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Making the popular clean: improving the traditional multipot biomass cookstove in Maharashtra, India

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Abstract The paper presents results of a study conducted to identify and modify the prevalent traditional multipot cookstoves in rural areas of Maharashtra, India. The flaws in the existing traditional stoves were identified through a survey comprising measurement of geometrical features of different specimens in the field and face-to-face interaction with the end-users. The end-users answered a structured questionnaire including the information about existing cooking practices, per day fuel consumption, willingness to adapt to a new stove type and related things. A popular model was then modified to develop an improved multipot cookstove, which was compared against the popular cookstove by conducting a set of experiments. The parameters evaluated during the experimentation were specific fuel consumption, burning rate, thermal efficiency, time taken to do a specific cooking task and CO emissions. It was found that the modifications to the popular stove resulted in increase in thermal efficiency, decrease in burning rate and specific fuel consumption but a decrease of firepower and turn-down ratio. The activity resulted in developing a better cookstoves for the targeted community.

Keywords Multipot · Cookstoves · Efficiency

Abbreviation

CO	Carbon monoxide
LPG	Liquefied petroleum gas
WBT	Water boiling test
TMBC	Traditional multipot biomass cookstove

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IMBC	Improved multipot biomass cookstove
LCV	Lower calorific value
SFC	Specific fuel consumption
FP	Firepower
TDR	Turn-down ratio

1 Introduction

Around 3 billion, i.e. almost 40% of the world population and about half of those living in developing countries rely on the traditional use of biomass for cooking and heating their homes (WEO 2016). About 66% of India's population rely on traditional use of biomass and almost 32% of the total primary energy used in the country is still derived from biomass (MNRE 2017). Conventional cookstoves are used along with the traditional fuel such as wood, charcoal, bagasse, and animal and vegetable wastes for cooking food. The smoke coming out from the stove is injurious to health, may cause diseases like asthma, eye irritation, lung disorder, and sometimes may prove fatal. Around 4 million people prematurely die worldwide every year due to indoor air pollution and many are affected by birth defects (WHO 2014). In spite of such consequences, people have not stopped using cookstoves. Though in many urban areas, firewood for cooking has been predominantly replaced by LPG or other modern fuels, the use of traditional biomass in many rural areas has seen no significant change (Geremew et al. 2014; Samson et al. 2001). Most houses in rural areas in India are equipped with either a single or a multipot biomass cookstove. The current research is mostly focused on reduction of pollutants coming from the traditional cookstoves through the introduction of the 'improved single pot' cookstoves (Singh et al. 2012; Pennise et al. 2009; Grabow et al. 2013; Singh et al. 2014; Hankey et al. 2015). Across the world, a wide variety of cookstoves with varying design and performance exists (Kshirsagar and Kalamkar 2014; Sedighi and Salarian 2017; Mehetre et al. 2017; Sutar et al. 2015; Kumar et al. 2013; MacCarty et al. 2010; Baldwin 1988). Many parameters influencing performance for cookstoves are identified and studied by researchers (Agenbroad et al. 2011a, b; Agenbroad 2010; Kshirsagar and Kalamkar 2015), such as the effect of moisture content (Bhattacharya et al. 2002a, b; Yuntenwi et al. 2008), use of different types of fuels (Bhattacharya et al. 2002a, b; Shen 2016; Suresh et al. 2016; Kaoma and Kasali 1994) and different design aspects (MacCarty et al. 2010; Oanh et al. 2005; Still et al. 2011). In addition, researchers (Alam and Chowdhury 2010; Adkins et al. 2010a, b) conducted field surveys and evaluation of many improved 'single pot' cookstoves. However, the majority of work so far deals with the single pot cookstoves and very few researchers have reported a detailed work on 'multipot' natural draft biomass cookstoves (MacCarty et al. 2010; Bhattacharya et al. 2002a, b; Honkalaskar et al. 2013; Joshi and Srivastava 2013; Still et al. 2011).

2 Scope of the work

The concept of *'Making the Popular Clean, as well as making the Clean Popular'* was put forth by Smith and Sagar (2014). All so-called 'Clean' (advanced and improved) biomass cookstoves involve some sort of modification over the 'popular' (traditional) cookstoves. Researchers often developed 'clean' stoves in laboratories, followed by their dissemination to the field, as a replacement of the 'popular' stoves. However, most of 'clean' stoves demand considerable change in cooking practices and fuel preparation. This results in very low adoption rates of such relatively 'clean' cookstoves and subsequently the failure of the mission-*'making the Clean Popular'*. A better alternative could be *'making the popular clean'* that is, improving the 'popular' cookstove while retaining most of its original features, allowing continuation of original cooking practices such as side-feeding large pieces of fuel, use of multiple pots, and use of user-preferred cooking pots.

In line with the approach of *'making the popular clean,'* the work presented here was aimed to identify and modify the 'popular traditional multipot cookstove' for the region of Maharashtra, India, to develop a better design of multipot biomass cookstove. The flaws in the existing popular stoves were identified through a survey comprising measurement of geometrical features of different stove specimens in the field and face-to-face interaction with the end-users. The end-users answered a structured questionnaire including the information about existing cooking practices, per day fuel consumption, willingness to adapt to a new stove type and related things. CAD models of popular multipot cookstoves were constructed from the geometrical and qualitative inputs obtained from the survey. The most popular model was then modified to develop an 'improved multipot' cookstove while retaining most of its original features. Both the models were compared experimentally to evaluate different parameters like, specific fuel consumption, burning rate, thermal efficiency, time taken to accomplish a specific cooking task and CO emissions.

