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A comprehensive review and a systematic approach to enhance the performance of improved cookstove (ICS)

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Abstract

The biomass has been the choice of the heat source for cooking purposes since ancient times. The inefficient combustion process in traditional cookstoves has its shortcomings in the form of adverse consequences on human health and pollution of the environment. Research and development of improved cookstove, for those who are yet to adopt the cleaner fuels for the cooking, has occupied the scientific community and social workers alike to improve the conditions of these people. Most people who live in urban settings are using natural/petroleum gas or electricity for cooking. On the other hand, a large section of the people living in the hinterlands continue to use traditional cookstoves, which are of low efficiency and create indoor air pollution, which leads to severe health issues. To overcome these issues, many researchers have proposed various designs for improved cookstoves. This paper summarizes the available literature related to different cookstove designs, performance and emissions. The review covers detailed discussion on various parameters to enhance the performance of biomass cookstoves. In addition to that a comparison of different types of cookstoves, different fuels used in them, their efficiency and particulate matter emissions are studied. This paper also explores the possibility of the implementation of additional accessories such as thermoelectric generators.

Keywords Improved cookstove · Biomass · Performance parameter · Design · Thermoelectric generator

Introduction

As per the global scenario, 2.7 billion people heavily depend on the traditional biomass cookstove for cooking purposes, with the major share from developing countries [1–3] of Asia, Africa and Latin America. Improved cookstoves have been developed, which significantly reduced emissions of harmful gases and increased thermal efficiency. Every year due to emissions produced by traditional stoves in the developing countries results in approximately 1.6–4 million deaths annually [4, 5]. The harmful emissions exhausted from traditional stoves are reported to claim the lives of many children under the age of 5 years, which is grave concern [6]. Because of the limited resources, people use solid fuels such as wood, animal dung, rice husk and crop residue throughout the developing world [7]. The fabrication and widespread adaption of the cookstove like top-lit updraft could be the way to overcome the problem of emissions [8]. The particulate matter emissions from traditional cookstoves have a notable impact on the climate. According to the 2011 Census of India [9], 67.2% of the total households used solid fuels and 88% of these households are in rural India. Every year about 16 million hectares of forests are consumed for cooking fuel [10].

Present scenario

In developing countries such as India, people are still habituated in using traditional cookstoves (three-stone fire) because of the limited budget, unawareness of technology and easy access to cheap (generally free) biomass fuel. The three-stone fire is the simplest and most common cookstove used throughout the landscape [11] (Fig. 1).

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Fig. 1 Traditional cookstove use in rural communities [12–14]

The need for improved cookstove

Traditional cookstove designs have different types of setup such as three-stone fire or brick and mortar models. These designs have been inefficient (thermal efficiency around 15%) at converting energy into necessary heat for cooking. The amount of biomass fuel needed for cooking purposes can be as high as 2 tonnes per family annually [4]. This cookstove causes indoor air pollution (CO, SO_x, NO_x, particulates, etc.) [15–17], which result in health-related complications [18]. Due to the harmful emissions, it also contributes to global warming. With the increase in the population, the demand for firewood has increased, which increases the deforestation at an alarming rate [19]. Improved cookstoves are developed by the researchers as the replacement of the existing conventional cookstoves [20], so they are designed to run on the same fuel like dung, firewood and biomass with better efficiency and cleaner operation [21], which also have social implications on the lives of communities [22, 23]. These ill effects on human health, spiraling deforestation and greenhouse gas emission in addition to the toxic fumes have necessitated the search [24–26] for more efficient cookstoves.

Challenges in the widespread adaption of improved cookstove

Looking into the advantages of improved cookstoves over conventional ones gives the impression that the users will wholeheartedly adopt the new ones [27], but the reality is not the same as one wishes to be. Many of the past biomass cookstove programs have not succeeded due to the lack of in-depth analysis of the socio-behavioral factors affecting the people [28], who use these devices [29]. In addition to that, lack of the willingness of the people to change the status quo [30–32] and inability to pay even the subsidized rate of cookstove has compounded the problem.

