

**ARTICLE**

# Development of Advanced Biomass Cookstove and Performance Comparisons Using the Modified Star Rating Methodology

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**ABSTRACT**

A disruptive approach to a fundamental process has been applied in a biomass combustion device with two variable speed fans to supply air for gasification and another for combustion processes, separately. Besides, the pre-heating of secondary air, required for combustion process was also ensured through annulus chamber before being fed into the combustion chamber. The turbulent flow and homogenous mixing were also ensured by controlling the flow rate resulting in the reduced emissions of carbon monoxide (CO) and fine particulate matter (PM 2.5, particulate matter having aerodynamic diameter <2.5 micron). The design approach applied here has also ensured the homogeneous mixing of preheated air with the volatiles, resulted in cleaner combustion. This arrangement has led to the emissions of PM2.5 and CO much better than those of the earlier cookstove models, and very close to that of a liquefied petroleum gas (LPG) stove. Further, the comparative analysis based on the modified star rating of total 15 (14 are biomass and another LPG) cookstove models tested using the same standard methodology has been done and presented in this study. Based on the star rating, the performance of the LPG stove was found to be best and assigned as a 5-star product followed by the IITD model (4-star), while the other 13 models got different ratings starting from 1-star to 3-star, respectively. Also, the thermal performance of the IITD cookstove model is found to be the highest, while the emission characteristics are found to be the least among all biomass cookstove models, presented here.

**KEYWORDS**

Star rating; biomass pellet cookstove; thermal performance; fine particulate matter (PM2.5); carbon monoxide

**Nomenclature**

$A_{\text{duct}}$ :	Cross-sectional area of duct ( $\text{m}^2$ )
$\text{CO}_{2\text{e}}$ :	Carbon-dioxide equivalent (tone)
CV:	Calorific value of fuel (kcal/kg)
D:	Diameter of cookstove (m)
$E_s$ :	Specific energy of food (kcal/kg)
FCR:	Fuel consumption rate (kg/h)
H:	Height of cookstove (m)
$H_d$ :	Total energy delivered to pot (kcal)



$M_f$ :	Mass of food (kg)
LPG:	Liquefied petroleum gas
P:	Concentration of CO (ppm)
Q:	Total volume of diluted exhaust gas (l)
$Q_n$ :	Energy required to cook food per unit time (kcal/h)
t:	Total duration of experiment (h)
T:	Absolute temperature of flue gas at sampling point (K)
$V_{duct}$ :	Average velocity of flue gas at sampling point in duct (m/s)
$\eta$ :	Efficiency of cookstove (%)
$\rho_{th}$ :	Density of fuel ( $\text{kg/m}^3$ )

## 1 Introduction

Around 40% of world population (2.4 billion people) rely on solid biomass fuel to meet their day to day cooking energy demand, using the traditional cookstoves particularly, in the developing countries. These traditional cookstoves are very inefficient and release harmful emissions into the kitchen, which is product of incomplete combustion. The indoor air pollution is harmful to the cook and her family members, particularly, the children below the age of 5 year and responsible for more than 4 million death each year, globally [1]. The smoke from the cookstove is associated with a number of diseases, including acute respiratory illnesses and even cancer, with women and young children affected disproportionately [2]. The level of fine particulates inside the kitchen-cum-house is up to 40 times higher than the maximum limits recommended by the World Health Organization [3]. The prolonged exposure to cookstove emissions leads to respiratory, cardiovascular and reproductive malfunctioning in human body especially, the emission of fine and ultrafine particulate matters (PM<sub>2.5</sub> and below) [4].

Further, the uncontrolled open burning consumed more solid biomass and releases more greenhouse gases (GHGs) and harmful soot into the environment which has number of secondary pollutants including polycyclic aromatic hydrocarbon (PAHs), elemental carbon (EC), black carbon (BC) and others [5]. Number of studies has established a correlation between occurrence of cardiovascular disease and exposure to fine particulates from the indoor air pollution which is attributed mainly to the cooking and water heating activities using the traditional cookstove having very poor thermal performance and combustion characteristics [6–8].

Joon et al. [9] carried out the experiments on the traditional cookstoves using different fuels and found that the emission level of CO was 40, 43, 75 times higher than that of LPG stove, while it was found to be of 9, 16, 31 times higher for PM emission for wood, crop residues, dung cake, respectively [9]. The similar observation was also reported by Venkatraman et al. [10] that the emission released from any cookstove differ with the type of fuel used, and it is therefore, apparent that there is an impact of fuel on the performance and emissions characteristics of a cookstove.

The feasibility of using TEG during cookstove operation is already in progress and several authors designed and developed the prototype models and presented the detailed study including the thermal performance and durability of the battery charging and discharging mechanism for more few months of operation [11,12]. These studies experimentally demonstrated that a small TEG was capable of delivering small amount of off-grid electricity with continuous operation using the traditional fuel, without altering the cooking practices while, meeting the basic needs such as charging a mobile, LED lantern, running a small fan, etc. using a single thermoelectric module. The technical feasibility of a combined heat and power generation through a common solid-fuel cookstove system was studied experimentally [13]. They designed and demonstrated the experimental system having water heating used for different

purposes while the pumping was done by running a small pump attached with the TEG along with other small utilities mentioned above. They were also able to generate on average 600 W of thermal and 27 W of electrical energy experimentally during two-hour long operation of the cookstove.

