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Article

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Design and development of affordable cookstoves for the low-income households in developing countries like Bangladesh

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Abstract:
In this research work, biomass based low-cost energy efficient and low polluting household mud-built cookstoves were designed and developed targeting the rural population of Bangladesh who otherwise cannot afford to carry the overload of health cost due to indoor air pollution and purchasing excessive biomass fuel required for their existing traditional cookstove. Four mud-built stoves e.g., i) single pot circular grate (MS-1), ii) double pot circular grate (MS-2), iii) double pot elliptical grate (MS-3) and iv) triple pot circular grate (MS-4) was designed with double chimney to fit the average household cooking need in context of rural Bangladesh. The models were designed with the preheating facility of primary combustion air to facilitate better combustion. To compare the thermal and emission performance of the developed mud stoves (MSs), two concrete built single chimney improved cookstove (ICS) models e.g., single pot concrete stove (CS-1) and double pot concrete stove (CS-2) were procured from a leading NGO (Grameen Shakti). The purchased stoves were single chimney concrete stoves (CSs) and claimed to be the most popular variants among the general households in Bangladesh. Standard water boiling test (WBT) and controlled cooking test (CCT) were performed to evaluate the overall performances of the stoves. The thermal performances of MS-2, MS-3, MS-4 were better compared to CS models. The elliptical grate mud stove (MS-3) was better than circular grate mud stove (MS-2). In terms of CO_2, CO and CH_4 emission, MS models were less emissive compared to CS models except MS-1 that emits more CH_4 compared to CS-2. The NO emission was found to be lower for all MS models. Therefore, the developed MS models were thermally efficient, low polluting and low cost, which can be a better alternative to CS for the rural population of Bangladesh.

Keywords: Cookstoves; thermal efficiency; low emission; low cost; rural communit

Highlights:

1. Thermally efficient and cost-effective mud-based stoves (MSs) were fabricated and compared with available ICSs (CSs).
2. The overall thermal efficiency (at high power) of double pot elliptical grate stove (MS-3) was ~120% higher than the procured ICSs.
3. The highest turn down ratio (TDR) of 2.40±0.1 was obtained for MS-3 model.
4. The MS models showed lower emissions (CO_2, CO, NO and CH_4) compared to the procured CS models.
5. The construction cost of CSs models were ~2 times greater the fabricated MSs models.

Abbreviations

MS-1	Single pot mud stove (circular grate) [Designed]
MS-2	Double pot mud stove (circular grate) [Designed]
MS-3	Double pot mud stove (elliptical grate) [Designed]
MS-4	Triple pot mud stove (circular grate) [Designed]
CS-1	Single pot concrete stove [Procured]
CS-2	Double pot concrete stove [Procured]
MSs	Mud stoves
CSs	Concrete stoves
ICSs	Improved cookstoves
GHG	Greenhouse gas
PIC	Products of incomplete combustion
IAP	Indoor air pollution

1. Introduction

Bangladesh is the 8th most populous country in the world with an estimated population of 164.7 million and a population density 1265 persons per square km. About 20.5 % of the entire population lives below the national poverty line. In 2021, approximately 61 % of the population in Bangladesh were residing in rural areas. The increasing population contributes to the accelerating electricity and fuel demand in Bangladesh. The scarcity of natural gas and declining reserve have become a major obstacle for Bangladesh in the path achieving 100 % electricity coverage goal, which has now turned into a situation of searching for efficient fuel for household cooking (Saha et al., 2021). The urban users in Bangladesh use natural gas (NG) as their primary cooking fuel as they have access to the pipe NG supplied by gas distribution companies (Islam et al., 2022). In peri-urban and rural areas, people do not have access to the national gas grid; hence, they must use the imported or domestic liquefied petroleum gas (LPG) cylinders. The high cost of LPG has confined its use in a negligible portion of peri-urban and rural users.

Therefore, in Bangladesh the rural households mainly depend on biomass fuels for their primary sources of energy supply (Miah et al., 2010). Most of the rural population relies primarily on biomass fuels for cooking, which includes jute stick/wood/bamboo, cow dung, straw/leaf, and husk/bran (Huda et al., 2014). Lack of technological awareness and affordability gaps has led to low penetration of modern technologies like LPG and electric stoves, in both rural and peri-urban areas. Thus, most of the rural population of Bangladesh use traditional stoves for the cooking. A traditional stove in Bangladesh is generally a mud-built cylinder dug out in the earth with three raised points on which cooking utensil rests (Hossain, 2003). The common biomasses used for cooking purpose are firewood, leaves, tree twigs, agricultural crop e.g., rice straw, rice husk, jute sticks, sugarcane bagasse, sawdust, cow dung etc. (Mamun et al., 2009). The energy efficiencies of these traditional stoves vary between 5 and 15 %. The poor thermal efficiency of the traditional stove is due to large distance between the fuel bed and utensils (30 to 60 cm), low draught that causes stagnant fluid film over the bottom surface of the utensils, inaccessibility and improper distribution of combustion air at the bottom of the stoves (Khan et al., 1995). Therefore, with a poor thermal efficiency traditional cookstove has several disadvantages with respect to deforestation, biomass collection time, indoor air pollution and health impact, and climate change. Though large quantity of carbon dioxide (CO_2), regarded as one of the potential greenhouse gases (GHG), are emitted from these stoves, the emission from the use of biomass is considered as GHG neutral if the biomass fuel cycle relies on renewable harvesting (Smith et al., 2000a).

Design deficiency of the traditional cookstoves leads to incomplete and inefficient combustion which produces significant quantities of 'products of incomplete combustion' (PIC) importantly respirable particulates that have more global warming potential (GWP) than CO_2 (Panwar et al., 2009). Incomplete combustion of biomass in traditional cookstoves also releases carbon monoxide (CO), nitrous oxide (N_2O), methane (CH_4), polycyclic aromatic hydrocarbons (PAHs), particles composed of elementary or black carbon, and other organic compounds (Bhattacharya et al., 2000). Venkataraman et al. (2010) reported emission factors for traditional cookstoves using different biomasses which are shown in Table 1 (Venkataraman et al., 2010).

Table 1. Traditional stove emissions (g/kg fuel) from laboratory tests using the water-boiling test to determine emissions of biomass fuel types in Indian traditional cookstoves (Venkataraman et al., 2010)

Fuel type	Pollutant emission factor (g/kg)							
	Short-lived pollutant					Long-lived pollutant		
	CO	NMVOC	PM	BC	OM	CO_2	CH_4	N_2O
Wood	69±15	7.0±3.0	3.2±2.0	0.60±0.15	2.8±2.5	1358±43	5.0±4.0	0.09±0.09
Agricultural residue	65.6	8.5	6.3±2.5	0.60±0.23	4.6±3.3	1302	7.6	0.050
Dung	39.9	24.2	3.0±1.9	0.12	2.5	1046	4.5	0.30

In rural Bangladesh, women are the main cook in household cooking process and most of the households use traditional cookstoves for preparing their daily meals. Traditional stoves usually lack chimneys, which release the combustion products directly into the unventilated small kitchen causing indoor air pollution (IAP) that poses a serious health impact on the women (Rahman, 2007). Moreover, several pollutants in the biomass smoke are climate active (Bensch et al., 2021). The most important are nitrous oxide and methane, both well-understood greenhouse gases with much higher global warming potentials (GWPs) per tonne than CO_2 (Goldemberg et al., 2018). The CO_2 from burning of wood that is not harvested renewably (leading to deforestation) does contribute to global warming. Whether warming or cooling, the particles from biomass combustion contribute to regional air pollution (Chen et al., 2017). Biomass cookstoves are also contributors to ozone levels; one estimate put their contribution of ozone precursors as one-sixth globally and perhaps one-quarter in South Asia and their contribution to carbon monoxide emissions as one-third globally (Unger et al., 2006).

To address the poor efficiency and pollution issues, improved cookstoves (ICS) have been introduced. In general, the cookstoves with chimneys and closed combustion chambers are usually considered ICS. An improved stove can be designed to improve energy efficiency, remove smoke from the indoor living space, or lessen the drudgery of cooking duties (Urmee,Gyamfi, 2014).

The Institute of Fuel Research and Development (IFRD) of Bangladesh Council of Scientific and Industrial Research (BCSIR) started work in 1978 to develop ICSs in context of Bangladesh. IFRD developed several ICSs which include fixed and portable type, metal and clay, single and multiple pot, with chimney and without chimney, with grate and without grate, etc. (Rahman et al., 2006). Two NGOs, GIZ and Grameen Shakti, are the leading sellers of ICSs developed by IFRD, BCSIR in the local market. Different studies were conducted to find the performances of these ICSs in Bangladesh.

Arif et al., (2011) conducted household kitchen performance tests on different ICSs, e.g., i) portable single pot with grate and without grate, iii) double pot with chimney and with grate, and iii) double pot with chimney and without chimney and iv) traditional single pot portable cookstove in rural Bangladesh to compare thermal and fuel saving efficiency, cooking time and pollution level (Arif et al., 2011). The group reported higher fuel consumption, lower thermal efficiency, longer cooking time and less pollution for double pot ICS with chimney compared to traditional cookstove whereas, lower fuel consumption, higher thermal efficiency, shorter cooking time and alike pollution level for portable single pot ICS without chimney compared to the traditional cookstove. Since then, there were no such studies on the performance and overall feasibility of these ICSs to the rural community. Every year new cookstove models have been introduced with sophisticated design and technology, however the rural community can hardly manage or afford these stoves for their household cooking.

Therefore, with the goals in mind for conserving biomass fuel, reducing smoke emissions in the cooking are, reducing global warming potential, reducing deforestation, limiting the drudgery of women and children for biomass collection and reducing cooking time, this research work was endeavored to design and develop mud-built ICSs that may serve several million poor households in villages and semi-urban areas in Bangladesh. To compare the thermal and emission characteristics of designed mud-built cookstoves of this study, two highly disseminated and popular ICS versions marketed by a popular NGO (Grameen Shakti) have been sourced and used. From the socio-economic and environmental aspects, a strong emphasis was given in design phase of the ICSs in this project, as most of the people of the villages and semi-urban areas in Bangladesh use agricultural residue fired cookstoves. Materials of construction were selected accordingly to provide people easy access to those materials to build their own cookstoves. Moreover, emphasis was also given to reduce IAP and health impact, to reduce global warming potential from the emission, and to reduce fuel requirement for cooking of the designed ICSs.

