cons│   1.078218   .0546742    19.72   0.000      .967801    1.188635
───────────────┴────────────────────────────────────────────────────────────────

────────────────────────────────────────────────────────────────────────────────────
-> Stovename = F. Forced-draft TEG

      Source │       SS       df       MS              Number of obs =      46
─────────────┼──────────────────────────────           F(  6,    39) =    2.85
       Model │  .007812023     6  .001302004           Prob > F      =  0.0211
    Residual │  .017787972    39  .000456102           R-squared     =  0.3052
─────────────┼──────────────────────────────           Adj R-squared =  0.1983
       Total │  .025599995    45  .000568889           Root MSE      =  .02136

───────────────┬────────────────────────────────────────────────────────────────
modifiedcombu~y│      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
───────────────┼────────────────────────────────────────────────────────────────
    FirepowerkW│   .0033819   .0039873     0.85   0.402    -.0046831    .0114469
        Nonwood│   .0536264   .0521835     1.03   0.310    -.0519247    .1591775
Moisturecontent│  -.0053045   .0799566    -0.07   0.947     -.167032     .156423
      sticksize│   .0000616   .0016087     0.04   0.970    -.0031923    .0033155
    potdiameter│    .001746   .0005704     3.06   0.004     .0005922    .0028998
       Location│  -.0190184   .0082387    -2.31   0.026    -.0356827   -.0023541
          _cons│   .9055824    .025736    35.19   0.000     .8535265    .9576384
───────────────┴────────────────────────────────────────────────────────────────
```

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------------------------------------------------------------------------------------
-> Stovename = G. Forced-draft pellet
note: Nonwood omitted because of collinearity

      Source |       SS       df       MS              Number of obs =      43
-------------+------------------------------           F(  5,    37) =    1.33
       Model |  .004343487     5  .000868697           Prob > F      =  0.2716
    Residual |  .024098385    37  .000651308           R-squared     =  0.1527
-------------+------------------------------           Adj R-squared =  0.0382
       Total |  .028441871    42  .000677187           Root MSE      =  .02552

------------------------------------------------------------------------------------
modifiedcombu~y |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------+-------------------------------------------------------------------
    FirepowerkW |   .0067571   .0057888     1.17   0.251    -.0049722    .0184864
        Nonwood |          0  (omitted)
Moisturecontent |   .1667735   .3490614     0.48   0.636    -.5404921    .8740391
      sticksize |  -.0242876    .119869    -0.20   0.841    -.2671652    .2185901
    potdiameter |   .0015067   .0008065     1.87   0.070    -.0001273    .0031408
       Location |  -.0097695   .0126298    -0.77   0.444    -.0353598    .0158209
          _cons |     .98606   .4043302     2.44   0.020     .1668093    1.805311
------------------------------------------------------------------------------------
```

Operational conditions and fuel efficiency (MJ/person-meal)

```
-> Stovename = A. Trad Chulha

      Source |       SS       df       MS              Number of obs =      78
-------------+------------------------------           F(  6,    71) =    1.29
       Model |   39.732164     6  6.62202733           Prob > F      =  0.2715
    Residual |  363.572354    71  5.12073738           R-squared     =  0.0985
-------------+------------------------------           Adj R-squared =  0.0223
       Total |  403.304518    77  5.23772102           Root MSE      =  2.2629

---------------------------------------------------------------------------------
Fuelconsumpti~J |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------+----------------------------------------------------------------
    FirepowerkW |   .2244602   .1426461     1.57   0.120    -.0599681    .5088885
        Nonwood |   1.688459   1.262503     1.34   0.185    -.8289001    4.205817
Moisturecontent |   2.654632   5.234582     0.51   0.614    -7.782829    13.09209
      sticksize |   .0301774   .0641685     0.47   0.640    -.0977709    .1581257
    potdiameter |  -.0120007   .0525885    -0.23   0.820    -.1168592    .0928579
       Location |   .9595323   .6808496     1.41   0.163    -.3980433    2.317108