There are more than 500 cookstove models available globally and everyone claims that his model is an improved one, which is also true up to certain extent due to the fact that any technical intervention will improve the performance as compared to the traditional one. Majority (more than 99%) of these improved and approved cookstove models were tested under laboratory conditions and their emission factors were measured using wood logs of specified size and moisture. Most of these cookstove models being used by majority of poor world population, consume solid fuel mainly wood and agro-residues, varying in sizes and the moisture content round the year. Most of the developmental and field studies on cookstove have emphasized on improved design and performance of the cookstove without taking into account the fuel quality, particularly the moisture content and size of the fuel. Among these several hundred cookstove models, any of two different models, behave differently and there is a huge variation in the performance parameters, including the thermal efficiency and emissions of CO and PM<sub>2.5</sub> while tested under the same laboratory conditions using the same methodology.

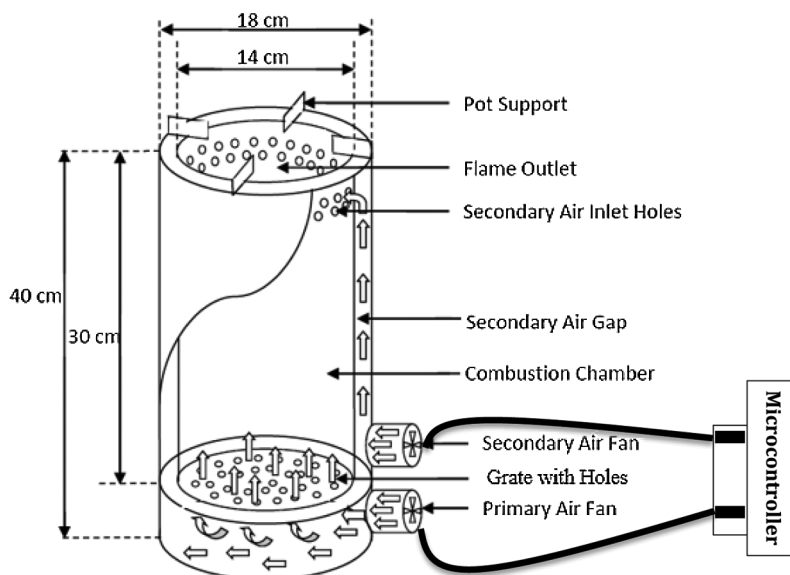
One such database of more than 53 Natural and forced draft cookstove models was made available in the public domain by the Ministry of New and Renewable Energy (MNRE), Government of India for the certification and dissemination of clean cookstove under the Unnat Chulha Abhiyan [14]. However, the performance of the forced draft cookstove models were found to be superior than those of the natural draft models, while both were called improved and placed under the category of approved models, which were analyzed and criticized [15]. They emphasized that by putting the horse cart and motor car under the same category, when sold under the tendering process is actually killing the innovation, rather than encouraging it and should be discouraged. Some authors observed that the gasifier stoves can perform better than that of a rocket type stove because of the improved combustion characteristics and hence, the emission of CO and PM<sub>2.5</sub> can be reduced significantly by varying secondary air flow rate, this is also apparent from the list of approved models, globally [10,16,17].

Very recently the relative grading of cookstoves was proposed for around 53 cookstove (natural and forced draft) models while tested under the same laboratory conditions following the same standard testing protocols [15]. They also suggested the remediation and changes in the policy for better marketing, dissemination and wider adoption of improved cookstoves by the end users. Further, the reward in the form of incentives for innovation to the better performing cookstove was also suggested, while linking with the performance-based costing. It was suggested to remove the existing ambiguities in the purchase through tender involving public money. It was also proposed that an equivalent amount of charge in the form of carbon tax may also be fixed on the LPG stove, while a percentage of the cost of the biomass cookstove may be subsidized, so as to make the two comparable. Further, the LPG being fossil fuel should not get the superior treatment in the form of subsidy and promotion over the carbon neutral agro-residue waste pellets.

This study presents the comparative analysis of 13 biomass cookstove models tested using the same standard methodology and available in public domain with the one developed by our group, named as advanced biomass (IITD model) cookstove. The emission of harmful pollutants such as, PM<sub>2.5</sub> and CO was also evaluated and compared with the best model, i.e., the LPG stove and the worst model, i.e., the traditional biomass cookstove along with 13 other forced draft models, mentioned above [18]. The performance parameters such as, thermal efficiency and emissions of PM<sub>2.5</sub> and CO were clubbed into a single parameter named as star indices for developing the star rating and the results are discussed in detail.

## 2 Design Methodology

The developed IITD model is a forced draft cookstove having cylindrical combustion chamber having an arrangement for variable speed fans operated on battery and can be controlled through the knobs attached with a microcontroller, and the line diagram of the same is shown in Fig. 1.