3 Methodology

3.1 Survey method

3.1.1 Profile of the study area

Maharashtra is the second most populous state of India with a population of 112,374,333 (9.28% of India's population). The 2011 census for the state found 55% of the population to be rural (Maharashtra Population Census data 2011), and agriculture is the largest part of the state's economy. Maharashtra has 36 districts, as shown in Fig. 1, which are grouped into five main regions based on geography, history, and political sentiments as Vidarbha (Nagpur and Amravati Divisions), Marathwada (Aurangabad Division), Konkan (Konkan Division), Khandesh and Northern Maharashtra Region (Nashik Division) and West Maharashtra (Pune Division).

The survey was carried out in such a way that at least a single village should be covered from every division where the use of biomass cookstove is more dominant for cooking and heating purposes. More than 90% of people from the selected villages used a biomass cookstove as a primary cooking device. The places covered include *Mohpa* from *Umred* Taluka in *Nagpur* district (*Nagpur* Division), *Salpi* and *Sanghvi* village in *Barshitakli* Tehsil of *Akola* district (*Amravati* Division), *Ganjur* from *Chakur* Taluka in *Latur* district (*Aurangabad* Division), *Dalvatne* village in *Chiplun* Taluka of *Ratnagiri* district (Konkan Division), *Vadgaon Bk.* in *Chopda* Taluka of *Jalgaon* district (*Nashik* Division), and *Sangaon-Kasaba* village located in *Kagal* of *Kolhapur* district (*Pune* Division). Table 1 shows the total population of the surveyed villages and other details.

The people from different places used different types of cookstoves. The survey identified widely used multipot stoves; i.e., stoves having two or more pots to cook food

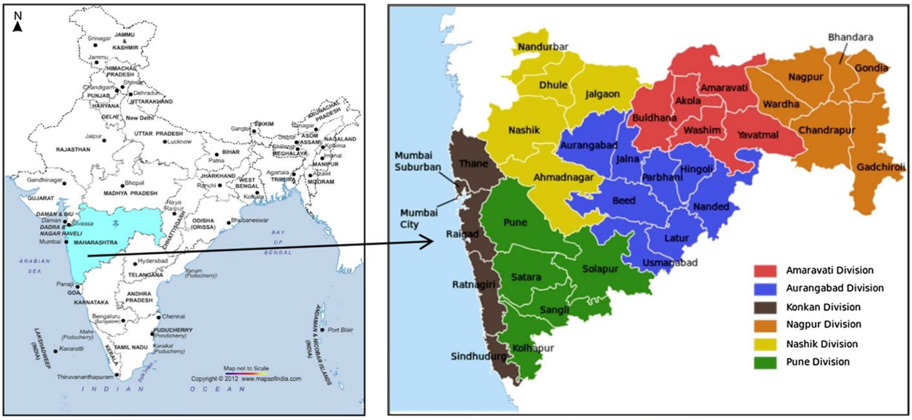

Fig. 1 Map of surveyed area

Table 1 Population and number of houses of study area

Region	Village name	Total population (no. of people)	Total no. of houses	Number of male	Number of female
1. Nagpur	Mohpa	410	112	214	196
2. Amravati	Salpi	530	131	268	262
	Sanghvi	250	220	117	133
3. Konkan	Dalvatne	1855	376	914	941
4. Nashik	Vadgaon	2285	550	1174	1111
5. Aurangabad	Ganjur	2370	467	1233	1137
6. Pune	Sangaon Kasaba	11,182	2316	5600	5582

Population State census 2011–The Census 2011 is the 15th National census survey conducted by the Census organization of India

simultaneously. The basic structure consists of two chambers, one where the food is cooked from direct heat of the fire, while in the second chamber the heat of the combustion exhaust is used for cooking. Different places had different names for it. '*Ula*' in Nagpur and Amravati division, '*Wail*' in the Konkan region, '*Sobna*' in Latur district, '*Ul-Chul*' in Nashik and '*Ula-Chul*' in Pune division. Further, these are classified as left hand and right hand based on the person who is handling. It was observed that different materials are used in each region for stove construction with considerable variation in design. Figure 2 shows different types of traditional cookstoves.

3.1.2 Sampling

The survey was conducted during the month of October 2015. The important dimensions of various biomass cookstoves found in different homes of each village were measured, and a structured questionnaire was asked to the person actually operating each cookstove:

1. Name-

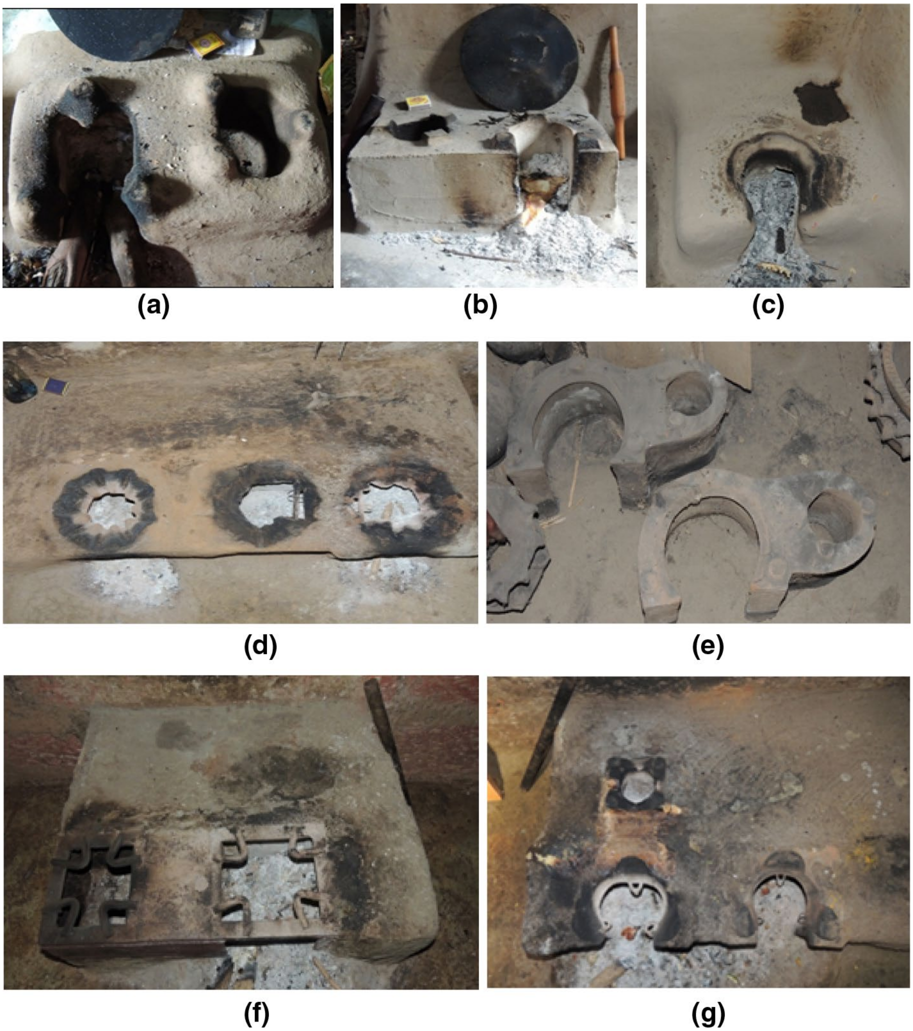

Fig. 2 Different types of cookstoves from the field. **a** Traditional stove, **b** Cement stove, **c** Sobna stove, **d** Lotus shape stove, **e** Khapar stove, **f** Iron reinforced stove, **g** Traditional (in-line) stove

2. Number of people in family-

   Adults-
   Children under 16-
   Children above 16-

3. Occupation-
4. What is the income per day/month-
5. Type of house: permanent/temporary-
6. Is the house equipped with electric supply-
7. Type of material used to make the stove-
8. Type of fuel used-

9. Type of wood-
10. Approximate length-
11. Quantity of fuel required per day-
12. Fuel availability and cost of the fuel used-
13. Is there a seasonal change of cost in fuel-
14. Who gathers the wood-
15. Number of pots-
16. How is it maintained properly-
17. Age of stove-
18. Time required for cooking a variety of food/boil water-
19. What is the frequency of cookstove used daily-
20. Is the family Vegetarian or Non-Vegetarian-
21. Do you change the location of cooking according to season-
22. Any other type of cooking system used-
23. Any health issues-
24. Why wood stove and not LPG-

    (a) Economics
    (b) Taste
    (c) Acquaintance
    (d) Non-availability

25. Views about modernization of stove-

3.2 Experimental method

3.2.1 Testing method

Different testing protocols both in-field as well as laboratory tests are available for evaluating the performance of cookstoves (Granderson et al. 2009; Arora et al. 2014). Generally, laboratory tests are preferred over field-testing due to the high time and finance required for the conduction of the latter (Lombardi et al. 2017). More than half of cooking operations such as boiling of water for bathing and making curry and rice fall under WBT category (Bailis et al. 2007). Hence, a standard WBT was performed in a laboratory to compare the thermal performance of different cookstoves. It is useful to compare different designs of cookstoves since the task to perform is the same in all cases. A WBT is performed to estimate the fuel consumed by a stove to heat water in a cooking pot and the CO emissions produced during the process.

4 Experimental setup

The existing popular traditional multipot biomass cookstove (TMBC) from the survey and the improved multipot biomass cookstove (IMBC) were compared by experimentation. The experimental setup is shown in Fig. 3. The stove was placed on top of two asbestos sheets on the floor. WBTs were performed with the same pot and thermal efficiency was calculated. Initial practice test was performed for familiarization with the testing procedure.