Comparison of cookstove

Improved cookstoves are classified into two types, namely natural draft and forced draft cookstove [33]. In natural draft design, the air required for combustion is provided by the draft created due to the density difference between hot and cold air, which results consequent natural circulation. On the other hand, in the forced draft cookstove, the air is provided using an external source such as a fan or a blower [34] (Fig. 2).

The natural draft cookstoves are available in single- or double-pot option, while the forced draft cookstove uses single-pot cooking at a time [38]. Natural draft cookstove efficiency ranges in 19–36% [38], while the forced draft cookstove can operate with hiked efficiency up to 44% [13] as shown in Table 1. Various researchers have found various efficiencies [39] in a variety of cookstove models.

Objectives of the work

The main aim of this work is to highlight the present scenario of the cooking setups and emphasize the implementation of the improved cookstove in households [42, 43], where conventional cookstoves are still being used in developing countries. The potential of improved cookstoves to enhance the indoor air quality is well proved [44], and a decrease in biomass consumption has correlation with rate of forest destruction [45]. This paper also describes the effect of various design–operation parameters and characteristics of the fuel on the thermal efficiency and emissions of the improved cookstove. For that, different parameters such as excess air ratio, inlet area ratio, chimney height, insulation, pot gap width, swirl flow, grate, skirt and materials are studied and their effects are compared for different cookstoves. In addition to that, the possibility of power generation using TEG is also explored. Limitation of improved biomass cookstove is also discussed.

Fig. 2 Various improved cookstoves developed by researchers [35–37]

Table 1 Comparisons of major cookstove category

S. no.	Type of cookstove	η/%	CO emission/g L^{-1}	PM emission/mg L^{-1}	References
01	Three-stone fire (natural draft)	16	11.1	472.6	[40]
02	Three-stone fire (natural draft)	10–15	NA	NA	[41]
03	Natural draft open fire (without chimney)	19–24	3.1–10.1	258–858	[40]
04	Natural draft with chimney (metal stove)	16–36	3.9–9.6	136–1020	[40]
05	Forced draft cookstove	40–44	1.37	5.4	[40]

Parameters vital to thermal efficiency of cookstove

It is important to determine the effect of various operating and geometric parameters on the performance of the cookstove. The range of variables is studied and investigated by the scientific fraternity after establishing sound procedures [46] for experimental [47, 48] and numerical [49] investigations. The safety aspects [50] of stove design and usage cannot be underestimated.

Thermal efficiency and other performance parameters of cookstove have been analyzed by researchers mainly using different standards developed by the agencies in different jurisdictions, e.g., BIS 13152 (part 1) 2013 in India. Thermal efficiency of cookstove can be calculated using the relation given below.

$$\eta = \frac{M_w \times C \times (t_2 - t_1) + M_s \times L}{M_f \times CV} \tag{1}$$

where η = thermal efficiency, %; M_w = mass of water taken in the utensil, kg; C = specific heat of water, kJ kg^{-1} K^{-1}; t_2 = final temperature of water, °C; t_1 = initial temperature of water, °C; L = latent heat of evaporation of water, kJ kg^{-1}; M_s = mass of water evaporated, kg; M_f = mass of fuel used, kg; and CV = lower calorific value of fuel, kJ kg^{-1}.

The power input to the stove can be calculated using this relation.