**Figure 1:** Schematic diagram of the advanced biomass cookstove model

The material used for the construction of the cookstove was mild steel of 0.3 cm thickness. The air requirement for combustion was fulfilled by supplying both primary as well as secondary air through axial fans. The ratio of the primary air to the secondary air flow rate was varied in the range of 1:3–1:5. The primary air is supplied by the fan attached at the bottom of the inner cylinder to supply required amount of air for gasification of the biomass pellets through the grate placed at the bottom portion of the cookstove. The secondary air entered combustion chamber through holes located at the top portion of the inner cylinder. Secondary air was preheated before being supplied to the combustion chamber by passing it through the optimized air gap between the concentric cylinders. The fuel used in this study was biomass pellets of 0.8 cm diameter, respectively. The proximate analysis of the fuel used is given in Tab. 1, as below:

**Table 1:** Proximate analysis of biomass pellets used in this study

S. No.	Component	% by weight
1.	Moisture content	8.08
2.	Volatile matter	71.96
3.	Fixed carbon	14.89
4.	Ash content	5.07

For the design and development of the model, basic energy requirements, fuel consumption rates, specific gasification rate and fuel density was considered as the important criteria. The energy

requirement was calculated based on the amount of food to be cooked along with the specific heat. The energy required to cook a particular food per unit time can be determined by using following formula [19,20]:

$$Q_n = \frac{M_f \times E_s}{t} \quad (1)$$

where,  $Q_n$  is the energy required to cook food,  $M_f$  is the mass of food to be cooked (kg),  $E_s$  is the specific energy of food (kcal/kg), and  $t$  is the time taken for cooking (h). The amount of fuel required to be fed in the cookstove can be calculated by evaluating energy requirement of the cookstove, calorific value of fuel and assuming minimum permissible value of stove efficiency according to type of the stove. The quantity  $Q_n$  also depends on the amount of food to be cooked and the specific energy that is required to cook food. The specific energy of food is the total amount of the thermal energy that is required to cook a particular type of food which includes both the sensible heat required to boil water and the latent heat which is required for prolonged boiling the water to cook the food item. The amount of fuel burnt per unit time is called fuel consumption rate (FCR) and can be calculated by following relation [19,20]:

$$FCR = \frac{Q_n}{CV \times \eta} \quad (2)$$

where, FCR is the fuel consumption rate (kg/h), CV is the calorific value of fuel (kcal/kg) and  $\eta$  is the efficiency of the cookstove (%). The diameter of the cookstove is the inner diameter of the combustion chamber in which fuel is burnt. It is a function of fuel consumption rate (FCR) and the specific gasification rate (SGR) of biomass and can be computed as follows [19,20]:

$$D = \left( \frac{(4/\pi)FCR}{SGR} \right)^{0.5} \quad (3)$$

where, D is the diameter of the cookstove (m), SGR is the specific gasification rate of biomass (kg/m<sup>2</sup>-h). The height of the cookstove depends on the total duration for which cookstove needs to be operated in single batch of fuel, specific gasification rate of biomass and density of biomass [21,22]. It can be calculated by using following formula [19,20]:

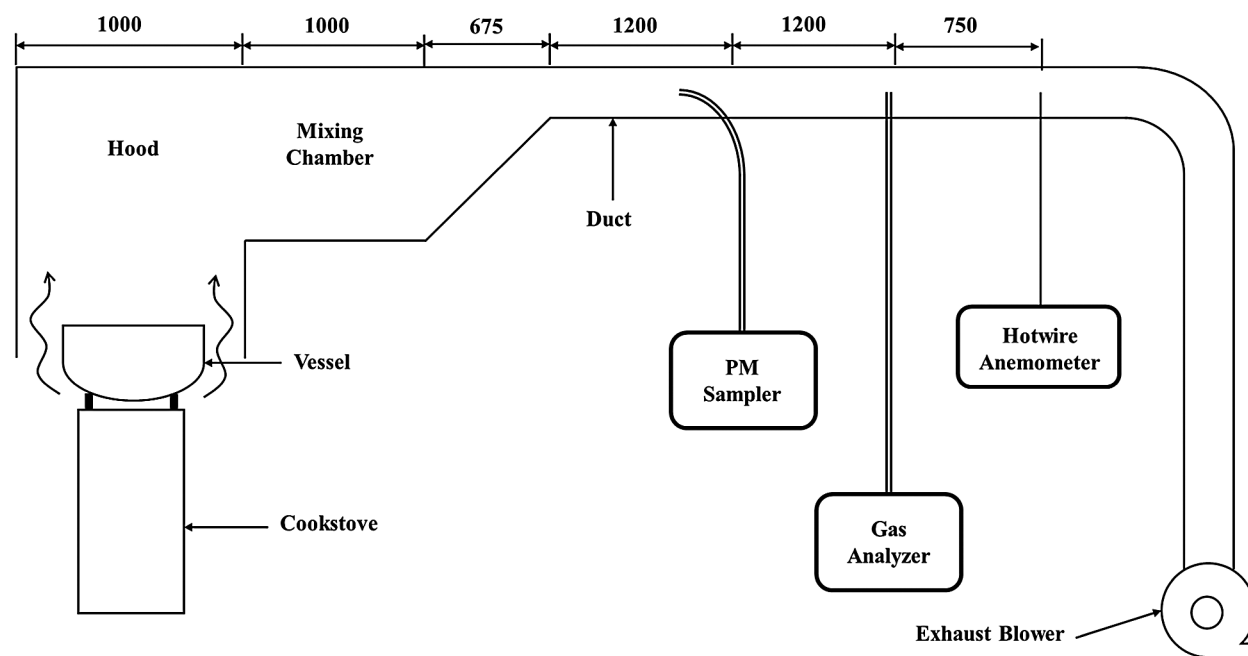
$$H = \frac{SGR \times t}{\rho_{rh}} \quad (4)$$

where, H is the height of the fuel bed in the combustion chamber (m), t is the operation time for cookstove in single loading of fuel (h),  $\rho_{rh}$  is the bulk density of fuel. The developed cookstove model consists of two concentric cylinders with inner and outer diameter of around 14 cm and 18 cm, respectively, while the H/D ratio of the combustion chamber from grate to secondary holes was kept around 2, as shown in Fig. 1.