2. Design and Experimental Methodology

Four mud-built cookstoves were designed and fabricated to evaluate and compare the thermal and emission performances with the mostly disseminated ICSs in Bangladesh. The mud-built ICSs were designed and installed in the Department of Chemical Engineering, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh. The designed stoves were: 1) single-pot mud stove (circular grate), 2) double-pot mud stove (circular grate), 3) double-pot mud stove (elliptical grate), and 4) triple-pot mud stove (circular grate). These models are denoted as MS-1, MS-2, MS-3, and MS-4 respectively. Two types of ICSs were purchased from Grameen Shakti (a leading NGO involved in disseminating ICSs in Bangladesh), to compare the performances with the designed stoves. The ICSs of Grameen

Shakti were: 1) single-pot concrete stove (circular grate) and 2) double-pot concrete stove (circular grate). These models were denoted as CS-1 and CS-2 respectively.

2.1. Construction features of the stoves

Considering the cooking needs, shapes of cooking pots and types of biomass fuels, the four experimental cookstoves were designed. The stoves were constructed with locally available materials (mud, metallic grate, 'O' ring, and concrete chimney). All the MSs models have two chimneys to distribute the flames evenly under the utensils during cooking. The schematics of MSs models are shown in Figures 1 (A, B, C, D).

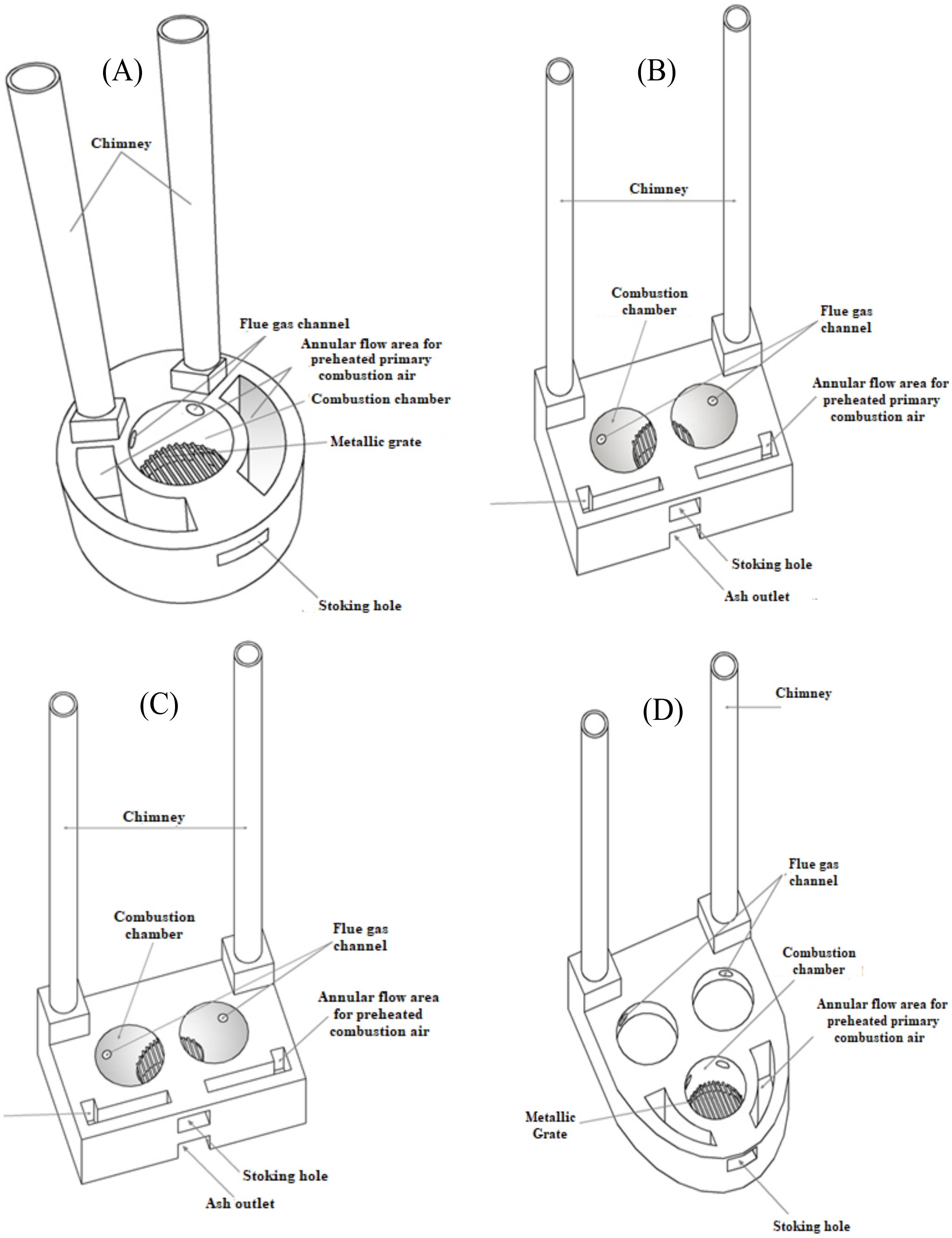

Figure 1: The schematic diagrams of (A) MS-1, (B) MS-2, (C) MS-3 and (D) MS-4 (all of the models contains ash outlet)

All the MSs models contain features that would help effective burning of the fuel, good heat transfers to cooking pot and diminution of indoor air pollution. Some common design rules were followed while sizing different dimensions of the stoves. The sizing and deciding parameters for combustion are chamber height (H) and wall thickness, pot mouth, metallic grate, stack or chimney, inlet air hole diameter, stack hole, ash-pit and ash hole etc.

The combustion chamber height (H) and wall thickness are important parameters for designing a cookstove. Combustion chamber height (H) was calculated using the formula, $H = A + P + L$. Where, A is the primary combustion air hole height in cm, P is the least height from air hole to pot bottom which is 0.4 times pot diameter for cylindrical pots, which can be extended for spherical pots and L is the distance between the pot bottom and the pot mouth in cm. Considering all these, the height of chamber of each stove was taken to be 20 cm from ground (floor) surface. For mud built cookstove, wall thickness should be in the range of 5.08-7.62 cm. In this case 5.08 cm wall thickness was chosen as design value (Baldwin, 1987).

The pot mouth of a cookstove is a hole where the utensil sits on. Pot mouth diameter for the was taken as 25.4 cm as this size of pots are usually used in general household in Bangladesh. A metallic 'O' ring of same diameter of pot mouth was placed on each of the pot mouths to prevent erosion of mud.

A metallic grate was used inside the combustion chamber of each type of stoves which was placed just above the primary combustion air inlet holes. The grate acts as fuel bed and allows better mixing of combustion air and fuel. Rectangular slits were incorporated in the grate instead of circular holes for better mixing of primary combustion air with fuel. This type of grate is also very useful for wood, leaves and agricultural residues as cooking fuels.

Stack or chimney acts as an integral part of an improved biomass cookstove providing clean indoor environment. Each of the stove models has two chimneys. It is a standard rule to take chimney height same as roof top height (~210-310 cm) for not being exposed to smoke. Considering this along with the provision of draft ranging from 10-15 Pa, the chimney height was taken as 215 cm. It is beneficial for combustion to have a flue gas velocity of 2-3 ms^{-1} within the chimney. Considering this, the internal diameter (ID) of the chimney was calculated to be 5.08 cm. For field application, ID of each stack was taken as 7.62 cm. A 2.08 cm provision was provided for deposition of soot particles to avoid excessive pressure drop after long-run operation (Shaha, 2018).

For designing efficient cookstove, it is a good practice to maintain constant cross-sectional area for combustion air inlet and combustion gas exit. That is why, along with the diameter of the chimney inlet, six primary air holes of 5.08 cm diameter were placed at the bottom of the combustion chamber wall.

A stoke hole or secondary combustion air inlet was placed in each of the stove models above the gate or fire bed to provide stoke (fuel) in the combustion chamber and secondary combustion air to the diffusion flame zone for better combustion. This hole dimension was so chosen to keep the hole size minimum and to adopt with reasonable size of stokes.

A second wall of 5.08 cm thick was provided outside the combustion chamber wall maintaining an annular space for each of the stove models to minimize heat loss to environment through convection, to minimize burn risk during cooking. The annular area of the double wall was also designed for preheating the primary combustion air to maximize waste heat utilization. In all stove models, a 15.28 cm-deep ash pit was provided underground at the bottom of combustion chamber with a view to lessen the cookstove mass and excessive heat loss. Ash hole was provided to collect ash and it was connected to ash pit through underground channel. Ash hole remains closed during cooking. All the MSs models with proper dimensions have been supplied in Supplementary Figure S1-4. The isometric view with dimensions of procured CS-1 and CS-2 are given in Supplementary Figure S5-6. The working mechanism of the designed MSs is supplied and visualized in video files.

Figure 2: Mud-stove fabrication and curing processes

2.2. Mud built stove construction procedure

First of all, all the initial structures were made with moulded sticky mud. Then structures were allowed to dry for 1-2 days in natural environment under the shade. After that a desired shape was given to the structures with knife and hands. Again, the structures were allowed to dry completely by keeping them under the shade for another 5-7 days. During this drying process structures were rubbed with mud and water to fill up the cracks. It is customary to rub the structure with moulded sticky mud twice a week. After several weeks of occasional firing and filling up the cracks with mud, no more new cracks were found and the stoves became strong like fired bricks. Different fabrication steps and curing are shown in Figure 2.

2.3. Cookstoves performance evaluation by WBT and CCT

All the cookstoves were fixed type and placed inside the kitchen. Standard Water Boiling Test (WBT) was followed to evaluate the performances of the MSs and CSs (ISO/IWA, 2014). WBT was carried out for cold and hot start in high power phase and simmering in low power phase. The cold start in high power phase began with the stove at ambient temperature and used a pre-weighed bundle of fuel to boil a measured quantity of water in aluminum pot. The hot start in high power phase followed immediately after the cold start in high power phase while the stove was hot. Simmering in low power phase started immediately after hot start in high power phase on the retained water in the pot and continued for 45 minutes and the temperature of the water in the primary pot was maintained average 3 ^{o}C below the local boiling point of water. Real time in-stack measurements of emission from all the cookstoves were also done during different phases of the entire WBT.