Table 2 Flame temperature for various excess air ratios

Excess air ratio/μ	Flame temperature/°C	References
1.10482	1082.43	[51]
1.9547	940.54	[51]
2.80453	818.92	[51]
4.41926	681.08	[51]
6.96884	587.84	[51]
15.9773	450.00	[51]
29.4901	397.30	[51]
1.9732	534	[57]
2.33	1027	[58]

$$P_i = \frac{CV \times B_r}{3600} \quad (2)$$

where P_i = power input, kW, and B_r = burning rate of fuel, kg $h^{-1.}$

Excess air ratio (μ)

It is a parameter, which controls the availability of oxygen in the cookstove for the combustion process and temperature of flame [51, 52]. Excess air ratio is defined in terms of the percentage of oxygen in the flue gases as shown in Eq. (1). With an increase in excess air ratio, the flame temperature decreases. It was found in the work that maximum fuel burning rate, i.e., power, is obtained at $\mu = 1$, but at that harmful gases will be quite high and efficiency will be low. The value of excess air ratio can be found for the optimum value of combustion efficiency [53]. Table 2 summarizes the results of an empirical study performed by Agenbroad et al. [54–56].

$$\mu = \frac{\%O_2}{21 - \%O_2} \quad (3)$$

But with consideration of emission of CO and PM in mind, the limiting values for excess air ratio are 1.95–5.8.

Inlet area ratio

Kshirsagar and Kalamkar [59] during their work identified an important term, i.e., inlet area ratio. As the air comes into the stove combustion chamber through the vents, it needs to be evacuated as well. This is done from the top of the stove beside the container. For an efficient combustion process to happen, the value of the inlet area ratio is found to be more than 0.7 [51].

Table 3 Efficiency for different chimney heights

Chimney height/mm	η/%	References
70	26.05	[58]
100	26.47	[58]
181	32.56	[59]
197	30.67	[59]
228	27.70	[59]
267	24.92	[59]
308	22.85	[59]

Chimney height

An increase in chimney height enhances the combustion efficiency due to the higher draft [60]. The decrease in chimney height means the decrease in cookstove height, which is good from the economics point of view. The data relating chimney height to the efficiency of the small-scale cookstove are shown in Table 3.

Insulation

Insulation of cookstove is very important to increase the performance, as it reduces the heat loss through the heated walls. With proper insulation of the cookstove, efficiency was found to be increased by 8% and consumption of fuel was found to be reduced by almost 5% [33]. The conductivity of material highly influences the selection of insulating material [61]. Glass wool, ceramic wool, fire brick, etc. are widely used as cookstoves' insulation. With the increase

Table 4 Efficiency for different insulation thicknesses

Insulation thickness/mm	η/%	References
6	47.82	[62]
6.35	25.45	[63]
10	27.22	[20]
12	55.72	[62]
12.07	29.54	[63]
15	56.23	[62]
20	29.02	[20]
25	57.11	[62]
25.4	33.17	[63]
30	29.99	[20]
50	37.01	[64]
50	31.15	[20]
50.0	36.41	[63]
70	32.11	[20]
76.2	37.65	[63]
101.6	38.53	[63]

in the thickness of insulating material, efficiency increases since it reduces heat losses. But after certain thickness of insulation, the decrease in the heat loss reduces and makes it economically non-beneficial to add more insulation thickness. The optimum thickness of insulation should be selected by the parametric study of the cookstove under consideration. Table 4 shows the efficiency of small-scale cookstoves with different insulation thicknesses.

Effect of the pot gap width

With a decrease in pot gap width, efficiency increases [65]. A very small pot gap width is not desirable, because it leads to blockage with soot deposition, which will decrease its efficiency [51]. Pot gap depends on the rate of fuel combustion. The minimum gap required for burning rate greater than 2 kg h^{-1} is 15 mm [66]. If the pot gap is too large, flue gas will not make complete contact with the pot surface, and if it is too small, then air supply becomes limited [66, 67].

Swirl flow creation

As an engineer, one knows the type of burners used in the boiler of thermal power plants, where turbulence in the flame is utilized for better mixing of air with fuel and higher combustion efficiency. Similarly swirling airflow condition can be created in cookstove to increase the efficiency. It increases combustion efficiency and gives a stable flame [33]. A gasifier stove with central holes for gasification gas and channels around them for swirling airflow was suggested by Deng et al. [68]. With this design, the thermal efficiency of the stove was observed to be increased by 10% and gasification efficiency by 2%.