### 3 Experimental Setup

The experiments on the fuel used were performed using the standard testing methodology for cookstoves as prescribed by Bureau of Indian Standards. The results reported in the present manuscript have been averaged from six experiments under the similar operating conditions to ensure repeatability. Standard deviation for all the performance parameters has been calculated and it was found to be less than 2%. The air flow rates during the operation of cookstove in each experiment were maintained using a microcontroller that was able to regulate the voltage supply to primary and secondary air fans in four steps. The air flow rates were kept low during the starting phase and thereafter, increased gradually till the propagation of flame over the fuel bed and, reduced during the char combustion period at the end of cookstove operation. The schematic diagram of experimental setup is shown in Fig. 2. The main

components of the setup include, the hood, duct, blower, PM sampler, flue gas analyzer attached with the desktop computer for online sampling. The emissions from cookstove are first collected in the hood and then diluted by mixing ambient air with the help of exhaust blower installed at the exhaust of the duct, shown in Fig. 2. The emissions of CO were measured by inserting sampling probe of gas analyzer in the duct at an appropriate distance from the hood. The resolution and range of gas analyzer for measuring CO emissions were 1 ppm and 0–10000 ppm respectively.



**Figure 2:** Schematic of the experimental setup (all dimensions in mm)

The thermal performance and emission characteristics such as particulate matter (PM 2.5) and carbon monoxide (CO) for three different models viz. the traditional cookstove, LPG stove, and IITD cookstove were evaluated using the standard operating methodology of the Bureau of Indian Standard (BIS) under similar operating conditions [18]. The emissions of CO were measured using flue gas analyzer (Testo 350XL) in parts per million (ppm), while the measurements for PM were carried out gravimetrically with the help of sampler using the quartz filter of 47 mm diameter placed in PM2.5 cyclone sampler. In the starting phase, the primary air fan was running at slow speed and secondary air fan was kept off. After sometime when the combustion progressed, the secondary air fan was switched on slowly and the speed of the fan was increased gradually as per the requirements till the steady state was achieved. Similarly, towards the completion of the experiment, the primary and secondary air supplies were reduced gradually according to the color and intensity of the flame.

The emissions were monitored continuously during the experiment by interfacing the gas analyzer with the computer through the software. The flue gas was passed through cyclone sampler with the help of inbuilt pumping arrangement and the measurement of total volume sucked along with the velocity were recorded automatically, while the mass of the total particulate matter deposited on the filter paper was recorded manually by subtracting initial and final weight of filter. The electronic weighing scale having least count of 1  $\mu\text{g}$  was used for measuring weight of filter. Temperature readings of water in the pot were noted by using PT-100 type probe having least count of 0.1°C. The amount of water to be filled in the vessels was



measured with the help of digital weighing balance having least count of 1 g. The experiments were performed at an ambient temperature of around 30°C.

#### 4 Uncertainty Analysis

The uncertainty analysis has also been carried out to determine the uncertainty associated with calculation of emissions of PM2.5, CO and thermal efficiency of the cookstove. In the present case, the uncertainties reported are not only based on the resolution of instruments but also the uncertainties associated at each step during the process of determination of thermal efficiency and emission of CO and PM2.5, which have already been incorporated during the calculation of performance parameters of the cookstove. The random uncertainties include the weighing of fuel, pot, water, filter paper while, the systematic uncertainties include the measurement of CO concentration, measurement of velocity and temperature of diluted exhaust gas inside the duct. When Q is function of number of independent variables  $x_1, x_2, x_3, \dots, x_n$  and  $u(x_1), u(x_2), u(x_3), \dots, u(x_n)$  are their corresponding uncertainties, then the uncertainty in Q can be determined by following relation [23]:

$$U_Q = \left[ \left( \frac{\partial Q}{\partial x_1} u_1 \right)^2 + \left( \frac{\partial Q}{\partial x_2} u_2 \right)^2 + \left( \frac{\partial Q}{\partial x_3} u_3 \right)^2 + \dots + \left( \frac{\partial Q}{\partial x_n} u_n \right)^2 \right]^{1/2} \quad (5)$$

Based on the least count of instruments as mentioned in the previous section, the uncertainties in the calculation of thermal efficiency, fine particulate matter (PM2.5) and carbon monoxide (CO) were found to be 0.16%, 0.47% and 2.02%, respectively.

#### 5 The Star Rating Methodology

It is very clear from Tab. 2 that only one of the MNRE's approved models has slightly better emission parameters of carbon monoxide (~7.7%) but none of them has higher thermal performance and lower emission of particulate matter than the present model. A huge variation is apparent among the approved models, while tested under the same methodology [18]. Therefore, it is desirable to develop a single unit that can accommodate all the performance parameters of a cookstove model based on the importance of each. As mentioned above, the natural draft models were having very poor performance and emission characteristics, and therefore, left out from this study [15].