For WBT of different cookstoves, aluminum hemispherical-bottom pots were used. Each of the pots was identical with respect to their dead weight, capacity and dimensions. Each pot had a dead weight of 350 g and a thickness of 1.1 mm with a hemispherical bottom. Each of the pots was 116 mm high and the opening mouth diameter was 245 mm. The highest diameter of the pot was at the middle which was 290 mm.

For MS-1, MS-2, MS-3, and MS-4, WBT required one, two and three pots respectively for single test run. For each test run, initially each pot was charged with exactly 4,150 mL water. The cooking fuel used for WBT was locally available rice straw with measured moisture content: 6% (wet basis), higher heating value (HHV) on dry basis: 14.40 MJ/kg and a calculated lower heating value (LHV) on dry basis: 13.08 MJ/kg. HHV was determined in the laboratory using bomb calorimeter. Rice straw was collected from a single source of a local market. For multi-pot cookstoves, WBT was terminated with the boiling in the primary pot. No lid was used to cover the pot, so that evaporated water freely escapes from the pot. Fuel required heating up the known quantity of water to its local boiling point and the amount of evaporated water up to boiling point was recorded for each test run on all types of cookstoves. The stoking for entire WBT was carried by a several years experienced woman since stoking rate is highly person dependent. Photographs of WBT on different ICSs are shown in Supplementary Figure S7. From WBT, time to boiling, burning rate, specific fuel consumption, specific energy consumption, firepower, cooking power, turndown ratio, and overall stove thermal efficiency were determined. Combustion efficiency was determined as percentage of airborne fuel carbon released as CO_2. Thereafter, heat transfer efficiency and ESI were calculated.

Time to boil (Δt_c) is the time to boil water in the primary pot and it is simply a clock difference and expressed as Eqn. (1),

$$\Delta t = t_f - t_i \qquad (1)$$

Where, t_f is the final clock time (min) and t_i is the initial clock time (min).

Temperature corrected time to boil (Δt^T) adjusts the time to boil to a standard 75 °C temperature change (from 25 °C to 100 °C) to compensate different initial temperature and local boiling point which was calculated using Eqn. 2 (ISO/IWA, 2014),

$$\Delta t^T = (t_f - t_i) \times 75/(T_f - T_i) \ (2)$$

Where, T_f is local boiling temperature of water (°C) and T_i is initial temperature of water (°C)

Overall stove thermal efficiency (η) is a ratio of the work done by heating and evaporating water to the energy released by burning equivalent amount of dry fuel and expressed as Eqn. (3) (Ko,Lin, 2003),

$$\eta = \frac{[4.186 \times \sum_{j=1}^{3}\left(P_{ji} - P_j\right) \times (T_{jf} - T_{ji})] + 2260 \times (W_v)}{f_{d \times LHV}} \qquad (3)$$

Where, 4.186 J/g°C is specific heat of water, P_j is weight of empty pot (g), P_{ji} is weight of pot with water before test (g), T_{ji} is water temperature before test (°C), T_{jf} is water temperature after test (°C), f_d is equivalent dry fuel consumed (g), W_v is amount of water vaporized (g), LHV is lower heating value or net heating value of the dry fuel (kJ/kg).

Burning rate (r_b) was calculated from the recorded initial and final weight of the fuel and time taken for completing WBT. It was calculated by dividing the equivalent dry fuel consumed during test run by the time required for the test, which is expressed as Eqn. (4),

$$r_b = \frac{f_d}{(t_f) - (t_i)} \qquad (4)$$

Where, r_b is burning rate (g dry fuel/min), f_d is equivalent dry fuel consumed (g).

Specific fuel consumption (SC) was measured as the amount of equivalent dry wood required producing one g of boiling water (g fuel/g water) and is expressed as Eqn. (5),

$$SC = \frac{f_d}{\sum_{j=1}^{3}\left[(Pj_f - Pj) \times \left(\frac{Tj_f - Tj_i}{T_b - Tj_i}\right)\right]} \qquad (5)$$

Where, P_j is weight of empty pot (g), P_{jf} is weight of pot with water after test (g), T_{ji} is water temperature at the beginning of the test (°C), T_{jf} is water temperature after test (°C) and T_b is local boiling point of water (°C).

Temperature corrected specific fuel consumption (SC^T) corrects the specific fuel consumption to account for differences in initial water temperatures. This correction accounts for a standard temperature change of 75°C (from 25 to 100°C), and calculated as Eqn. (6),

$$SC^T = \left[(SC) \times \left(\frac{75}{T_f - T_i}\right)\right] \qquad (6)$$

Temperature corrected specific energy consumption (SE^T) was determined by multiplying SC^T with the net calorific value of the fuel and the unit is kJ/liter

Firepower (FP) is the equivalent dry fuel energy consumed by the stove per unit time and the unit of the firepower is watt. This parameter is useful for high and low power phase since turndown ratio of a cookstove can be found from high and low power phase firepower and expressed as Eqn. (7),

$$F_P = \frac{(f_d) \times (LHV)}{(60) \times (\Delta t)} \qquad (7)$$

Where, f_d is equivalent dry fuel consumed (g), LHV is lower heating value (J/g), Δt is duration of test run (min).

The cooking power (F_{CP}) is the average rate of energy released from fuel combustion that is transferred to the pot over the duration of the test and the unit of the useful/cooking power is watt. Cooking power was calculated for the cold start and hot start, but not for the simmer, because cooking power cannot be accurately measured during the simmer phase of the WBT, as discussed in the article. Cooking power is expressed as Eqn. (8),

$$F_{CP} = F_p \times (\eta) \qquad (8)$$

Turndown ratio (TDR) shows the operability of a stove with low power input and is the ratio of hot start firepower in high power phase to simmering firepower in low power phase.

Environmental stove index (ESI) is composed of two parameters e.g., $\frac{1}{(1-NCE)}$ is a direct indicator of how much products of incomplete combustion (PIC) is released and η indicates the effective amount of fuel used. ESI is expressed in Eqn. (9),

$$ESI = \ln(\frac{\eta}{(1 - NCE)} \qquad (9)$$

Here, NCE (Nominal combustion efficiency) is defined as the percentage of airborne fuel carbon released as CO_2 and evaluated by [1/(K+1)] and K is defined as [(FC/CO_2) – 1] (Kirch et al., 2018).

Where, Fuel carbon (FC) = (fuel consumed × carbon fraction) – (ash produced × carbon fraction), CO_2 indicated the carbon as carbon-di-oxide in flue gas η is overall stove thermal efficiency and is expressed as Eqn. (10),

$$\eta = NCE \times NHE \qquad (10)$$

Here, NHE (Nominal heat transfer efficiencies) is defined as the percentage of heat released by combustion that is absorbed by the water in the pot. This was not measured directly in our experiments and was determined using Equation, since both NCE and η are available from the tests.

In Bangladesh cooked rice is a traditional food and almost every general household cooks rice twice a day. Therefore, controlled cooking tests (CCT) were performed on every cookstove by cooking parboiled rice (Gebreegziabher et al., 2018). A several years experienced household female cook was hired to cook the parboiled rice. The same pots used in WBT were also used in CCT. A 40 kg bag of parboiled '*miniket*' rice was purchased from local market to maintain the homogeneity in rice quality. To conduct CCT on single pot cookstove, 750 gm parboiled *miniket* rice and 3,900 gm water were taken into a single pot. For double and triple pot cookstoves, two and three pots of equal dimensions were used respectively each of which contained 750 gm *miniket* rice and 3900 gm water. Stoking rate and termination time for cooking rice were solely determined by the cook based on her experience. Each cookstove was tested thrice for cooking identical amount of parboiled rice with water. Pot lid was used for each CCT run to maximize heat utilization. During CCT on each cookstove, amount of fuel consumed and time required were estimated. Some mentionable photography of CCT are shown in Supplementary Figure S8.

For WBT and CCT, in-stack flue gas compositions for CO, NO, and stack temperature and draft were measured using a portable combustion analyzer (PCA-3, Bacharach Inc., USA). Besides, flue gas samples were collected from the chimney in Tedlar bags at an interval of two minutes during CCT and WBT for each type of cookstove. The samples were then analyzed for CO_2, and CH_4 using gas chromatography (FID-GC-17A, Shimadzu, Japan). Background ambient concentrations of all above mentioned parameters were also measured to find out the net emission compositions of flue gas from combustion. Flue gas and ambient air compositions were measured on wet basis. An electronic weight balance (LP5001A, Gromy Industry Co. Ltd., China) was used in WBT and CCT for weight measurements. Stack temperature, flame zone temperature, fuel bed temperature, combustion air temperature was also measured using thermocouple (Allosun EM502C, China) with electronic reader during entire WBT for cold and hot start in high power phase, simmering in low power phase and CCT.

3. Results and discussions

3.1. Thermal Performance of stoves in WBT

The primary combustion air temperature for all stove models is presented in Figure 3 (A).

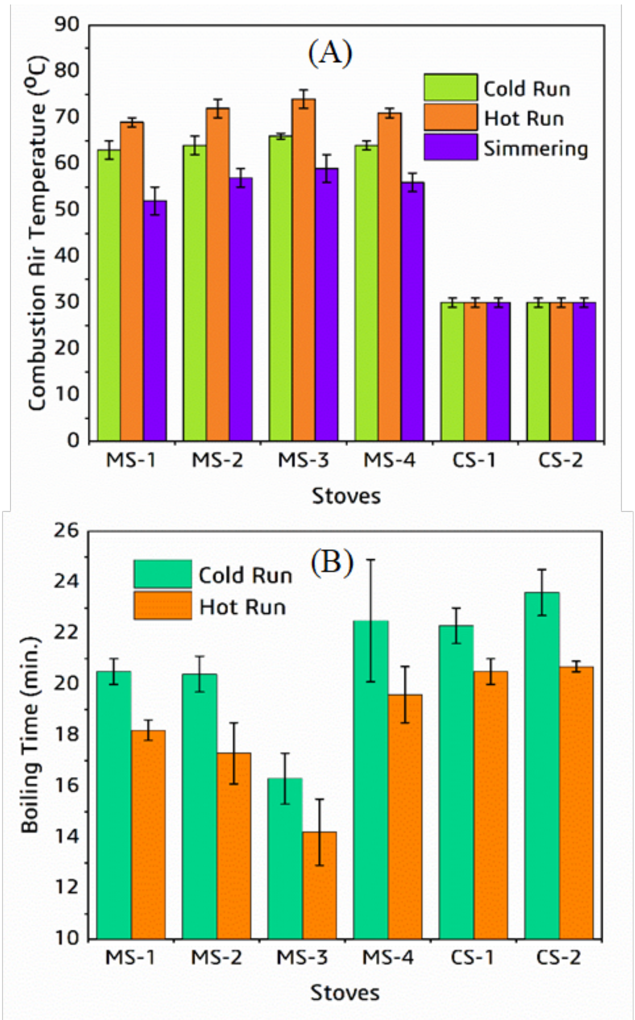

Figure 3: (A) Primary combustion air temperature (°C) of different stove models in high power (cold and hot run) and low power simmering phase, (B) temperature corrected boiling time (min.) for different stove models in high power phase (cold and hot run)

Figure 3 (A) refers that, the provision for preheating combustion air for MS-1, MS-2, MS-3 and MS-4 renders higher temperature of primary combustion air compared to CS-1 and CS-2. From Table 2, the combustion air temperatures of MSs varied from 63 to 74 ºC for high power phase (cold and hot run) and 52 to 59 ºC for low power simmering phase. Whereas, combustion air temperatures of CSs were found to be the ambient temperature (30 ºC) for both high and low power phases.