Grate

Proper implementation of grate can increase efficiency and reduces the amount of pollutants [33]. It was found that the mean efficiency of a traditional cookstove can be increased by 7% when it is equipped with grate [69].

Skirt

It is a metallic part which is placed circumferentially around the pot. It is used to guide the flame on the pot increasing heat transfer, decreasing fuel combustion and hence efficiency [33]. 25–30% improvement in fuel consumption and CO emission are observed when pot with skirts was used [70].

Material for cookstove

The material used for manufacturing has a role to play in deciding the efficiency of the cookstove. The heat loss through the wall of the stove is influenced by the conductivity of the barrel material. In the same way, the heat absorbed and retained by the material is a type of loss of heat as well. These phenomena are heavily influenced by the selection of the material of the cookstove. Thermal properties of different materials for cookstove are shown in Table 5. It is observed that heat absorbed by metal is higher than clay. But since the heat transfer rate of metal is far better than clay, its heat recovery rate is faster. The selection of material has an impact on the cost

Table 6 Comparison of different biomass fuels

Fuel	PM/g kg^{-1}	CV/MJ kg^{-1}	η/%	References
Crop straw	5.6	16	16	[77–82]
Firewood log	1.8	18	18	[81–84]
Wood branches	2.6	17	14	[78, 79, 82, 83]
Anthracite chunk	1.1	21	14	[80, 82, 85–90]
Bituminous chunk	12	28	14	[80, 82, 85–90]
Anthracite briquette	0.59	21	32	[80, 82, 85–90]
Bituminous briquette	7.1	28	32	[80, 82, 85–90]
Crop straw pellet	2.1	14	37	[84]
Wood pellet	0.85	16	29	[84, 91]
Natural gas	0.16	51	57	[82]
LPG	0.27	49	44	[82]

Table 5 Different materials available for fabrication of cookstove

Materials	Density/kg m^{-3}	Specific heat/J $kg\ K^{-1}$	Thermal conductivity/W $m^{-1}\ K^{-1}$	References
Ceramic wool	84	1070	0.09	[40]
Clay	2400	1381	0.65	[40]
Fire bricks	1280	1000	0.30	[40]
Metal sheet (MS)	7870	447	80.20	[40]
Metal sheet (SS)	7900	477	14.90	[40]
Vermiculate	90	960	0.06	[40]
FeCrAl	7150	460	11	[71]

Table 7 Cookstove–fuel combination in India and China and their efficiency

Description—venting—material	Fuel	η/%	References
Wood stove(traditional)—unvented—open fire or mud stove	Wood	18	[95]
Indian wood stove(improved)—unvented—metal	Wood	23	[95]
Chinese wood stove(improved)-vented-brick	Wood	24	[96]
Mexican wood 'patsari' stove—vented—masonry	Wood	24	[96]
Indian wood karve 'gasifier'—unvented—metal	Wood	32	[36]
Wood 'Philips fan' stove—unvented—metal	Wood	40	[36]
Indian charcoal stove(use production)—unvented—metal/mud	Charcoal	18	[95]
Chinese coal stove—unvented—metal	Coal	14	[82]
Chinese coal stove—vented—metal	Coal	17	[82]
India kerosene wick stove—unvented—metal	Kerosene	50	[95]
Indian LPG stove—unvented—metal	LPG	54	[95]