The emission of particulate matter (PM2.5 and below) and carbon monoxide are directly related to human health, the cook and her family members particularly, the kids below 5 years of age who are found to be playing around the cooking area [15]. Moreover, the emission of particulate matter (PM2.5 and below) is highly severe because it can percolate into human lungs and affect their functioning, which is also having some carcinogenic elements [7]. Further, the ultrafine particulates can even mix with human bloodstream as they can easily pass through lung tissue leading to blood clots and other cardio vascular diseases. Therefore, more weightage should be given to PM2.5 than the CO. The thermal efficiency is directly related to fuel consumption which is renewable in the present case and it should get the least weightage among the three performance parameters, mentioned above. The proposed "Star Rating" to carry out comparative performance of different cookstove models along with the LPG stove and other forced draft models, approved by MNRE, is given as below:

$$\text{Star Rating} = \left( \begin{array}{l} 50\% \text{ Weightage to PM} \\ +30\% \text{ Weightage to CO} \\ +20\% \text{ Weightage to Thermal Efficiency} \end{array} \right) \quad (6)$$

$$\text{Star Rating Indices} = \left( \begin{array}{l} \{1 + (150 - \text{Test value of PM in mg/MJ}_D)/150\} \times 50 \\ + \{1 + (5 - \text{Test value of CO in g/MJ}_D)/5\} \times 30 \\ + \{1 + (\text{Thermal Efficiency in \%} - 35)/35\} \times 20 \end{array} \right) \quad (7)$$

**Table 2:** Performance and emission characteristics of different cookstoves

S. No.	Cookstove	Thermal efficiency (%)	PM2.5 (mg/MJ <sub>d</sub> )	CO (g/MJ <sub>d</sub> )	Star rating
1.	LPG	53.48	17.38	0.69	5
2.	IITD	41.34	38.91	0.98	4
3.	Surya FDD	40.90	133.43	1.80	2
4.	TERI SPT 0314	40.81	140.67	2.09	2
5.	TERI-SPF 0414S	40.78	71.36	1.28	3
6.	Eco Chulha 2.5	39.28	114.77	2.46	2
7.	Orja K3 Dix	37.26	128.26	1.12	2
8.	Biolite	36.92	120.02	0.91	2
9.	TERI SPT-0610	36.84	147.40	2.25	1
10.	TERI IMPMUD SPF 0143	36.77	100.94	2.13	2
11.	XXL Echo Chulha	36.52	56.29	1.14	3
12.	Atom	35.91	124.27	2.73	2
13.	TERI IMPMUD PMU0414D	35.52	107.56	3.63	2
14.	PMTS	35.47	117.03	3.20	2
15.	OJAS	35.33	78.82	2.57	2
16.	Traditional cookstove	14.35	1111.11	23.96	NA

As mentioned by Tyagi et al. [15] that not even a single product is available in the market that can be considered at par with or near the LPG stove, the ‘Gold Standard’. Therefore, it requires rigorous research and development and will take a long time to develop products that could easily penetrate the market and can utilize the indigenously available fuel, viz. processed biomass, to meet the cooking energy needs of the majority of the population in the country—which is equally applicable elsewhere, especially, in developing economies. Since the present model is having emission characteristics comparable to that of the LPG stove, therefore, it has been included in the present manuscript and the Star Rating methodology has also been modified accordingly, which shall give a true feel for a Five Star Rated appliance or product or service.

The star rating was done by giving 50% weight to PM2.5 and 30% to CO emissions (being most health hazardous to the cook and her family members, especially children below 5 years of age) and only 20% to thermal efficiency, as the fuel can be made available locally in rural areas of the country, and because thermal efficiency does not impact health directly like the PM2.5 and CO. Based on the star indices, mentioned in Eq. (7), a graph representing the comparative performance of total 15 cookstove models (including the LPG stove) is shown in Fig. 7, while the star rating was done using Eq. (6).



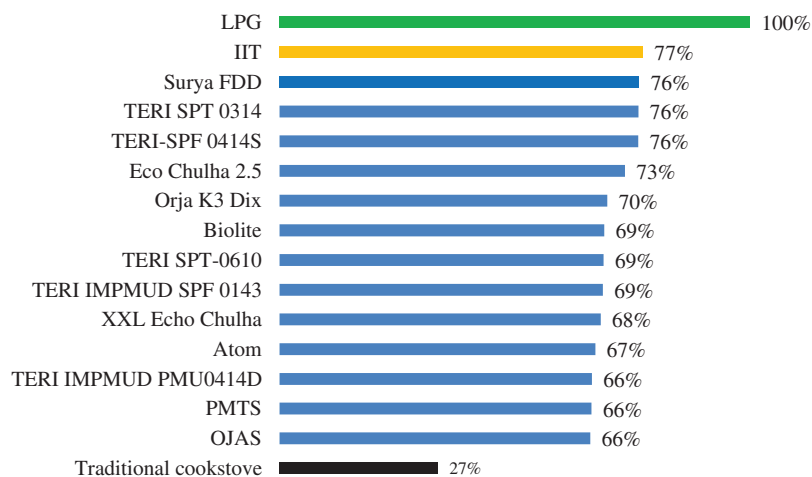
The modified star rating is being proposed to increase the norm for other stoves to meet improved thermal efficiency with decreased indoor air pollution. Further studies would be needed to evaluate this star rating on stove cost, dissemination and improved consumer uptake. Based on Eq. (7), the star rating index is calculated for all 15 cookstove (forced draft) models, and presented in such a way that there is no star given for up to 100 points, while from 101 to 120 one star (\*) is given, and only one cookstove model could get one star. Similarly, from 121 to 140, two stars; 141–160, three stars; 161–180, four stars; and 181–200 five stars, respectively, are given, as shown in Fig. 7. It is further clear from Fig. 7 that out of 13 approved models from the government (MNRE)-approved Cookstove Test Centers in India, only two models could achieve Three Stars, while none could achieve Four Stars, in the star rating. On the other hand, all models (13 models) obtain stars on the star rating; but the majority achieve a low star rating, i.e., below the four-star rating. Further, only three models out of the 13 approved models would get a three-star rating in the present scenario.