Table 2: Combustion air temperature, fuel bed temperature, flame zone temperature, stack flue gas temperature, draft inside WBT of all the stoves

Parameters		Stove Type					
		MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
		Mean ± S.D.					
Combustion air temperature (ºC)	Cold Run	63±2	64±2	66±0.6	64±1	30±1	30±1
	Hot Run	69±1	72±2	74±2	71±1	30±1	30±1
	Simmering	52±3	57±2	59±3	56±2	30±1	30±1
Fuel bed temperature (ºC)	Cold Run	605±5	616±1	632±3	611±9	570±8	583±12
	Hot Run	623±3	645±5	660±10	647±6	588±8	601±4
	Simmering	584±3	605±4	611±5	590±8	549±5	560±8
Flame zone temperature (ºC)	Cold Run	712±3	713±3	722±3	710±5	673±15	667±6
	Hot Run	722±8	762±10	760±5	723±8	683±6	678±8
	Simmering	685±9	698±8	696±7	687±10	648±7	644±5
Stack flue gas temperature (ºC)	Cold Run	298±29	320±36	306±31	313±28	342±44	356±47
	Hot Run	307±27	341±40	340±40	315±33	348±51	338±45
	Simmering	240±30	291±32	287±30	281±29	307±25	310±27
Draft inside chimney (-Pa)	Cold Run	*7.4±1.14	*7.5±1.15	*7.5±1.12	*7.4±1.11	7.9±1.197	7.5±1.133
	Hot Run	*7.4±1.16	*7.5±1.14	*7.4 ±1.13	*7.5±1.11	7.8±1.11	7.6±1.13
	Simmering	*6.5±1.15	*6.7±1.14	*6.7±1.11	*6.61.11	6.9±1.18	6.8±1.12

This preheating phenomenon made a clear distinction between MSs and CSs with respect to thermal behavior, i.e., fuel bed temperature, and flame zone temperature. Detailed of the temperature and draft profiles during WBT of all the stoves is summarized in Table 2.

Table 2 summarizes the fuel bed temperature of MSs varied from 605 to 660 ºC in high power phase and 584 to 611ºC in low power phase, whereas the temperature varied from 570 to 601 ºC in high power phase and 549 to 560ºC in low power phase for CS ICSs. Flame zone temperature of MSs varied from 710 to 762 ºC in high power phase and 685 to 698ºC in low power phase, whereas it varied from 667 to 683 ºC in high power phase and 644 to 648ºC in low power phase for CSs ICSs. Stack flue gas temperatures of MSs stoves were lower than those procured CSs in both high and low power phases and ranges from 298 to 341 °C in high power phase and 240 to 291°C in low power phase for MSs, whereas these temperatures varied from 338 to 356 °C in high power phase and 307 to 310 °C in low power phase of CSs ICSs. These temperatures show a clear indication of better combustion and effective heat utilization in MSs compared to CSs ICSs. All of the designed MSs have double chimney to compensate excess pressure drop due to annular flow of pre-heated combustion air. Draft in each chimney of designed MSs varied from – 6.5 to – 7.5 pa for entire WBT test, whereas for single chimney of CSs, draft varied from – 6.8 to – 7.9 pa.

The WBT performance parameters (boiling time, burning rate, specific fuel and energy consumption, firepower, cooking power, turn-down ratio, and overall thermal efficiency) of all stoves are summarize in Table 3.

Table 3. WBT performance parameters (boiling time, burning rate, specific fuel and energy consumption, firepower, cooking power, turn-down ratio, and overall thermal efficiency) of stoves

Parameters		Stove Type					
		MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	MS-5 Circular Grate	MS-6 Circular Grate
		Mean±S.D.					
Boiling time (corrected) (min)	Cold Start	20.5±0.5	20.4±0.7	16.3±1.0	22.5±2.4	22.3±0.7	23.6±0.9
	Hot Start	18.2±0.4	17.3±1.2	14.2±1.3	19.6±1.1	20.5±0.5	20.7±0.2
	Simmering	na	na	na	na	na	na
Burning rate (gm/min)	Cold Start	44.4±1.7	53.8±1.8	67.0±2.9	46.0±2.4	56.5±3.4	59.4±2.3
	Hot Start	39.4±2.4	56.4±2.7	67.7±3.7	42.6±1.4	57.1±3.0	64.8±1.4
	Simmering	19.3±0.1	25.4±0.2	27.9±0.7	22.8±0.6	27.5±0.6	30.6±1.2
Sp. Fuel consumption (corrected) (gm/liter)	Cold Start	233.5±15.8	136.2±1.6	136.0±3.2	110.8±7.1	316.4±30.0	237.1±16.8
	Hot Start	182±16.2	120.5±3.7	119.0±6.4	93.2±3.5	290.4±20.5	220.9±10.1
	Simmering	260.9±6.6	172.7±3.3	188.6±4.2	129.6±2.0	356.4±13.3	246.9±10.5
Sp. Energy consumption (corrected) (kj/liter)	Cold Start	3054±207	1781.9±21	1779.2±42.2	1449.2±92.4	4137.9±392.8	3100.7±219.4
	Hot Start	2380.6±212.2	1576.4±48	1556.4±83.6	1219.2±45.1	3798.7±267.9	2889.2±132.5
	Simmering	3412.6±86.8	2258.7±42.7	2466.5±55.5	1695.1±25.9	4661.2±174.3	3229.6±137.6
Firepower (watt)	Cold Start	9,684±362.4	11,721±390.1	14,599±627.8	10,018±521.1	12,327±750.9	12,954±506.7
	Hot Start	8,590±520.4	12,300±593.6	14,755±813.4	9,290±305.4	12,446±656.1	14,121±296.8
	Simmering	4,195±29.4	5,527±68.8	6,094±172.8	4,930±112	5,924±225	6,702±253.1

Parameters		Stove Type					
		MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	MS-5 Circular Grate	MS-6 Circular Grate
		Mean±S.D.					
Turn down ratio	Simmering	2.31±0.1	2.12±0.1	2.40±0.1	2.03±0.1	2.08±0.1	1.93±0.1
Cooking power (watt)	Cold Start	1,549±57.9	2,696±89.7	3,504±150.7	2,705±140.7	1,233±75	1,684±65.9
	Hot Start	1,718±104	3,075±148.4	3,836±211.4	2,880±94.7	1,245±65.6	1,836±38.5
	Simmering	na	na	na	na	na	na
Overall thermal efficiency (%)	Cold Start	16±0	23±0	24±1	27±1	10±0	13±1
	Hot Start	20±1	25±1	26±1	31±1	10±1	13±1
	Simmering	na	na	na	na	na	na

na: means not applicable for the said purpose

The boiling time for different stove models in high power (cold and hot run) phase is presented in Figure 3 (B). From the cold and hot run, temperature corrected average boiling time was calculated and among the stove models, the average boiling time (temperature corrected) was found to be the lowest for MS-3 which was 15.25 min. and the 2nd lowest boiling time was 18.85 min. for MS-2. For MS-1 and MS-4, the average boiling time were 19.35 min. and 21.05 min. respectively. The CSs showed higher boiling time compared to MSs. The average boiling time was 21.4 min. and 22.15 min. for CS-1 and CS-2, respectively. Thus, the designed MSs were more efficient in rapid boiling compared to CSs.

From Table 3, the highest fuel burning rate during high power phase was obtained for MS-3, however the burning rate of this cookstove in low power phase was lower than CS-2. However, the lowest boiling time of MS-3 (Figure 3(B)) reveals better heat utilization pattern. The burning rate of the rest three MSs was lower than those CSs for both high and low power phases.

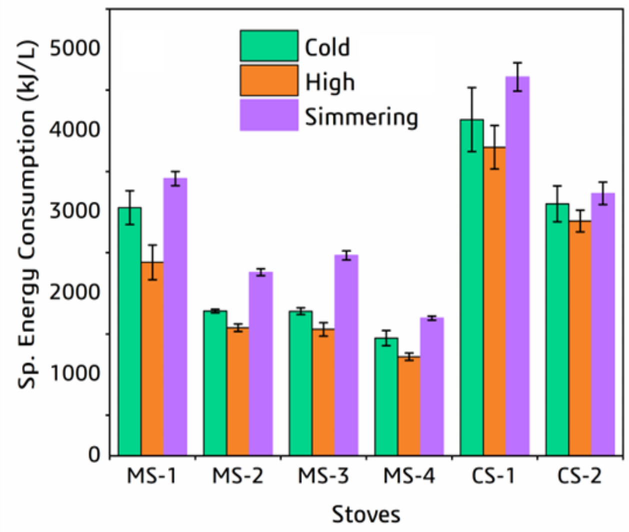

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Figure 4: The specific energy consumption (kJ/L) for different stove models in high power (cold and hot run) and low power (simmering) phases

The specific energy consumption (kJ/L) for different stove models in high power (cold and hot run) and low power (simmering) phases is presented in Figure 4.

Specific energy consumptions (temperature corrected) of MSs were lower than CSs in both high and low power phases except MS-1 that consumed higher specific fuel and energy during simmering in low power phase compared to CS-2 but in comparison to single mouth CS-1, single mouth MS-1 consumed lower specific fuel and energy in in all phases of WBT (Figure 4). Specific fuel and energy consumptions were found to be the lowest for MS-4 during all power phases, whereas the highest specific fuel and energy consumptions were found for CS-1 in all power phases.