Table 8 Different cookstove–fuel combinations in India

Type of stove	Fuel type	η/%	References
Abhinav/Jetan	Fuelwood	22.0	[97]
	Dung	11.4	[97]
Astra	Fuelwood	30.0	[97]
	Dung	14.6	[97]
Bio-classic	Wood	26.01	[35]
Chulika	Wood	29.77	[35]
Dengli	Wood	25	[98]
	Dung	22.9	[98]
	Wood + dung (1:1 by mass)	19.7	[98]
Doachhi	Fuelwood	20.2	[97]
Doachhi	Dung	17.4	[97]
Economical chulha	Fuelwood, crop residue, charcoal	22.0	[97]
Envirofit PCS	Wood	25.46	[20]
Gaurav	Wood	28.1	[98]
	Dung	15.8	[98]
Harsha	Fuelwood	24.8	[97]
Harsha	Dung	18.5	[97]
Harsha	Charcoal	21.9	[97]
Laxmi	Fuelwood	22.0	[97]
Laxmi	Charcoal	14.7	[97]
Janta	Dung	24.6	[98]
Mamta	Fuelwood	24.0	[97]
Mamta	Dung	16.0	[97]
	Mustard stem	14.0	[97]
Mud-coated bucket chulha	Charcoal	21.0	[97]
Priagni	Fuelwood	26.0	[97]
Sheet metal un-insulated chulha	Charcoal	18.0	[97]
Sugam-II	Fuelwood	28.2	[97]
	Dung	24.2	[97]
Sugamseva	Fuelwood	25.1	[97]
	Dung	23.0	[97]
Sukhad	Fuelwood	25.0	[97]
	Dung	20.6	[97]
Surbhi-T	Wood	30.4	[98]
	Dung	20.0	[98]
UDAI	Fuelwood	20.0	[97]
	Dung	16.4	[97]

Table 9 Comparison of different agriculture residual fuels [98, 99]

Group	Crop	Residual type	RPR/kg kg^{-1}	CV/MJ kg^{-1}
Cereals	Rice	Straw	1.5	15.54
		Husk	0.2	15.54
	Wheat	Stalk	1.5	17.15
		Pod	0.3	17.39
	CC[a]	Stalks	1.3	18.00
SN	Sugarcane	Bagasse	0.33	20.00
		Top and leaves	0.05	20.00
CN	Cotton	Stalk	3.8	17.40
		Husk	1.1	16.70
		Boll shell	1.1	18.30

[a]CC includes crops like bajra, maize, barley, small millet, ragi, etc.

of cookstove [71], which needs to be kept in mind, while designing the cookstove.

During a water boiling test [72], it was found that a metal cookstove achieves peak temperature in 17 min during the fourth phase (the phase which involves cooling of the material using water, thereby measuring the heat gained by the water), while a clay stove takes 36 min. In metals, mild steel is cheaper than stainless steel, but its life is quite shorter (1–3 years).

Fuel

Different types of feedstock

Verhaart [73] analyzed the cooking processes and energy requirements in a household for a range of culinary practices [74]. During the test, it is important to make sure that the entire amount of fuel is oxidized [75, 76] (Table 6).

1. The addition of new fuel to the test stove should be avoided until previous lot completely burns out including volatiles.
2. The air supply to the stove can be regulated by a variable flow blower to maintain the constant thermal output of the stove.
3. Once the liquefied fraction of the fuel is completely burnt, airflow can be increased to increase the heat release from the char.

Use of pellets/briquettes

Small pellets are formed from compressed biomass fuels, which results in better burning of fuel and hence better efficiency [92, 93]. It also decreases particulate emissions [94]. It is always desirable to use pellets or briquettes instead of loose biomass, because of the higher energy density of pellets (Table 7).

Features of improved cookstoves in India

Efforts put in by the research community in the development of improved cookstoves are explored and tabulated in Table 8. A wide range of cookstoves are developed for different fuels.