## 6 Results and Discussion

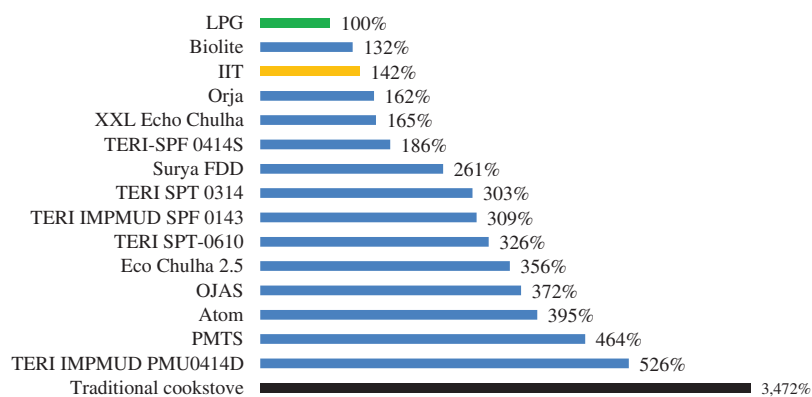
The thermal performance and emission characteristics of IITD cookstove model were compared with the widely used traditional cookstove as well as already approved forced draft cookstove models of MNRE [14], and the results are shown in Tab. 2. It can be seen from Tab. 2 that the thermal efficiency of the cookstove model developed by IITD is found to be 41.34% which is 2.3 times higher than that of the traditional cookstove, while all other forced draft cookstove models approved by MNRE exhibit lower thermal efficiency as compared to IITD cookstove model. The improvements in thermal efficiency were ranged between 1% and 17%, while comparing the efficiency of IITD stove with MNRE approved stoves.

The star rating number corresponding to each forced draft cookstove model can be seen from Tab. 2. However, the proximate analysis and fuel used (wood logs or pellets) for each stove is not available in the public domain. Hence the biofuel we used in our experiment may not be the recommended fuel for these stoves with uncertain effect on their efficiencies and its consequent effect on the star rating. Further in real world setting too, more often the recommended fuel for a particular stove may not be available and other fuels may be used by consumer. Star rating may be refined in future studies if feasible, by using a more standard fuel e.g., wood pellets, etc., so that the star rating is more comparable across various cookstoves. However, wood pellets will be having higher energy density and therefore, the performance and hence, the star rating will improve further without much change and/or modifications in these stoves including the IITD model.

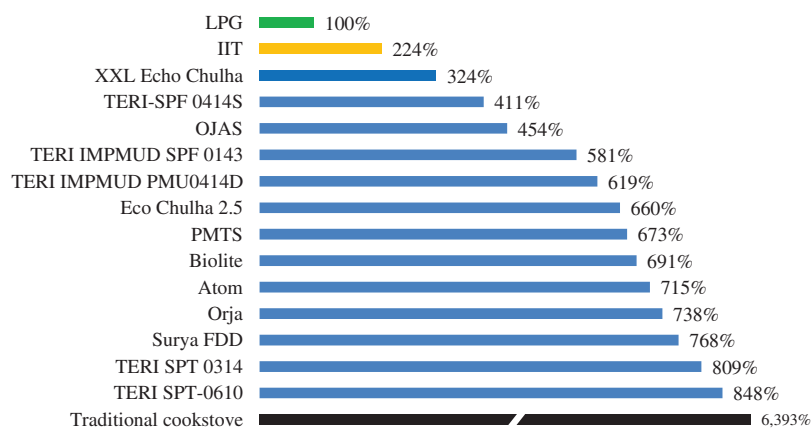
The rankings of IITD cookstove model for various performance parameters such as thermal efficiency and emission of CO and PM<sub>2.5</sub> w.r.t LPG stove and 13 forced draft cookstove models certified by MNRE have also been evaluated, while considering the performance of LPG stove as 100% which is usually acknowledged as gold standard. It can be seen from Fig. 3 that IITD cookstove model is ranked at 2<sup>nd</sup> position just after LPG stove, while comparing the thermal efficiency of IITD cookstove with LPG stove and other MNRE approved stoves. The thermal efficiency of three cookstove models viz. Surya FDD, TERI SPT 0314 and TERI-SPF 0414S are found to be comparable to the efficiency of IITD cookstove, however, these stoves are ranked at 7<sup>th</sup>, 8<sup>th</sup> and 6<sup>th</sup> positions, respectively, for the emission of CO as shown in Fig. 4, while IITD cookstove model is ranked at 3<sup>rd</sup> place. Further, it is shown in Fig. 5 that IITD cookstove model is positioned at 2<sup>nd</sup> place for the emission of PM<sub>2.5</sub>, whereas, Surya FDD, TERI SPT 0314 and TERI-SPF 0414S cookstove models are placed at 13<sup>th</sup>, 14<sup>th</sup> and 4<sup>th</sup> position, respectively.