In performance evaluation cookstoves, firepower is an important parameter, which is the output power of a stove and indicates how much energy a cookstove can produce per time. Average firepower of the stoves varied from 8,590 to 14,755 watt in high power phase and 4,195 to 6,702 watts in low power phase. The lowest firepower was found for MS-1 in all power phases, whereas MS-3 was found to be the highest energy generator per time during high power phase. During simmering in low power phase, CS-2 showed the highest firepower (Table 3.). On the other hand, cooking power is the fraction of the firepower that is eventually transferred to the cooking pot for boiling water. The ratio of cooking power to firepower indicates the fraction of firepower actually used for cooking. The larger the fraction, the larger will be the effective cooking power. Figure 5 (A) presents the cooking power (watt) of the stove models in high power phase. The highest and lowest cooking power were obtained for MS-3 (3,836 watt) and CS-1 (1,245 watt), respectively. The ratios of cooking power to firepower in high power phase were 0.18, 0.24, 0.25, 0.29, 0.10, 0.13 for MS-1, MS-2, MS-3, MS-4, CS-1 and CS-2 respectively.

Turndown ratios of all the stoves were satisfactory and varied from 1.93 to 2.4 (Figure 5 (B)). The higher the TDR value, the better is the switching between power levels. All the MSs models showed a turndown ratio (TDR) above 2 referring MSs were capable to simmer water with a 50% reduced burning rate compared to hot start in high power phase. Turndown ratio of CS-2 was below 2, whereas for CS-1 turndown ratio was above 2 (Table 3). The highest TDR was obtained for MS-3 model.

All MSs models showed higher thermal efficiency compared to CSs models. Overall high power thermal efficiencies of MS-1, MS-2, MS-3, MS-4, CS-1 and CS-2 were 18%, 24%, 25%, 29%, and 10%, 13% respectively. About 41.66%, 84.61%, 115.38% and 123.07% increment were obtained for MS-1, MS-2, MS-3 and MS-4 respectively compared to the highly disseminated ICS CS-2.

Nada Chulha, an improved double pot mud stove with chimney of India, very similar to the procured CSs showed almost similar performance using rice straw as fuel. *Nada Chulha* showed overall thermal performances of 10%, 10.9%, 13.5%, 19.7% and 23.5% using cow dung, rice straw, mustard residue, root fuel and wood (Acacia) as fuel respectively in WBT. *Sugam Chulha, India* is a version of *Nada Chulha*, *India* that used ceramic lining inside the fire boxes, flue gas passing line and inside chimney, showed much better overall thermal efficiency using rice straw as fuel. This *Sugam chulha, India* showed overall thermal efficiencies of 12.8%, 18.5%, and 29% using cow dung, mustard residue, and wood (Acacia) as fuel respectively in WBT (Smith et al., 2000b). In comparison with the *Indial Nada Chulha*, the designed MSs performed better, contrarily performance of CSs models is very similar to *Nada Chulha* using rice straw as fuel.

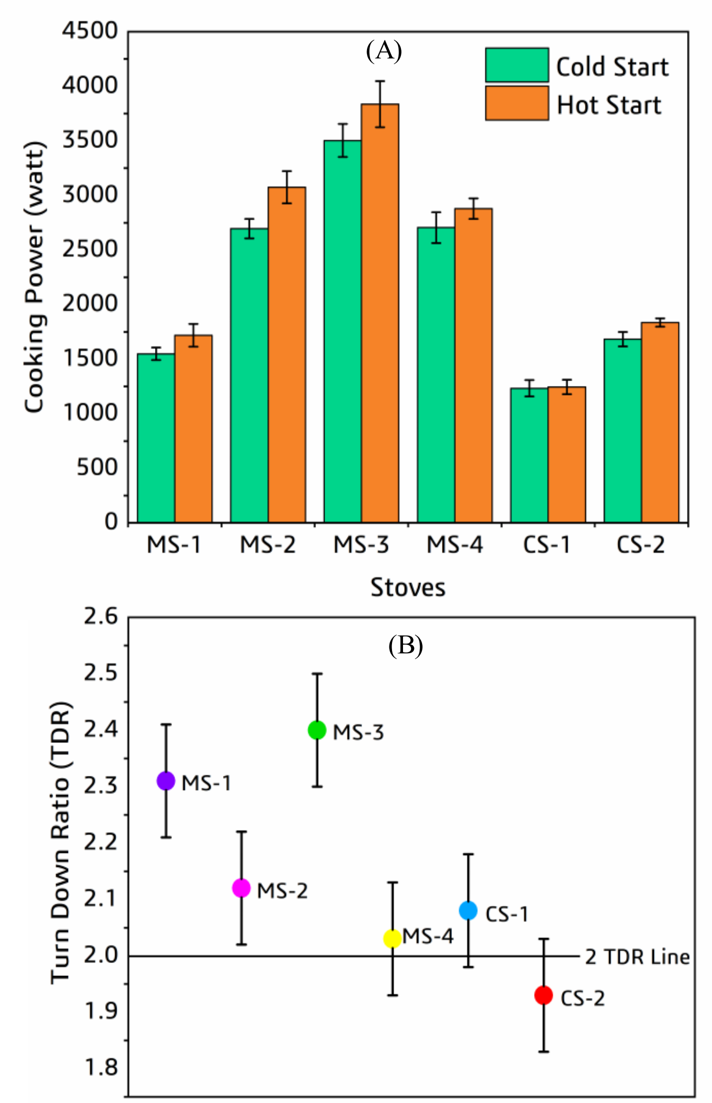

Figure 5: Cooking power in cold and hot start (A) and Turn down Ratio (TDR) (B) for stove models

The benchmark fuel and energy requirements to boil 5 L water and then simmer it for 45 min. for all stove models were calculated and shown in Table 4.

It was found that the lowest and the highest fuel or energy consuming cookstoves were MS-3 and CS-1 respectively. The fuel and energy consumptions per 5 L water for MSs varied from 1,158 to 2,343 g and 15,147 to 30,650 kJ respectively. The energy consumption standard to boil 5 L water and then simmer it for 45 min. for all types of biomass-based ICSs with chimney set by Aprovecho Research Center for Shell Foundation should be below 1500 g for wood or below 30,000 kJ for using alternative biomass fuel (Still,MacCarty, 2006). On this basis energy consumptions of MS-2, MS-3 and MS-4 were below the standard value of 30,000 kJ. Energy consumption of MS-1 was slightly higher than the standard value. Energy consumptions of the procured cookstoves CS-1 and CS-2 were much higher than the standard energy consumption value set by Shell Foundation (Table 4) (STOVE).

Table 4. Benchmark fuel and energy consumption values of stoves for entire WBT (5-liter water)

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	MS-5 Circular Grate	MS-6 Circular Grate
	Mean					
Dry Fuel (rice straw) consumed benchmark value (gm/5 liter)	2,343	1,505	1,580	1,158	3,299	2,379
Energy consumed benchmark value (kj/5 liter)	30,650	19,689	20,671	15,147	43,147	31,123
*Aprovecho-Shell Foundation benchmark fuel/energy consumption for wood burning chimney stove to boil 5-liter water and then simmer it for 45 minutes	Less than 1.5 kg wood/5-liter water or less than 30,000 kJ/5 liter water					

In literature, it was shown experimentally for several biomass cookstoves using different biomass fuel that overall thermal efficiency (η) of a biomass cookstove increases by moving up the energy ladder from dung cake to crop residue to wood (Smith et al., 2000b). Increasing thermal efficiency for a single cookstove with the biomass energy ladder (dung cake to crop residue to wood) means higher amount of effective energy utilization which in turn means less energy input. Therefore, there is every possibility for all the MSs in this study to perform better with the biomass energy ladder (dung cake to crop residue to wood) and hence an opportunity to become true ICSs (Venkataraman et al., 2010).

3.2. Emission performances of stoves in WBT

In-stack measurements of flue gas compositions on wet basis was performed for CO_2, CO, NO and CH_4. Composition of the relevant gaseous components (vol %), and combustion efficiencies during cold and hot start in high power phase and simmering in low power phase are shown in Table 5.

For entire WBT of MS and CS models, CO_2 concentrations varied from 6.52 to 6.88 vol%, and 6.29 to 6.57 vol% respectively. CO concentrations of MS and CS models varied from 0.325 to 0.381 vol% and 0.317 to 0.364 vol% respectively. NO concentrations of MS and CS models varied from 0.0047 to 0.0072 vol% and 0.0027 to 0.007 vol% respectively. Basically, NO forms at high temperature. Since the combustion temperatures of all MS models were higher than CS models, NO concentrations in flue gases were usually higher for MS models than for CS models. CH_4 concentrations of MS and CS models varied from 0.061 to 0.091 vol% and 0.063 to 0.073 vol% respectively. Combustion efficiencies of all MS models were found higher than CS models almost in all phases of WBT (Table 5). This may be attributed to the preheating process of primary combustion air in all MS models (Phusrimuang,Wongwuttanasatian, 2016). Combustion efficiencies of all MS and CS models for entire WBT varied from 80 to 85% and 77 to 81% respectively. However, combustion efficiencies of all stoves in low power phase were lower than in high power phase. Since the fuel burning rate was lower in low power phase compared to high power phase, combustion temperature was lower in low power phase. Therefore, combustion efficiencies of all stoves in low power phase fell down compared to high power phase.

Table 5. Emission characteristic and combustion efficiency of stoves for WBT (cold and hot start-high power phase; simmering-low power phase). Compositions are given in wet basis.