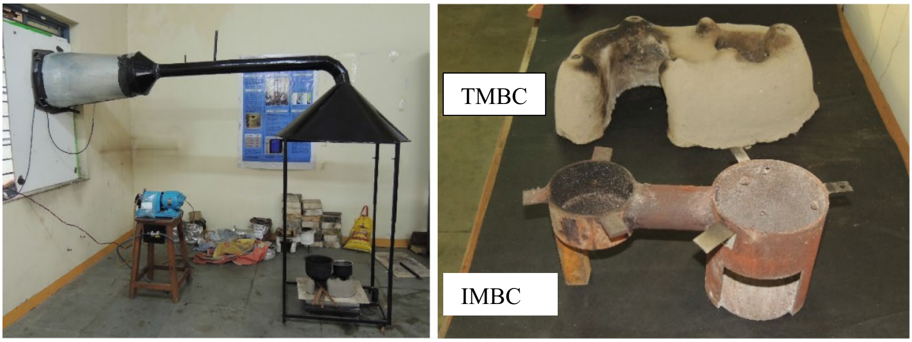

Fig. 3 Pictorial view of experimental setup and type of stoves

Later on, three different sets of WBTs were performed on each stove. The exhaust coming out of the stove was collected with a hood placed 1 m above the stove. The exhaust was collected in 10-l Tedlar bags with a peristaltic pump. Each test was performed by the same operator and due care was taken to repeat the experiment in the same manner such as feeding of fuel, starting of fire and all other processes to maintain the repeatability. An electronic weighing machine with a resolution of 5 g was used to measure the fuel bundle and charcoal left over after the experiment and the mass of water evaporated from both pots after reaching the boiling point for the water in Pot 1. Mercury thermometers with 0.1 °C resolutions were inserted in a wooden scale and placed over both pots. Both thermometers were placed at a distance of 5 cm from the bottom of the pot. Care was taken to neglect the weight of wooden scale and thermometer.

4.1 Hood

The conical shaped hood with 1-meter diameter was placed 1 m above the stove to collect the entire flue gas without affecting the stove behavior (Bailis et al. 2007; Ballard-Tremeer 1997). An exhaust fan was located at the end of a duct attached to the hood. Provision was made on the extension pipe to measure the temperature of flue gas by a mercury thermometer.

4.2 Fuel geometry

Wooden sticks ranging from 1.5 cm × 1.5 cm to 3 cm × 3 cm size are suggested in the WBT protocol. In this work, 1.5 cm × 1.5 cm size of wood was used for all tests. The length of sticks was 32 cm (1 ft). To maintain the consistency throughout the experimental work, the wood of same size was used.

4.3 Moisture content

Moisture content in the wood was measured and calculated on a wet basis by using a muffle furnace at 100–105 °C. All experiments were conducted with same species of wood (Babul tree) due to its availability in abundance. The average of three readings of moisture content was taken for calculation. One set of experiments was conducted in a day to avoid the change in moisture content of the wood (Bhattacharya et al. 2002a, b; Yuntenwi et al. 2008).

4.4 Characteristics of biomass fuel

Proximate and ultimate analysis was done in the laboratory. Table 2 shows the result of proximate and ultimate analysis. Lower calorific value of the fuel was calculated using Dulong's formula (NZIHOU et al. 2014), given below:

$$\text{LCV} = [4.18(94.19 * C - 0.5501 - 52.14 * H)] \tag{1}$$

The composition of fuel was known from ultimate analysis.

5 Results and discussions

This section discusses the outcomes of the survey and experimental work. The findings and implementation required on the basis of survey are discussed first, and later, the experimental results are compared with the previous work reported in the literature.

5.1 Survey outcomes

The survey outcomes can be categorized on the basis of the specification of the traditional cookstoves, type of fuel and fuel consumed, and the need and scope of improvement. The survey outcomes can be segregated under several categories and discussed point wise.

1. *Dimensions* The dimensions of different type of multipot cookstoves surveyed were measured and recorded. The average dimensions of different cookstoves with standard deviations are listed in Table 3.
2. *Cookstove construction and maintenance practices* The majority of the users construct traditional stoves themselves, and only in the case of emergency purchase the stove from a local artisan. The material used to manufacture the traditional cookstoves, *Sobna stove, lotus shape stove* are clay, cattle dung, water, pebbles and rice husk (which acts as a binding agent). The other type of cookstoves made of cement and iron are the replica of traditional ones and can be purchased from the local artisans. The user can prolong the life of any cookstove by plastering it every day with mud or cow dung. However, with prolonged use, the 'fuel feeding hole' and 'pot rest' disintegrates first due to continuous wear and tear from firewood sticks and loading and unloading of the utensils; respectively. The life of cement- and iron-reinforced chulha is longer, and these stoves do not need any plastering.

Table 2 Proximate and ultimate analysis of fuel

Proximate analysis (%)		Ultimate analysis (%)	
Moisture	10	Carbon (C)	45.19
Ash	01	Hydrogen (H)	6.51
Volatile matter	78	Nitrogen (N)	0.17
Fixed carbon	11	Oxygen (O)	48.10
		Sulfur (S)	0

Table 3 Average dimensions of different stoves

Characteristics	Traditional stove	Khapar stove	Cement stove	Lotus shape stove	Sobna stove	Iron-reinforced stove
Material of construction	Soil	Soil	Cement	Soil	Soil	Iron and soil
Length of chulha body, (a)	490 ± 50	410 ± 20	495 ± 30	510 ± 40	590 ± 50	660 ± 10
Width, (b)	345 ± 30	300 ± 20	310 ± 20	290 ± 70	450 ± 50	460 ± 80
Height, (c)	160 ± 40	180 ± 15	155 ± 30	245 ± 60	190 ± 20	190 ± 80
Diameter of first pot hole, (d) (D_1 * D_2)	125 ± 15	190 ± 10	140 ± 20	180 ± 20	190 ± 20	190 × 150 (± 55 ± 70) (rectangular cross-section)
Diameter of second pot hole, (e) (E_1 * E_2)	100 ± 10	100 ± 10	120 ± 20	105 ± 10	105 ± 10	190 × 200 (± 45 ± 90) (rectangular cross-section)