Table 10 Comparison of two modules of TEG

	HZ-14	HZ-9	TEG1-1263-4.3	TEG1-12610-5.1	TEG1-4199-5.3	Hybrid BiTe–PbTe TEG1-PB-12611-6.0
Thermal properties						
Hot side temperature/°C	250	250	300	300	300	350
Cold side temperature/°C	30	30	30	30	30	30
Maximum heat tolerance/°C	400	400	NA	NA	NA	NA
Electrical properties						
Power (at matched load, W)	14	9	5.2	5.1	7.5	21.7
Load voltage/V	1.65	3.28	5.3	3.9	6.7	4.6
Internal resistance/Ω	0.15	1.15	NA	NA	NA	NA
Current/A	8	2.9	1	1.3	1.12	4.7
Open-circuit voltage/V	3.5	6.5	10.7	7.8	13.4	9.2
References	[102]	[102]	[104]	[104]	[104]	[104]

Agricultural residual fuels

A large section of the rural population in India is dependent on the agriculture for their livelihood directly or indirectly. A large fraction of geographical area is used for agriculture and animal husbandry. Therefore, the availability of agriculture residual biomass and animal waste are significantly high in India. Three types of crops, i.e., cereal crops (rice, wheat, coarse cereals), sugarcane (SN) and cotton (CN), were analyzed [99]. The classification of crop residues is shown in Table 9 along with their respective properties like residue-to-product ratio (RPR) and calorific value (CV).

Effect of moisture content (MC) in fuel

People using traditional cookstoves end up using non-dried biomass many a time, which can have a significant amount of moisture content in it. The fuel with higher moisture content may give misleading readings of carbon monoxide, particulate matter, etc. as it will decrease the emission per mass of the fuel [100].

Electricity generation using thermoelectric generator (TEG)

According to the International Energy Agency (IEA) [101], around 1.2 billion people were deprived of electricity in 2016. In India, a large section of the hinterland is deprived of reliable electricity. Fortunately, cookstoves can generate electricity (in a small fraction) from heat lost by cookstoves. TEG is a semiconductor device used to convert heat energy into electrical energy as per Seebeck effect. A power of up to 5 W can be achieved by heat liberated from biomass cookstove, which is stored in Li-ion battery and can be further used to run DC fans, lighting LEDs and even charging mobile phones [102]. This utilization of waste energy increases the overall efficiency of the cookstove [103].

Table 10 shows two modules HZ-14 and HZ-9. The performance of different TEG modules is presented. One side of the module is attached to a hot plate, and a cold side is attached to a heat sink. Thermal and electrical properties are then recorded. Different thermoelectric generators are available in the market at reasonable prices. For example, 4.8 v open voltage, 100 °C temperature difference TEG is available in the range of ₹ 1100–1300 in India (Model: SP1848-27145).

Conclusions

After an extensive review of research papers on biomass cookstoves, it is observed that the natural draft cookstove is implementable in the rural areas of developing countries as compared to the forced draft. Various factors such as socio-cultural, socioeconomic, public awareness and quality of the product should be overcome in such a way that people from rural area can shift from their traditional cookstoves to the improved cookstove. Many of the cookstove testing standards are evaluated for the stove-based emissions. However, it is obvious that the most efficient cookstove is not always user-friendly. Proper investigations of local ecology, availability of biomass, the orientation of the user, type of application and government initiatives like subsidies should be considered before designing any cookstove. Factors such as lower chimney height, effective optimum thickness of insulation and material of stove, lesser pot gap width, swirl flow creation, optimum grate and skirt design, and use of pellets or briquettes of biomass are selected based on the application of the cookstove. The utilization of TEG in order to produce electricity from waste heat is desirable as add-on in the cookstove. Efficient cookstoves have the potential to popularize, provided they prove to be user-friendly devices.

There is an essential need for user-friendly biomass cookstoves. It is observed especially in rural areas of developing counties. Most of the locally successful stoves are not accepted widely because of the reason discussed earlier. It could be due to the fact that the testing of such stoves is in ideal conditions in the laboratory. General awareness about efficiency, health and environmental effect of traditional cookstoves is very important along with the development of the stoves. More investigations are required to integrate solar thermal and photovoltaic (PV) systems with biomass cookstoves. Stored electricity from the battery, generated by a small PV panel could be utilized to drive blower/fan in the case of the forced draft cookstove. The same could also be utilized for the lightning purpose for roadside street vendors or household applications. While designing cookstoves, local ecology and agriculture/biomass availability should also be considered.

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