Parameters		Stove Type					
		MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	MS-5 Circular Grate)	MS-6 Circular Grate
		Mean.'± S.D.					
CO_2 (vol%)	Cold Run	6.60±1.86	6.61±2.11	6.81±1.81	6.67±1.39	6.55±1.19	6.53±1.48
	Hot Run	6.74±1.06	6.84±1.09	6.88±1.24	6.66±1.62	6.46±1.03	6.57±1.63
	Simmering	6.53	6.52	6.69	6.61	6.29	6.37
CO (vol%)	Cold Run	0.335±.059	0.337±0.073	0.325±0.104	0.316±0.059	0.322±0.055	0.317±0.058
	Hot Run	0.364±0.10	0.376±0.107	0.349±0.0916	0.357±0.0915	0.352±0.088	0.349±0.091
	Simmering	0.369	0.381	0.371	0.367	0.359	0.364
NO (vol%)	Cold Run	0.0055±0.001	0.0056±0.00133	0.006±0.0012	0.005±0.00098	0.0027±0.0005	0.0062±0.0009
	Hot Run	0.007±0.0005	0.007±0.00096	0.0072±0.00076	0.0067±0.00066	0.007±0.0006	0.0064±0.0006
	Simmering	0.0051	0.0053	0.0056	0.0047	0.0051	0.0048
CH_4 (vol%)	Cold Run	0.085±0.002	0.091±0.006	0.061±0.004	0.074±0.003	0.068±0.003	0.065±0.002
	Hot Run	0.071±0.002	0.075±0.002	0.084±0.015	0.075±0.003	0.069±0.002	0.073±0.001
	Simmering	0.067	0.071	0.063	0.065	0.064	0.063
Combustion Efficiency (%)	Cold Run	81±4.90	81±4.15	84±3.64	82±5.50	80±2.53	80±3.28
	Hot Run	84±1.76	84±2.25	85±2.07	83±2.83	80±2.61	81±2.67
	Simmering	80±1.95	80±2.15	82±2.5	81±2.45	77±2.15	78±2.37

It is customary to report the emission status as the concentration ratio of a pollutant with respect to CO_2. As the ratio is dimensionless, it is very easy to compare the emission performance among the stoves. The emission ratios of all stoves in high and low power phase of WBT are shown in Supplementary Files Table S1.

Supplementary Table S2 shows the average emission ratios of all stoves for entire WBT. CO ratios of MS and CS models in high and low power phases of WBT varied from 0.047 to 0.055 and 0.049 to 0.057 respectively, whereas the average emission ratios for entire WBT varied from 0.051 to 0.055 for MS models and 0.053 to 0.054 for CS models. CO emission ratio of *Indian Nada Chulha* using rice straw as fuel varied from 0.0921 to 0.288 during the high and low power phases of WBT and the average CO emission ratio for entire WBT was found to be 0.1657 which is almost three folds higher than the emission ratios of all stove models of MS and CS (Smith et al., 2000b). NO ratios of MS and CS models in different power phases of

WBT varied from 0.00071 to 0.00104 and 0.00041 to 0.00108 respectively. The average NO emission ratios for entire WBT varied from 0.00082 to 0.00092 for MS models and 0.00077 to 0.00090 for CS models. CH_4 ratios of MS and CS models in high and low power phases of WBT varied from 0.0089 to 0.0138 and 0.0099 to 0.0111 respectively, whereas the average emission ratios for entire WBT varied from 0.0102 to 0.0119 for MS models and 0.0103 to 0.0104 for CS models. CH_4 emission ratio of *Indian Nada Chulha* using rice straw as fuel varied from 0.00916 to 0.0151 during the high and low power phases of WBT and the average CH_4 emission ratio for entire WBT was found to be 0.0118. CH_4 emission ratios are almost similar among MS models, CS models and *Indian Nada Chulha* (Smith et al., 2000b).

Emission factors by fuel mass on pollutant mass basis of all the stoves during different power phases of WBT are shown in Supplementary Table S3 and average emission factors by fuel mass on pollutant basis of all stoves for entire WBT are shown in Table 6.

Table 6. Average emission factors by fuel mass on a pollutant mass basis (gm/kg D.F.) of all stoves for entire WBT

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
CO_2(gm/kg D.F.)	979	980	1003	983	948	956
CO(gm/kg D.F.)	33.49	34.11	32.72	32.63	32.27	32.16
NO(gm/kg D.F.)	0.590	0.597	0.630	0.550	0.497	0.583
CH_4(gm/kg D.F.)	4.07	4.22	3.72	3.55	3.59	3.59

CO_2 average emission factor (g/kg) for MS models varied from 979 to 1,003 and for CS models varied from 948 to 956. The upper limit of CO_2 average emission factor for CS models is lesser than the lower limit of CO_2 average emission factor for MS models. Whereas, Smith et al (2000) reported an average CO_2 emission factor for *Indian Nada Chulha* of 983 g/kg using rice straw as fuel (Smith et al., 2000b). CO average emission factor (g/kg) for MS models varied from 32.63 to 34.11 and for CS models varied from 32.16 to 32.27. In comparison with the average CO emission factor of the Indian Nada Chulha (101 g/kg), all the models of MS and CS emit less CO per kg of fuel (rice straw). NO average emission factor (g/kg) for MS models varied from 0.550 to 0.630 and for CS models varied from 0.497 to 0.583. CH_4 average emission factor (g/kg) for MS models varied from 3.55 to 4.22 and for CS models it was 3.59. Average emission factor of CH_4 *for Indian Nada Chulha* was reported as 4.24 g/kg using rice straw as fuel, which is very similar to MS models.

Average emission factors of pollutant mass by fuel energy content basis (g/MJ) of all the stoves for entire WBT are shown in Table 7 and Figure 6.

Table 7. Average emission factors of pollutant mass by fuel energy content basis (gm/MJ) of all stoves for entire WBT

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
CO_2 (gm/MJ)	74.85	74.92	76.68	75.15	72.48	73.10
CO (gm/MJ)	2.56	2.61	2.50	2.50	2.47	2.46
NO (gm/MJ)	0.045	0.046	0.048	0.042	0.038	0.044
CH_4 (gm/MJ)	0.311	0.323	0.284	0.271	0.274	0.274

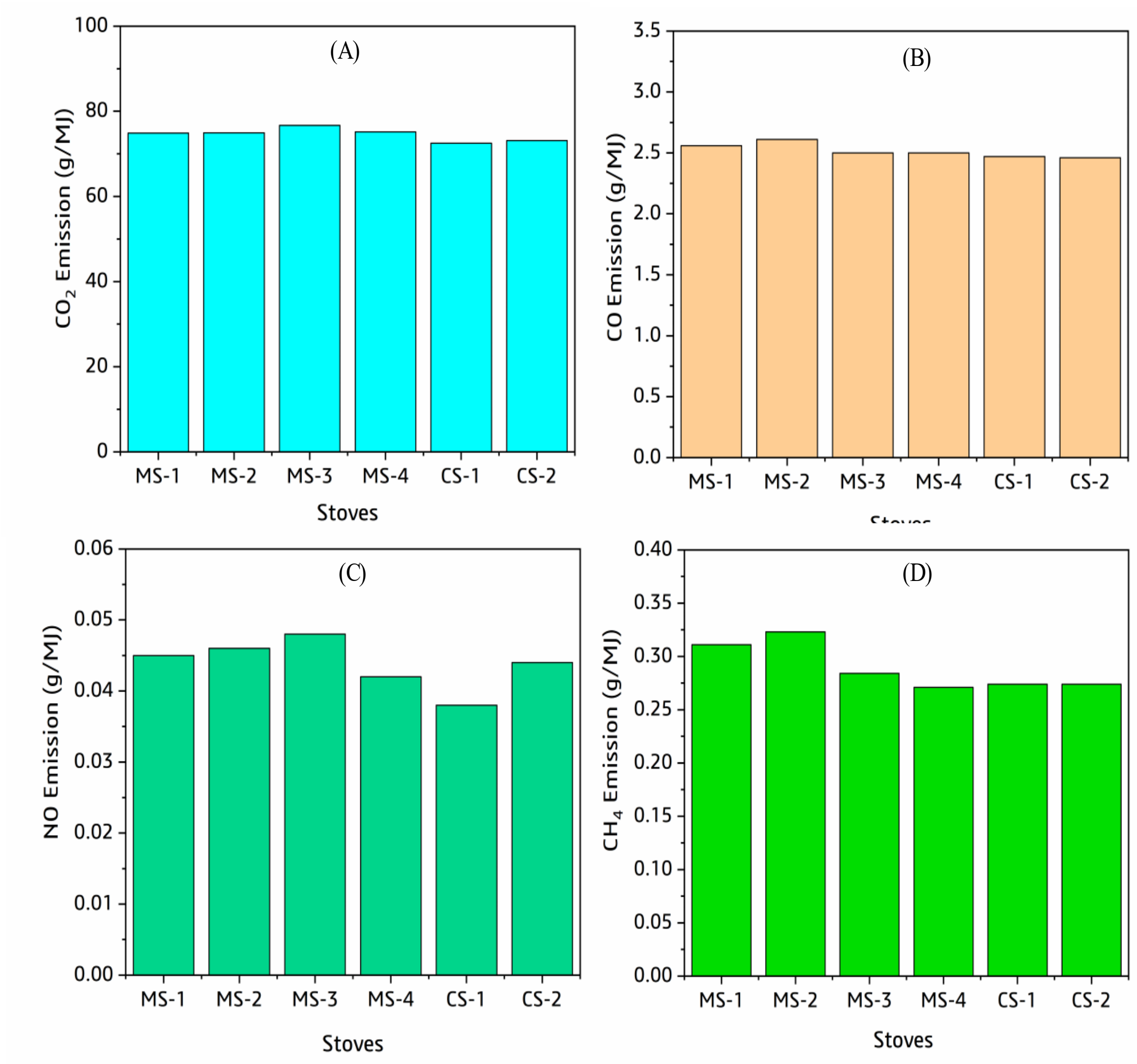

Figure 6: Average emission factors of (A) CO_2, (B) CO, (C) NO, (D) CH_4 mass by fuel energy content basis (g/MJ) of all the stoves for entire WBT

The CO_2 average emission factor (g/MJ) for MS models varied from 74.85 to 76.868, whereas this factor varied from 72.48 to 73.10 for CS models. CO average emission factor for MS models varied from 2.50 to 2.61 g/MJ, which was higher than CO emission factor for CS models that varied from 2.46 to 2.47 g/MJ. NO average emission factor for MS models varied from 0.042 to 0.048 g/MJ which was higher than NO emission factor for CS models that varied from 0.038 to 0.044 g/MJ. This was because of high combustion temperature in all MS models than in CS models. CH_4 emission factor (g/MJ) for all MS models were higher than CS models except for MS-4. CH_4 average emission factor for MS models varied from 0.271 to 0.323 g/MJ, whereas this emission factor for CS models was 0.274 g/MJ. Smith et al (2000) reported average emission factors of CO_2, CO and CH_4 to be 75.44, 7.751 and 0.3254 g/MJ respectively for *Indian Nada Chulha* using rice straw as fuel (Smith et al., 2000b).