All dimensions in mm

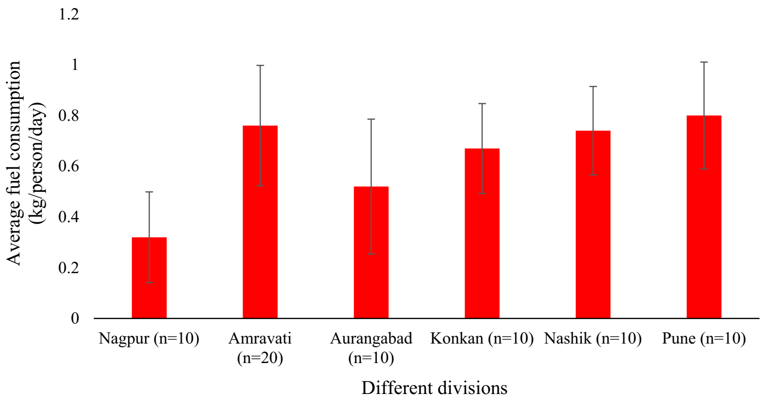

Fig. 4 Average specific fuel consumption (kg/person/day) with ± standard deviation for each division, (70 households)

Table 4 Predominantly used fuel types in different regions and their cost

Region	Village	Dominant fuel type used	Average cost of wood (rupees/kg)
1. Nagpur region	Mohpa	Babul	8
2. Amravati region	Salpi	Cotton residue	6
	Sanghvi	Cotton residue	5
3. Konkan region	Dalvatne	Coconut shell char	3
4. Nashik region	Vadgaon	Sugar cane/animal dung	4
5. Aurangabad region	Ganjur	Tur Stalk	6
6. Pune region	Sangaon Kasaba	Sugarcane char leaves	15

3. *Fuel type and fuel consumption* The average consumption of fuel per person per day in different places is shown in Fig. 4. It is difficult to gather wood and there is no surety about its every day availability. Hence, people prefer storing it. Every person in the family contributes to gathering of firewood. Freshly cut wood contains more moisture and is difficult to burn, so it is always good to have enough stock for drying and keeping it under suitable condition for later use. Many villagers used not only wood, but also crop residue left from the agricultural field. Crop residue varies with the region and season since crops in the field change according to season. Table 4 shows predominantly used fuel types in each region along with their cost. The variation in consumption for different places is due to different types of dishes cooked, cooking practices followed, and fuel type available locally. d) Lotus Stove
4. *General cooking procedure* The field survey results gave an idea about how real users ignite fuels and what are the precautions taken. Following are the observations:

    1. A small quantity of kerosene or waste paper or fine crop waste (like *tur* stalks) is used for initial firing.
    2. At the start, wood sticks with lesser dimensions (diameter) are used to establish a stable combustion. It takes 1–2 min to reach a steady-state flame.

   3. Usually, one or two larger diameter (up to 5 cm) wooden sticks are added once the fire is stabilized.
   4. The general length of wood logs is around 60–80 cm so that a slight movement of sticks can adjust the heat supply rate.
   5. Many times the fire may disappear due to insufficient oxygen that is needed for combustion; in that case, the user uses a device named '*fukni*' (a cylindrical pipe) for blowing air in feeding port and rekindling the fire. Simply blowing of air by mouth may serve the same purpose.
   6. After a few hours of operation, users may have a problem of excess charcoal left in the hearth zone, so it is necessary to remove the excess charcoal for further feeding of wood. Charcoal is saved and is used by the villagers for warming up the room during the winter and by the blacksmith in the local foundry.

5. *Utensils used* The size and types of utensils were also noted in the survey. Many types of utensils are used in the field. Utensils are plastered with soil to avoid black soot deposition. Table 5 shows the average size of the different types of utensils used in the field.
6. *Kitchen ventilation* Exposure to the smoke from biomass cookstoves leads to serious health hazards and may prove fatal in the long run. No special ventilation was used for the smoke from the cookstove in most of the kitchens. Generally, the permanent houses (made up of cement, bricks and laterite stone) had a provision for cooking outside the living rooms in a kitchen made up of temporary materials, such as plastic sheets, crop residues and bamboo sticks. Another side effect of using poor combustion traditional stoves was observed in the form of blackening of walls due to soot deposition. These findings indicate the need for cleaner combustion in traditional stoves to avoid life threatening conditions inside the poorly ventilated kitchens.
7. *Willingness to pay for a better cookstove* Problems faced by the villagers with the existing stoves and the acceptance of novel designs were the other important points of discussion in the survey. People were not willing to accept a complete changed layout of the stove; they wanted very few modifications in the existing cookstove, used in their homes. Though a few houses were equipped with LPG stoves, some people preferred cooking on biomass cookstoves, because some people could not afford LPG cylinders, and those who could afford LPG complained of irregular availability in the villages. Some preferred traditional cookstoves because of the taste of food cooked on them. The improved stoves approved by MNRE (like Jwala, Oorja-pellet stoves, Neerdhur) were very different compared with traditional stoves. The fuel used in such improved stoves was of pre-defined size and shape; the flexibility to use any other type of fuel (crop residue and locally available wood) was limited. The common expectations of people about a stove were robust to handle, no large difference from traditional stove, no restrictions on fuel type (size and shape), easy to switch to single pot configuration from multipot stove, and affordable cost.