**Figure 3:** Thermal efficiency rankings of IITD cookstove w.r.t different cookstove



**Figure 4:** CO emission rankings of IITD cookstove w.r.t different cookstove



**Figure 5:** PM2.5 emission rankings of IITD cookstove w.r.t different cookstove

It is clear from Fig. 4 that Biolite cookstove is ranked at 2<sup>nd</sup> place just after LPG for the emission of CO, whereas, for the emission of PM2.5 which is more hazardous for human health, it is ranked at 10<sup>th</sup> position as can be seen in Fig. 5. Therefore, there is only single cookstove model, i.e., IITD cookstove which is positioned closer to the gold standard LPG stove in terms of all the performance parameters (Thermal Efficiency—2<sup>nd</sup>, CO—3<sup>rd</sup> and PM2.5—2<sup>nd</sup>). The higher thermal efficiency and reduced emissions of CO and PM2.5 from IITD cookstove are attributed to even distribution of secondary air into the combustion chamber through air inlet holes located at the top of the combustion chamber. The secondary air is forced to pass through annulus chamber which assisted in preheating of the secondary air before being introduced into the combustion chamber as it comes in contact with the outer wall of the combustion chamber.

Thus, preheated secondary air resulted in higher combustion zone temperature leading to complete burning of particulate matter which otherwise could escape unburnt into environment. Even distribution of secondary air also created proper mixing of air with volatiles and turbulence in the combustion zone which resulted in better combustion and hence, higher thermal efficiency and reduced emissions of CO. Further it is also important to note that the efficiency and CO values of some cookstove models such as, Surya FDD and Biolite are close IITD model but PM2.5 performances of IITD model is much superior than the existing stoves.

It is found that IITD cookstove model scored 4 star, whereas all other biomass cookstove models approved by MNRE are ranged between 1 star and 3 star. It is clear from Fig. 6 that the performance of IITD cookstove is superior to all other cookstoves except the LPG stove, which could achieve Five Stars in the star rating due to its higher thermal efficiency and lower emissions. Four-star rating of IITD cookstove suggested that it has emissions comparable to LPG stove, and thus serve as an alternative to traditional cookstoves in order to provide clean cooking solution in remote area where biomass is available in abundant. Thus, IITD cookstove can complement LPG stove to provide clean cooking access in areas where LPG penetration is limited or unavailable.

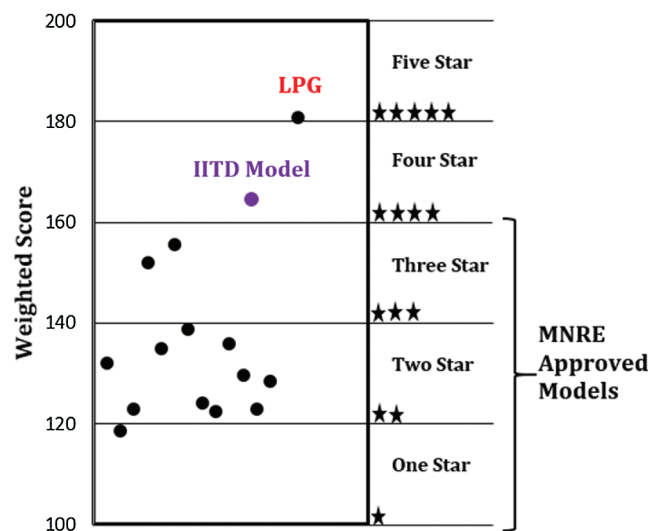


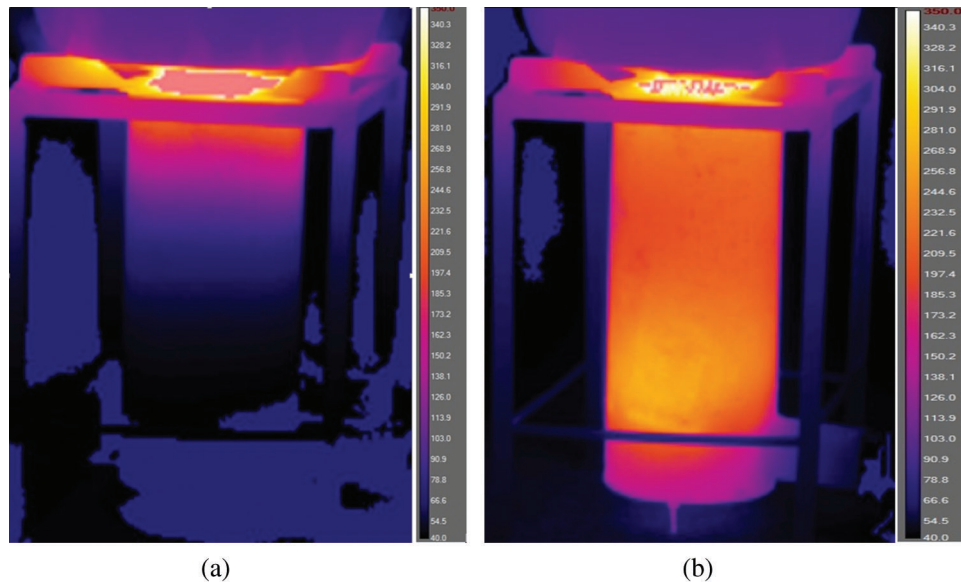
Figure 6: The weighted score and star rating of different cookstove models