Aggregated benchmark values of different polluting parameters (g/5-liter water) for boiling 5-liter water and then simmering it for 45 minutes during entire WBT are shown in Table S4. Total CO_2 emission values for entire WBT for 5-liter water of all MS models are lower than CS models except MS-1. Total CO_2 emission of MS-1 is somewhat higher than the CS-2. But in comparison with CS-1, MS-1 emits much lower content of CO_2 through the entire WBT for boiling 5-liter water and then simmering it for 45 minutes. The lowest CO_2 emission can be attributed to MS-4 whereas the second lowest CO_2 emitter is MS-2. MS-3 is the third lowest CO_2 emitter cookstove for entire WBT.

The ranking of all the stoves in terms of CO emission for entire WBT (to boil 5-liter water and then to simmer it for 45 minutes) is similar to that in terms of CO_2 emission. NO emission values were found to be lower for all MS models compared to CS models for entire WBT. The lowest NO emission can be attributed to MS-4. In terms of CH_4 emission for entire WBT, all the MS models emit less CH_4 compared to CS models except MS-1 that emits more CH_4 compared to CS-2 for entire WBT. Based on CH_4 emission, MS-4 can be ranked as the lowest emitter, the second lowest emitter is the MS-3 and the third lowest emitter is the MS-2. Among all the stoves, MS-4 emitted the lowest amount of each pollutant for entire WBT. The second and third lowest contributors to emission were MS-2 and MS-3 respectively.

3.3. Thermal Performance of stoves in CCT

During controlled cooking test (CCT) of all the cookstoves, combustion air temperature, fuel bed temperature, stack flue gas temperature and the draft inside the chimney were measure which are shown in Table 8.

The values found are almost identical to those found during WBT. Combustion temperature, fuel bed temperature, flame zone temperature is higher for MS models compared CS models. Although in some cases the average temperatures of some MS models were higher than CS-2, temperature difference between stack and flame zone was much higher in MS models compared to all CS models. Draft inside chimney of all MS models shows higher value compared to CS models which means better relative turbulence in MS models.

Table 8. Temperature and draft profile of all stoves during CCT

Parameters	Stove Type					
	MS-1	MS-2	MS-3	MS-4	CS-1	CS-2
	Circular Grate	Circular Grate	Elliptical Grate	Circular Grate	Circular Grate	Circular Grate
	Mean ± S.D.					
Combustion air temperature (°C)	71±5	68±3	70±5	72±6	30±1	30±1
Fuel bed temperature(°C)	633±8	628±8	638±8	645±6	602±4	606.±4
Flame zone temperature(°C)	731±10	726±6	726±8	724±9	690±13	683±10
Stack flue gas temperature(°C)	297±33	332±38	327±29	331±34	336±58	330±53
Draft inside chimney (-Pa)	*7.3±1.16	*7.5±1.12	*7.3.±1.11	*7.4±1.11	7.2±1.32	7.1±1.11

*All MS models have two chimneys. The draft reported here is the average draft per chimney.

Cooking menu of a traditional food (cooking of parboiled rice), average cooking time, average fuel requirement per cooking episode in CCT for each type of the stove model are shown in Supplementary Table S5. Normalized fuel and energy requirement per kg parboiled rice cooking following the same cooking menu for each type of the stove model, and therefore fuel and energy saving and cooking time saving taking the CS-1 and CS-2 as the reference stove separately are shown in Table 9.

Table 9. Fuel and energy consumption per parboiled rice cooking and fuel/energy saving and cooking time saving of the stoves considering CS-1 and CS-2 as the comparison base separately.

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
	Mean					
Fuel consumption (gm/kg parboiled rice cooking)	1504	1159.33	877.33	1044.44	1867.47	1378.67
Energy consumption (kj/kg parboiled rice cooking)	19,672.32	15,164	11,475.48	13,661.27	24,426.50	18,033
Fuel/energy saving	20%	38%	53%	44%	Base	26%
Time saving	8%	44%	60%	53%	Base	38%
Fuel/energy saving	(−) 9%	16%	36%	24%	(−) 35%	Base
Time saving	(−) 47%	10%	37%	24%	(−) 60%	Base

Figure 7 presents the energy consumed and boiling time for all the stoves. It was found that MS-3 (elliptical grate) consumed the lowest fuel and energy per kg parboiled rice cooking.

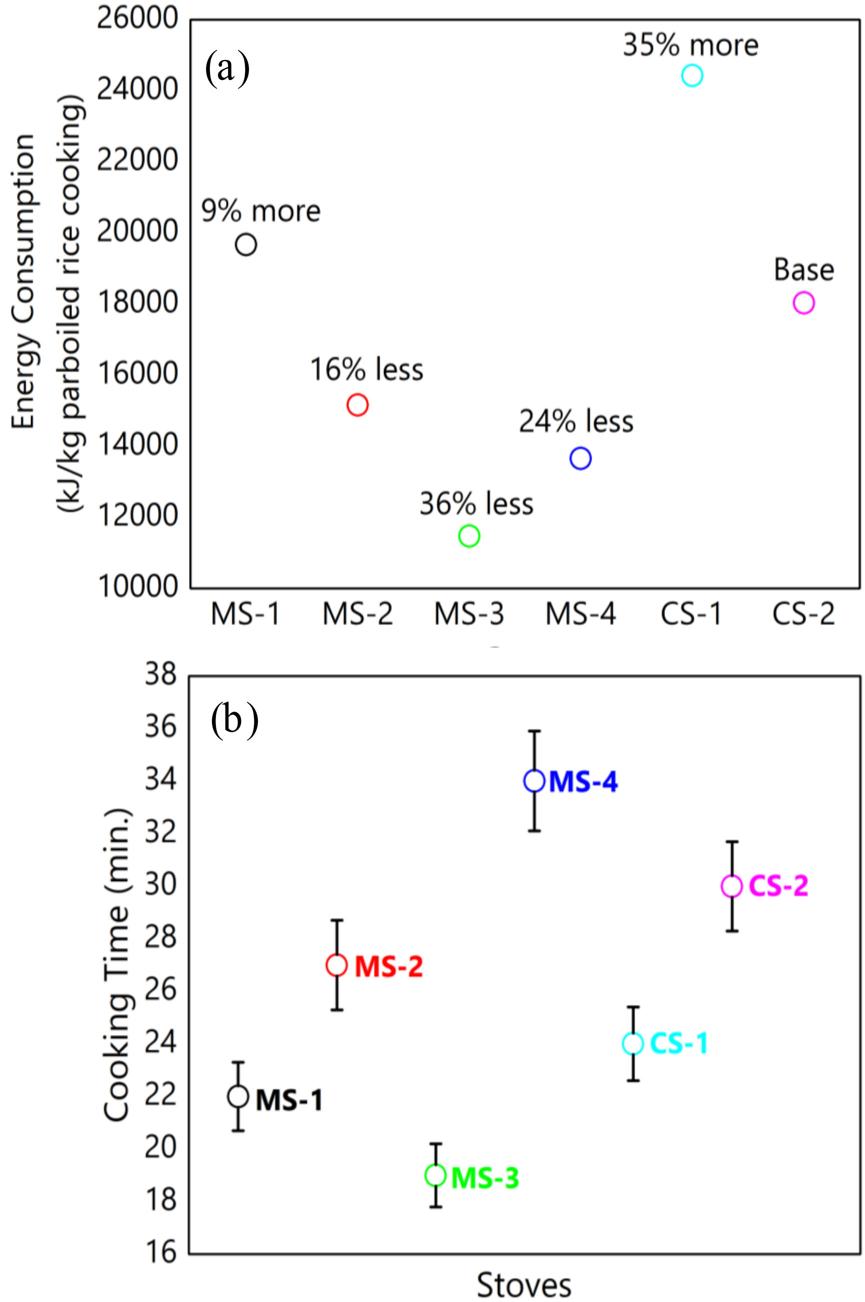

Figure 7: Energy consumption (kJ/kg) and cooking time (min) for all the stoves

As per Table 9, the rank order of the stoves (from the lowest to highest) based on the fuel and energy consumption for cooking 1 kg parboiled rice following the cooking menu is, MS-3 (the lowest fuel and energy consumer) < MS-4 < MS-2 < CS-2 < MS-1 < CS-1. Taking CS-1 as the base, MS-3, MS-4, MS-2, MS-1 and CS-2 save fuel/energy consumption by 53%, 44%, 38%, 19.50% and 26% respectively and save cooking time by 60%, 53%, 44%, 8% and 38% respectively. Even if the MS-3 and MS-2 (double pots) are compared with the CS-2 as a base, MS-3 (elliptical grate) and MS-2 (circular grate) mud stoves can save fuel/energy consumption by 36.4% and 16% respectively and save cooking time by 36.67% and 10% respectively. Whereas, MS-4e can save about 24.24% of fuel/energy compared to CS-2 (Table 9).

3.4. Emission performances of stoves in CCT

Pollutant concentrations (wet basis) of CO_2, CO, NO and CH_4 in flue gases and combustion efficiencies of all stoves during CCT are shown in Table 10.

Table 10. Emission characteristic and combustion efficiencies of different stoves during CCT (parboiled rice cooking)

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
	Mean±S.D.					
CO_2 (vol %)	6.63±1.20	6.76±1.35	6.61±1.77	6.61±1.38	6.44±1.03	6.49±1.73
CO (vol %)	0.286±.047	0.332±0.071	0.335±0.043	0.210±0.152	0.318±0.061	0.302±0.0478
NO (vol %)	0.006±0.00095	0.006±0.0016	0.0054±0.001	0.005±0.001	0.0055±0.001	0.005±0.0001
CH_4 (vol %)	0.073±0.001	0.081±0.002	0.069±0.002	0.070±0.002	0.071±0.002	0.069±0.001
Combustion efficiency	83±2.20	83±3.51	83±2.69	82±1.90	79±1.78	80±3.28

Average emission ratios of CO, NO and CH_4 in flue gases of all stoves during CCT with respect to CO_2 are shown in Table S6. It was noticed that the average emission ratios of CO of all the stoves during CCT were less compared to average emission ratios of CO of all stoves during WBT. Average CO ratios of MS models and CS models in CCT varied from 0.032 to 0.051 and 0.047 to 0.049 respectively (Table S6). Average NO ratios of MS models and CS models in CCT varied from 0.00076 to 0.00090 and 0.00077 to 0.00085 respectively. Whereas, average CH_4 ratios of MS models and CS models in CCT varied from 0.0104 to 0.0119 and 0.0106 to 0.0110 respectively.