Table 5 Average size of the different types of utensils used in the field

Sr. no.	Type of utensil	Size	
		Diameter (cm)	Height (cm)
1.	Pan (boiling water)	32	18
2.	Pan (cooking food)	17–32	10–24
3.	Tawa (roti tawa)	25	–

Hence, the survey outcomes show the need for an improvement in the existing cookstove. This is also evident on the basis of average fuel consumption which is around 0.634 kg/person/day. Two-thirds of the total state population (Sect. 3.1) depends upon traditional stoves (MNRE 2017), the estimated yearly consumption of fuel for cooking in Maharashtra region is 16.34 million tonnes. Ever-increasing demand of fuel wood to meet the daily needs of cooking and other heating purposes leads to cutting down of trees and is one of the reasons for deforestation. Need of fuel wood is responsible for 10% of deforestation worldwide (Callahan 1999). Hence, efforts should be taken to minimize the use of wood as a fuel to save the environment from deforestation. Many inefficient stoves consume more fuel than required. In addition, a lot of smoke is generated in traditional biomass cookstoves, which is injurious to health. In spite of such consequences, people prefer using traditional biomass cookstoves. However, the villagers were dissatisfied with some of the issues associated with the 'popular' multipot stoves:

1. Irrespective of its type, the traditional cookstoves generate a lot of smoke.
2. Very high fuel consumption rate.
3. No Portability possible for mud stoves.

Therefore, an improved multipot cookstove is needed which will have a better energy and emissions performance and help in reducing the problems faced by the villagers. Several modifications were incorporated in the existing popular cookstove. The modifications tried to address the findings from the survey and literature review to develop an improved 'popular' cookstove model:

1. *Elevating the opening for the second pot* The opening of the second cooking zone is placed at the bottom in most of the traditional cookstoves. The fuel feeding zone occupies the place where the provision for the entry of flames to the second pot is made. Therefore, the flame reaching the second pot is reduced due to obstruction by the fuel fed. Hence, in the modified 'popular model,' the entrance to the second pot is elevated above the fuel fed. Since hot gas rises with the increase in temperature, it will help the flue gases to pass through the gap and reach the second pot.
2. *Combustion chamber* The combustion chamber is the heart of any stove and proper working of a stove largely depends on it. In the case of traditional cookstoves, there is very little distance between the pot bottom and the fuel fed. In most of the cases, the flames brush the pot bottom, and as flames are quenched, combustion temperature is relatively low leading to a drop in combustion efficiency. Hence, to avoid this, the combustion chamber is given a minimum height of 150 mm, so that it can act as a chimney and create a draft for improved mixing of fuel and air leading to more complete combustion of fuel.
3. *Feed door* The fuel feeding area from the top is open for most of the existing traditional cookstoves as shown in Fig. 2, which causes the flame to come out when more number of sticks are fed. The fuel feeding area should be closed from the top to avoid the escape of flames to the surroundings.
4. *Spacing between two pots* The utensils used and the dimensions recorded help to determine the needed spacing between pots in designing multipot biomass cookstoves. Considering the average family members (4) from the survey, 3-l pots are sufficient to cook food. Hence, the spacing was designed such that two 3-l pots can sufficiently occupy the space.

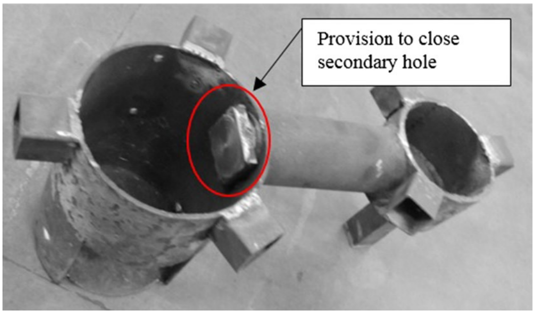

Fig. 5 Closing the secondary hole

Table 6 Dimension of popular traditional and modified popular cookstove

	Popular model (TMBC)	Modified popular (IMBC)
Pot 1 diameter, D_1	100	100
Pot 2 diameter, D_2	80	80
Diameter, D_3	70	50
Height, H	100	150
Pot gap, L	70	120
Fuel entry ($l \times w$)	100 × 100	70 × 80

All dimensions are in mm

5. *Closing the second pothole* A two-pot cookstove can be easily switched to a single pot by just closing the second pothole. Figure 5 shows the provision made to close the second pothole in the improved 'popular' biomass cookstove model. Table 6 shows the dimension of popular model: Traditional Multipot Biomass Cookstove (TMBC) and its modified version, Improved Multipot Biomass Cookstove (IMBC).

5.2 Experimental outcomes

A two-sample *t* test was conducted for IMBC and TMBC based on three trials each. From the data given in Table 7, it is clear that IMBC performs much better than TMBC in most of the indicators of stove performance. Here, the p value is significant and CoV is less than 10% in all the cases, except for turn-down ratio and time taken to boil, so there was no need to lower the standards of confidence or increase the number of test replicates.

The experimental values obtained are also compared against the corresponding values from literature for stoves: 'Uganda 2 pot', Onil stove, Justa stove, Nepalese 2 pot stove, 2 pot stove by Honkalaskar et al. and three stone fire (MacCarty et al. 2010; Bhattacharya et al. 2002a, b; Honkalaskar et al. 2013).