          _cons |    .277406   2.215392     0.13   0.901     -4.13996    4.694772
---------------------------------------------------------------------------------

----------------------------------------------------------------------------------
-> Stovename = B. Two-pot mud

      Source |       SS       df       MS              Number of obs =      89
-------------+------------------------------           F(  6,    82) =    5.17
       Model |    216.6468     6     36.1078           Prob > F      =  0.0001
    Residual |  572.663665    82  6.98370323           R-squared     =  0.2745
-------------+------------------------------           Adj R-squared =  0.2214
       Total |  789.310465    88   8.9694371           Root MSE      =  2.6427

---------------------------------------------------------------------------------
Fuelconsumpti~J |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------+----------------------------------------------------------------
    FirepowerkW |   .8063073   .1836923     4.39   0.000     .4408847     1.17173
        Nonwood |   .2055599   1.245371     0.17   0.869     -2.27188       2.683
Moisturecontent |  -5.538203   5.552285    -1.00   0.321    -16.58347    5.507061
      sticksize |   .0853568   .0860285     0.99   0.324    -.0857813    .2564949
    potdiameter |  -.0655132   .0693748    -0.94   0.348    -.2035217    .0724953
       Location |   .4357949    .716374     0.61   0.545    -.9893013    1.860891
          _cons |   1.627502   2.539267     0.64   0.523    -3.423908    6.678912
---------------------------------------------------------------------------------
```

```
-> Stovename = C. Rocket1

      Source |       SS       df       MS              Number of obs =      88
-------------+------------------------------           F(  6,    81) =    5.20
       Model |  47.4780722     6  7.91301203           Prob > F      =  0.0001
    Residual |  123.208691    81  1.52109495           R-squared     =  0.2782
-------------+------------------------------           Adj R-squared =  0.2247
       Total |  170.686763    87  1.96191682           Root MSE      =  1.2333

------------------------------------------------------------------------------
Fuelconsumpti~J |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------+-------------------------------------------------------------
   FirepowerkW |   .1675614   .1188241     1.41   0.162    -.0688612     .403984
       Nonwood |   3.820698   .8508294     4.49   0.000     2.127814    5.513581
Moisturecontent |  -9.041948   3.423023    -2.64   0.010    -15.85269   -2.231206
     sticksize |  -.0075781   .0519843    -0.15   0.884    -.1110106    .0958543
   potdiameter |  -.0297145   .0323792    -0.92   0.361     -.094139      .03471
      Location |   1.253449   .4138471     3.03   0.003     .4300235    2.076875
         _cons |   2.032542   1.002333     2.03   0.046     .0382126    4.026871
------------------------------------------------------------------------------

------------------------------------------------------------------------------
-> Stovename = D. Rocket2

      Source |       SS       df       MS              Number of obs =      89
-------------+------------------------------           F(  6,    82) =    2.80
       Model |  30.5151881     6  5.08586469           Prob > F      =  0.0157
    Residual |  148.744993    82  1.81396333           R-squared     =  0.1702
-------------+------------------------------           Adj R-squared =  0.1095
       Total |  179.260181    88  2.03704751           Root MSE      =  1.3468

------------------------------------------------------------------------------
Fuelconsumpti~J |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------+-------------------------------------------------------------
   FirepowerkW |   .1690665   .1853125     0.91   0.364     -.199579    .5377121
       Nonwood |  -2.056298   1.719096    -1.20   0.235    -5.476127    1.363532
Moisturecontent |  -4.857032   4.481509    -1.08   0.282    -13.77218    4.058118
     sticksize |  -.0305384   .0496191    -0.62   0.540    -.1292466    .0681699
   potdiameter |  -.0330058   .0267985    -1.23   0.222    -.0863165     .020305
      Location |    .817268    .320429     2.55   0.013     .1798326    1.454703
         _cons |   2.758923    1.61842     1.70   0.092    -.4606289    5.978476