Benchmark emission values of CO_2, CO, NO and CH_4 of all stoves for cooking one kg of parboiled rice using rice straw as fuel following the cooking menu are shown in Supplementary Table S7. In context of emission values of all the four gases (CO_2, CO, NO and CH_4) during cooking one kg parboiled rice, MS-3 (elliptical grate) was found to be the lowest emitter. The 2nd, 3rd and 4th lowest emitter were the MS-4, MS-2 and CS-2 respectively. CS-1 was found to be the highest emitter in context of all the four pollutants. Therefore, these stoves can be ranked in context of emission performance during CCT as follows: MS-3 elliptical grate (the lowest emitter) < MS-4 < MS-2, circular grate < CS-2 < MS-1 < CS-1 (the highest emitter).

Benchmark emission reduction by different stoves under consideration for cooking parboiled rice following the cooking menu given using rice straw as cooking fuel during CCT taking CS-1 concrete stove as reference stove are shown in Table S8. The highest pollution reduction was found in MS-3 (elliptical grate). The 2nd, 3rd , 4th and 5th highest emission reduction were found in MS-4, MS-2 (circular grate) and CS-2 and MS-1 respectively. Though the 5th highest emission reduction was found in MS-1 with respect to multiport cookstoves, it is better than Grameen Shakti-single pot concrete stove in context of emission reduction option.

CO_2, CO, NO and CH_4 emission reductions of MS models during CCT (considering CS-1 as reference stove) varied from 15 to 51%, 26-69%, 11 to 56% and 15 to 54% respectively whereas, these emission reductions were found to be 25%, 30%, 33% and 28% in CS-2. Though the emission reductions of CS-2 stove are close to those of MS-2, the latter is better in context of pollution reduction option.

3.5. Overall performances and insights of the stoves

The overall performance (overall thermal efficiency, combustion efficiency and heat transfer efficiency) and environmental stove index (ESI)) of all stoves (for entire WBT) using rice straw as fuel are shown in Table 11 and Figure 8.

Table 11. Benchmark efficiency values and environmental stove index of all cookstoves for WBT

Parameters	Stove Type					
	MS-1 Circular Grate	MS-2 Circular Grate	MS-3 Elliptical Grate	MS-4 Circular Grate	CS-1 Circular Grate	CS-2 Circular Grate
Overall thermal efficiency (%)	18	24	25	29	10	13
Combustion efficiency (%)	82	82	84	82	79	80
Heat transfer efficiency (%)	22	29	30	35	13	16
Environmental stove index (ESI)	0	0.29	0.44	0.48	-0.73	-0.43

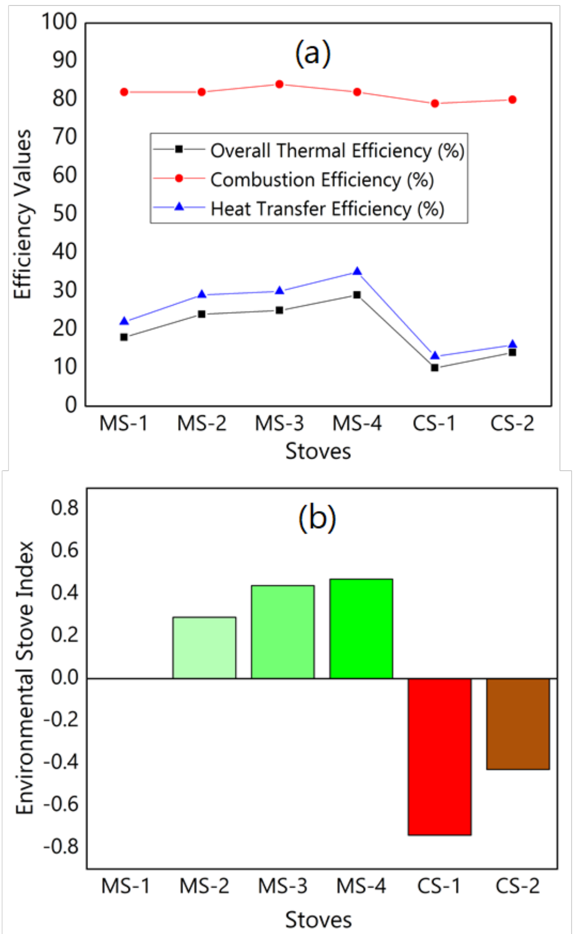

Figure 8: (a) Overall thermal efficiency, combustion efficiency, and heat transfer efficiency and (b) environmental stove index (ESI) of all stoves

All the parameters for MS models show higher values compared to CS models. Overall thermal efficiency, combustion efficiency, heat transfer efficiency and ESI of MS-1 and CS-1 stove were 18%, 82%, 22%, 0 and 10%, 79%, 13%, -0.73 respectively. If the MS-2 and MS-3 are compared with the CS-2, it can easily be seen that overall thermal efficiencies and heat transfer efficiencies of MSs are almost double than CS. Combustion efficiencies of MS-2/3 are also higher than CS-2. ESI of MS-2/3 is also much better than CS-2. The highest overall thermal efficiency and heat transfer efficiency were found for MS-4. Most of the performance parameters of MS models make them worthy to be ranked over the CS models.

Superiority of the MS models over CS models can be attributed to some unique design considerations of MS models. Preheating provision for combustion air, high fuel bed and flame zone temperatures, flame distribution pattern on pot bottom, reasonable draft in double chimney to create turbulence inside combustion chamber, comparatively short distance between fuel bed and pot mouth to facilitate radiative heat transfer, comparatively low stack temperatures and even distributions of combustion air channels under the fuel grate make all the MS models worthy to show their superiority over the CS models.

Some of the technical considerations have enhanced the thermal efficiency of the MSs stoves. There are some basic design principles for an effective biomass cookstove. The improved cooking systems (ICSs) possess low energy loss to surrounding environment, good combustion and heat transfer characteristics (Rathore et al., 2022). Insulation around the fire with light materials can resist heat from escaping to the surrounding (Okino et al., 2021). Wood ash was mixed with mud as insulating material in this study to fabricate all MSs as it is low-cost waste material (Urban et al., 2002).

Chimney increases the convectional heat transfer to the cooking pot. In convective heat transfer, surface boundary layer accounts to the primary resistance for heat flow by very slowly moving gas immediately adjacent to a wall (Xie et al., 2021). Within this region, heat transfer is primarily governed by conduction with low conductive gases. To improve the thermal efficiency of a stove, the thermal resistance of this boundary layer must be reduced by increasing the flow velocity of the hot gas over the surface of the pot (Karunanithy,Shafer, 2016). In the present study, it was followed for all the MSs models by increasing turbulence (Bryden et al., 2005). Increasing the radiative heat transfer from fire bed to cooking pot is another option to improve heat transfer efficiency of the cookstove. For the effective heating of cooking pot by radiation hear transfer directly from fuel bed, the average fuel bed temperature could be increased (without increasing the fuel consumption) by maintaining proper air to fuel ratio (Lucky,Hossain, 2001). Alternatively, radiative heat transfer can be increased by lowering the distance of cooking pot and fire bed or the view factor can be increased by increasing the size of the pot relative to the fire bed. In this work, all the stoves were designed to maintain the above criteria.

In this work, a unique phenomenon, preheating of combustion air, which raises the temperature of combustion chamber and provides relatively clean burning, was incorporated. All the cookstoves were designed with double wall to prevent burn, which is one of the most important safety factor of an improved stove. To mix the preheated combustion air with the fuel on fire bed for better combustion, total estimated combustion air was distributed evenly through several circular ducts under the fire bed (metal grate). Each of the stoves was fixed type and the base of the stove and floor surface were separated with insulating material (ordinary fired

brick) to prevent excessive heat flow to floor materials. To lessen the excess heat load of the stove body, the height of all stoves was maintained a minimum providing the ash pit underground. Ash pit and ash hole on the floor surface were connected through an underground channel.
To validate the economic feasibility, a facile cost analysis for the construction of stove models is summarized in Table 12.

Table 12: The comparative costing for the stove models

Stove Model	Estimated Unit price (USD)
MS-1	5.30
MS-2	5.30
MS-3	5.30
MS-4	5.30
CS-1	8.20
CS-2	11.6

The designed MSs made with mud did not cost money except for metal O ring, grate, and chimney. The technique for the construction of these MSs was comprehensively described in this manuscript and easy to follow. On the other hand, the CSs models require stone aggregates, sand, cement, and mould for the construction. The rural people may find it difficult to build these CSs at home. The construction cost of CS-1 is 54 % higher than MSs, whereas CS-2 has 118% higher cost than MSs.

4.0. Conclusions

This work deals with the construction and feasibility (operational and economic) analysis of easily fabricated MSs over procured ICSs CSs. The study found that the MS models were better designed stoves in context of combustion efficiency, heat transfer efficiency, overall thermal efficiency, and emission reduction. If one compares the performances of single pot stove between MS and CS models, theMS-1 will be ascertained as the better option with respect to lesser amount of fuel requirement, lesser time requirement to cook, and lesser amount of pollutant emission. If one compares the performances of double pot stove between MS and CS models, no doubt that MS will get ride on the CS stove in context of reduced cooking time, reduced fuel consumption, and reduced emission. However, MS-3 (elliptical grate) is the best engineered stove among the double pot stoves designed, every nook of stove performances. MS-4 (triple-pot) stove can also be considered as one of the best models among the multi pot stove variant in context of reduced fuel consumption, cooking time and pollutant emission. Therefore, all the MS models superseded the performances of CS models within their respective group. This performance superiority of MS models can be attributed some basic concepts in engineering design of the stoves, i.e., preheating combustion air, better mixing of incoming combustion air with fuel and volatiles inside combustion chamber through evenly distributed multi channels under the fuel bed, increasing radiative heat transfer by shortening the distance between grate and pot mouth, and increasing convective heat transfer through maintaining high draft in chimney. Moreover, the designed MSs were much low cost compared to the CSs, which makes the MSs as excellent cookstoves for the rural community of any developing countries.

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Data Availability Statement
The detailed data will be available on reasonable request from the corresponding author.

Conflict of interest
The authors declare no conflict of interest.

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