5.2.1 Cooking power/firepower (FP)

In most of the stove literature, firepower (fuel energy per time) is reported. However, 'Cooking power', which is the product of firepower and efficiency, is the genuine need of

Table 7 A two-sample *t*-test analysis for IMBC and TMBC

	IMBC			TMBC			Statistics	
	Mean	SD	CoV (%)	Mean	SD	CoV (%)	% difference between IMBC and TMBC	Significant with 95% confidence ($p < 0.05$)
Firepower, kW	1.99	0.08	3.89	3.55	0.19	5.33	78	Yes
Specific fuel consumption, g/l	63.08	3.71	5.88	95.67	2.52	2.63	52	Yes
Time taken to boil, min	24.74	0.39	1.56	20.86	1.62	7.77	− 16	No (0.056)
Turn down ratio	1.31	0.25	19.1	1.98	0.35	17.9	51	No (0.055)
CO emission, $g/MJ_{delivered}$	6.10	0.27	4.34	17.60	0.40	2.27	65	Yes
Thermal Efficiency, %	36.93	0.56	1.52	23.76	0.29	1.20	− 36	Yes

SD standard deviation, *CoV* coefficient of variation the cooking procedure. Each cuisine has a range of required cooking powers. The ideal cooking power range in India is 0.6–1.2 kW (Kshirsagar and Kalamkar 2016). It is necessary to ensure that a stove model supplies adequate cooking power required by the end-user.

The firepower of the stove is the product of calorific value of fuel and the fuel-burning rate. The higher the firepower, the more fuel is consumed by the stove. Figure 6a shows the comparison of firepower for different stoves. The firepower produced by TSF is very high as compared to the other stoves. This is because of the amount of fuel that can be fed into a TSF and in restricted amount for IMBC due to its shielded geometry.

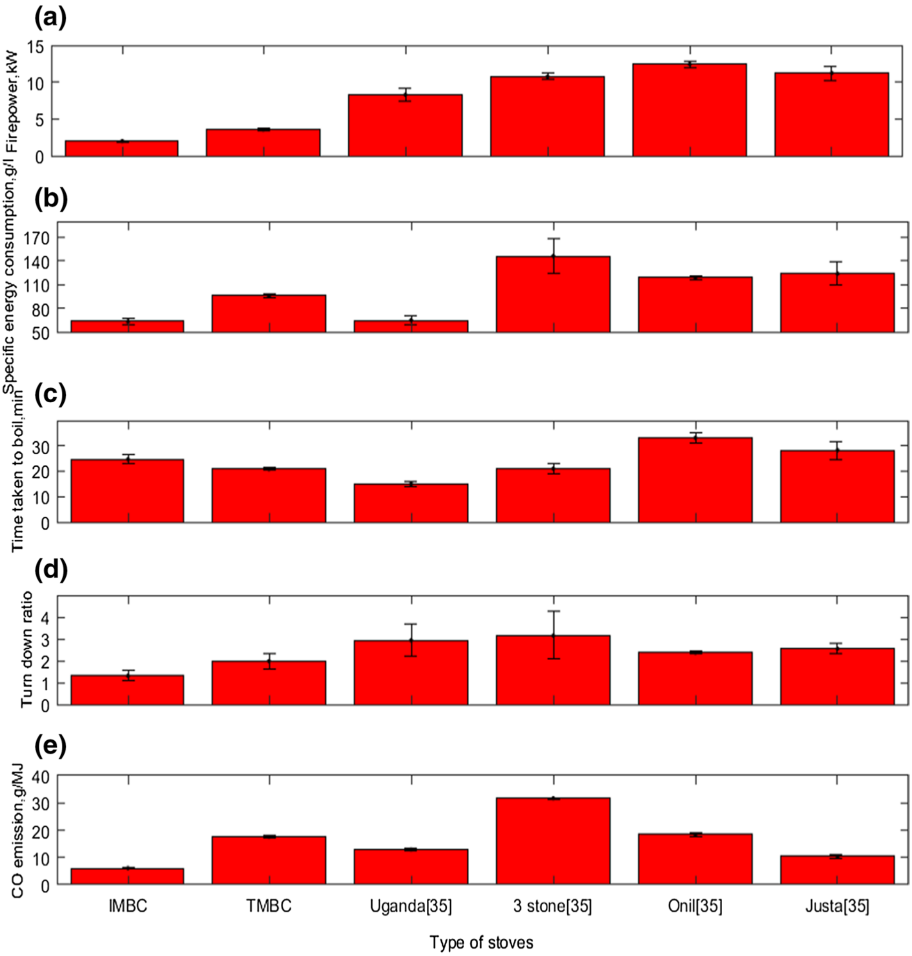

Fig. 6 Variation of mean values for different type of stoves. **a** Firepower (kW), **b** specific fuel consumption (g/l), **c** time taken to boil water from pot 1 (min), **d** turn down ratio, **e** CO emissions (g/$MJ_{delivered}$); for $n = 3$ with ± standard deviation

5.2.2 *Specific fuel consumption (SFC)*

The amount of fuel consumed per unit output is specific fuel consumption (SFC) and may sometimes be a better parameter to compare the performance of cookstoves than thermal efficiency. The comparison of SFC for different stoves is shown in Fig. 6b. The IMBC with least amount of specific fuel consumption is the best in the category, the poorest being TSF. The ratio of charcoal left to the dry fuel consumed is lower for TMBC than IMBC, and the dry fuel consumption is more in case of TMBC. Considering the ever-increasing demand of firewood, a small saving in fuel consumption will help prevent deforestation and may lead to financial gain and improving the environment.

5.2.3 *Time taken to boil*

The time taken to boil water from pot 1 for different stoves is shown in Fig. 6c. Although the time taken to boil for Pot-1 in IMBC is more than TMBC, the temperature of the water in the Pot-2 of IMBC was more than that in TMBC as shown in Fig. 7. This means that a greater portion of heat was supplied to the pot-2 in IMBC. The heat taken by pot-2 in traditional biomass cookstove is negligible as there is little increase in temperature, as indicated in Fig. 7. It seems that the TMBC stove was very ineffective for heating Pot 2. The maximum water temperature in Pot-2 for the traditional biomass cookstove is less than IMBC as shown in Fig. 7. This proves that the modification of the opening for the entry of flame at the top of the combustion chamber in IMBC helps to achieve higher temperature in Pot-2 and is beneficial.