------------------------------------------------------------------------------

------------------------------------------------------------------------------
-> Stovename = E. Natural draft TLUD

      Source |       SS       df       MS              Number of obs =      96
-------------+------------------------------           F(  6,    89) =    4.46
       Model |  76.6237445     6  12.7706241           Prob > F      =  0.0005
    Residual |  254.617245    89  2.86086793           R-squared     =  0.2313
-------------+------------------------------           Adj R-squared =  0.1795
       Total |   331.24099    95  3.48674726           Root MSE      =  1.6914

------------------------------------------------------------------------------
Fuelconsumpti~J |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------+-------------------------------------------------------------
   FirepowerkW |   .3297377   .1751586     1.88   0.063    -.0182987     .677774
       Nonwood |    3.40922   1.531272     2.23   0.029     .3666138    6.451825
Moisturecontent |   2.395655   4.748344     0.50   0.615    -7.039204    11.83051
     sticksize |  -.0647256   .0622601    -1.04   0.301    -.1884351    .0589839
   potdiameter |  -.0216998   .0383359    -0.57   0.573    -.0978723    .0544728
      Location |   1.920529   .5293757     3.63   0.000     .8686705    2.972387
         _cons |  -.8587236   2.225751    -0.39   0.701    -5.281242    3.563795
------------------------------------------------------------------------------
```

```
-> Stovename = F. Forced-draft TEG

      Source |       SS       df       MS              Number of obs =      90
-------------+------------------------------           F(  6,    83) =    3.07
       Model |  74.9957802     6  12.4992967           Prob > F      =  0.0092
    Residual |  337.752518    83  4.06930745           R-squared     =  0.1817
-------------+------------------------------           Adj R-squared =  0.1225
       Total |  412.748298    89  4.63762133           Root MSE      =  2.0173

------------------------------------------------------------------------------
Fuelconsumpti~J |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------+-------------------------------------------------------------
    FirepowerkW |   .0424031   .2159354     0.20   0.845    -.3870838      .47189
        Nonwood |  -.1593727   2.438314    -0.07   0.948    -5.009081    4.690336
Moisturecontent |  -9.503978   4.886329    -1.95   0.055    -19.22269    .2147334
      sticksize |   .0932462   .0817674     1.14   0.257    -.0693859    .2558783
    potdiameter |  -.0873706   .0423306    -2.06   0.042    -.1715645   -.0031768
       Location |    1.19886   .5115036     2.34   0.021     .1815001     2.21622
          _cons |   4.675869   1.749909     2.67   0.009      1.19537    8.156368
------------------------------------------------------------------------------

------------------------------------------------------------------------------
-> Stovename = G. Forced-draft pellet
note: Nonwood omitted because of collinearity

      Source |       SS       df       MS              Number of obs =      67
-------------+------------------------------           F(  5,    61) =    1.70
       Model |  21.5153971     5  4.30307942           Prob > F      =  0.1493
    Residual |  154.824931    61  2.53811362           R-squared     =  0.1220
-------------+------------------------------           Adj R-squared =  0.0500
       Total |  176.340328    66  2.67182315           Root MSE      =  1.5931

------------------------------------------------------------------------------
Fuelconsumpti~J |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
----------------+-------------------------------------------------------------
    FirepowerkW |   -.259157   .2762191    -0.94   0.352    -.8114912    .2931773
        Nonwood |          0  (omitted)
Moisturecontent |    8.16136   18.12358     0.45   0.654    -28.07898     44.4017
      sticksize |  -8.523194   6.545911    -1.30   0.198    -21.61255    4.566164
    potdiameter |  -.0079901   .0333994    -0.24   0.812    -.0747763    .0587961
       Location |   1.239449   .6017381     2.06   0.044     .0361994    2.442699
          _cons |   28.09319   22.09589     1.27   0.208    -16.09028    72.27665
------------------------------------------------------------------------------
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