Another important aspect which could be a game changer mainly for developing countries including the Asian and African subcontinents is to convert the access agro-wastes into pellets (densification) and utilize in cookstoves in place of woody biomass and dung cakes which has better utility for other applications. This could be turning point particularly, for the developing countries like India, where millions of tons of biomass is looking for an environment friendly disposal with value addition [24]. However, the sustainable disposal with value addition will require huge investment particularly, for developing a sustainable fuel supply-chain, ensuring the uninterrupted supply of the processed fuel (pellets) to the end-users. Also, making pellets of agro-wastes biomass is not only the cheapest but also clean and most efficient, when compared to the open field burning as in the present. The stubble burning emits huge amount of harmful pollutants, affecting both the human health and the environment. The efficient and clean cookstoves like IITD cookstove, if operated on agro-wastes biomass pellets, will not only eliminate harmful pollutant emissions from stubble burning but also can reduce hazardous emissions from traditional cookstoves, while fulfilling the clean cooking energy demand, which can also be replicated, elsewhere.

Regarding the Limitations, other parameters such as, potential of CO<sub>2e</sub> emission per unit of fuel consumption, convenience of use, availability of local fuel, socio-economic development of rural people and other related issues, etc. need to be evaluated before the dissemination in the field. As there is limited awareness about these parameters, therefore, they need to be considered in near future studies. The limitation of the developed cookstove model is that it can be used for processed fuels i.e., biomass pellets. However, it is evident from the literature that the emission factors viz. combustion characteristics and thermal performance cookstoves can be comparable to that of an LPG stove (the gold standard stove), only if the processed fuel of certain quality is used. This article not only support this fact but also justify it because the model developed and studied here is having the emission characteristics very close to that of an LPG stove.

## 7 Thermal Imaging Test

The outer surface temperature of the developed biomass cookstove model has also been monitored in the beginning and towards the end of the experiment using the thermal imaging camera as shown in [Figs. 7a](#) and [7b](#), respectively. The thermal image was recorded after every few minutes of operation from the beginning and similarly towards the end of the experiment to ensure the proper recording of the data. From these images, it is clear that the average temperature of the outer surface increases from the top to the bottom towards the completion of the experiment, which is obvious due to the nature of the fuel bed. In other words, as the burning of fuel starts, the bed starts moving downwards and the temperature of the outer body of the combustion chamber started increasing, as a result of heat transfer from inner surface to outer surface. As, there was no additional insulation, therefore, a significant share of available heat is lost to the environment. However, the heat loss from the outer body could be reduced significantly by applying suitable insulation to restrict the temperature of the outer surface to up to 60°C, as a mandatory requirement [18]. This will further enhance the overall performance of the cookstove and can also reduce the significant amount of fuel consumption, therefore, there is a scope of further improvement, which is underway and will be communicated separately.



**Figure 7:** Photographic view of the advanced biomass cookstove during experiment at (a) the beginning of the experiment and (b) towards the completion of the experiment using the thermal imaging camera FLIR A325sc

## 8 Conclusions

An advanced biomass cookstove model has been developed and evaluated experimentally along with the LPG and other cookstove models using standard testing protocols. Based on the experimental study, the particulate matter and carbon monoxide of the present model are found to be very close to that of the LPG stove and much better than those of the other approved models available in public domain, following the same testing protocols. Further, the emission factors such as PM<sub>2.5</sub> in milligram and CO in gram per mega joule of energy delivered to the cooking pot (MJ<sub>d</sub>) are found to be comparable to that of the LPG stove. On the other hand, the thermal performance of the IITD cookstove model is found to be the highest, while the emission characteristics are found to be the least among all other 13 cookstove models already approved by different testing centres in India under MNRE.

Since there is a huge variation among the performance parameters of different cookstove models discussed in this article, therefore, the star rating methodology was applied giving an appropriate weightage to different parameters, viz. the particulate matter, carbon monoxide and thermal efficiency. Based on the star rating, it is found that the present model has the better performance compared to other biomass cookstove models which is also comparable to the LPG stove. Although the LPG stove fares better in the star rating but may not be the best bet, because it burns the fossil-fuel and releases around 3.15 kg of CO<sub>2e</sub> per kilogram of (processed and bottled LPG) fuel into the environment. Also, the advanced model consumes the agro-waste biomass which is not only carbon neutral but also available indigenously and hence, should be preferred for better environmental health, which is degrading due to stubble burning. One estimate exhibits that it may reduce more than 10% of all CO<sub>2</sub> emissions, implemented on global scale [25].

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