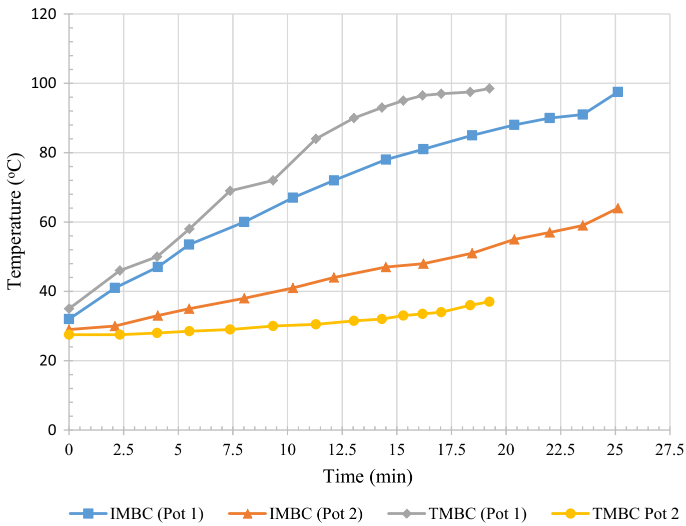

Fig. 7 Variation of water temperature in both the pots with time for improved multipot biomass cookstove (IMBC) and traditional multipot biomass cookstove (TMBC)

5.2.4 Turn-down ratio

Turn-down ratio refers to the ratio of maximum to minimum power at which the stove is operated. This ratio shows how well a stove can provide a range of firepower. The higher the value, the greater the range of power. Figure 6d shows the turn down ratio for different stoves. The IMBC shows the lowest TDR, likely due to the lower maximum firepower of the IMBC.

5.2.5 CO emissions

CO emission helps to judge 'cleanliness' of fire or quality of combustion. The value of CO emission per MJ of energy delivered to cooking pot is shown in Fig. 6e. A statistically significant reduction was obtained with the values of CO for IMBC compared to values for TMBC. This supports the modifications made for making the 'popular' clean. The modifications, as discussed in Sect. 5.1.9, lead to efficient burning resulting in higher temperature and lower CO emissions (Kumar et al. 2013). Hence, it is possible to improve the combustion in age-old traditional biomass cookstoves by applying scientific principals and to *'make the popular clean* 'without losing much of the operational ease. However, future testing should include the measurement of PM (particulate matter) emissions.

5.2.6 Thermal efficiency

The fuel consumed is more in case of TMBC compared with case of IMBC for the same output. However, the time taken to boil water is more in IMBC as compared to TMBC. These results are consistent with findings that lower firepower tend to be more efficient than higher firepower (Kshirsagar and Kalamkar 2016; Kshirsagar 2009). Figure 8 shows thermal efficiency of different stoves. The IMBC had a significant improvement in efficiency over the TMBC, Nepalese 2 pot, 2-pot improved stove by Honkalaskar et al., Onil stove, and Justa stove. The IMBC had a similar efficiency to the Uganda 2 pot, which is another improved multipot cookstove and uses sunken pots as reported in 'Two Pot Rocket Lorena Uganda' (2008).

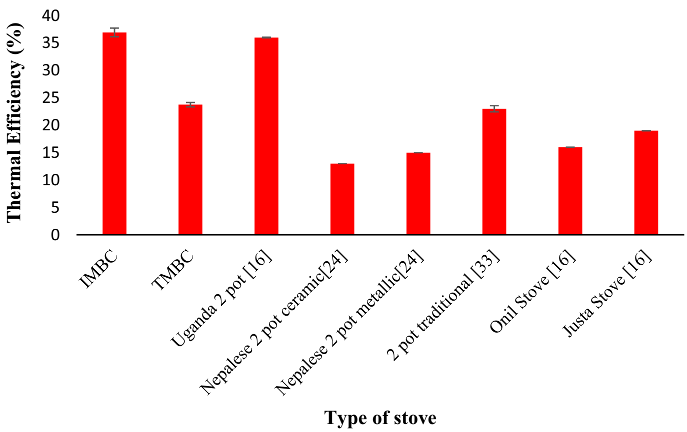

Fig. 8 Thermal efficiencies of different stoves with ± standard deviation as error bars ($n = 3$)

6 Conclusions

The approach advocating—'making the popular clean'—was tried and tested experimentally. The popular multipot cookstove advantages as well as its flaws were identified through a survey comprising measurement of geometrical features of different stoves and face-to-face interaction with the end-users. An improved multipot biomass cookstove (IMBC) was constructed and compared against the traditional version, by conducting a set of experiments. The results were also compared with corresponding values from the literature for the TSF and other multipot stoves. Modifications made in the traditional 'popular' stove resulted in increase in thermal efficiency and decrease in burning rate and specific fuel consumption. However, the IMBC had lower power and a lower turn-down ratio. Most importantly, the modifications resulted in a decrease in CO emissions and 'cleaning' of combustion. Hence, it is concluded that it is possible to *'make the popular clean'* by suitable technical modifications without losing much of operational ease.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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