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REVIEW ARTICLE

Novel Approaches on Renewable Biomass-Based Energy Source for a Changing World

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Abstract | Biomass as an energy source for the millions of under-privileged families in rural and semi-urban settings in India and over a large part of the World remains an ever-present necessity that remains acknowledged only in scholarly publications. Modern solutions for the combustion applications even when available are allowed to remain without adoption. This has resulted in attempts to deal with commercial applications as well as larger scale drying of perishables with novel techniques for fast drying while preserving the quality of dried products as approaches to make waste biomass use valuable to the society. This article provides a very brief history of improved cook stove development and dissemination both of fixed and portable forms with further evolution of fan-based technologies—batch and continuous combustion modes aimed at higher combustion efficiency and lower emissions. *The role of biomass quality that has remained unaddressed all along will be discussed with solution strategy for production and commercial supply of solid fuels.* That biomass fraction of *urban solid waste* is largely a *renewable* biomass source and can be treated to obtain quality biomass-based fuels for societal use is discussed in some detail and is argued to be a continuous source of supply of fuels to meet the energy demands.

1 Introduction

Fire wood and agricultural wastes have been used as domestic fuels for a very long time as there was no alternative. When liquid fossil fuels were discovered, kerosene-based wick stoves became available towards the early nineteen hundreds and became an alternative whenever the firewood available was too wet. This life cycle proceeded till liquid petroleum gas (LPG) got introduced as a cooking fuel. Most urban households switched to LPG and the relatively poor urban households and a large segment of rural house-holds were continuing to depend on three stone fires or mud based two pan cook stoves along with kerosene stoves for much longer periods. When the ministry of non-conventional sources of energy (MNES) got created under the central government in India, the idea of improved cook stove program took birth. During the Yam-Kippur war in 1973 and its aftermath, the fossil fuel prices increased steeply and agricultural operations involving diesel pump sets came under stress over years. This is what that led to discussions within the centre for Application of Science and Technology to Rural Areas (short form ASTRA) on what Indian Institute of Science could engage itself in areas that may make meaning to rural areas.

rural areas: This article is about the two important aspects related to biomass based high grade clean heat for cooking and semi-industrial applications as an economic and sustainable alternative in future. These relate to the scientific framework of the technology and the nature of quality biomass that can be used to service the requirements. The need for the change in the standards in controlling the quality of technology emphasizing water boiling efficiency to one that can separate the combustion efficiency from heat transfer efficiency is brought out. Also indicated is an approach to deal with it.

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kerosene stoves: The role of efficient low-cost continuous biomass combustion systems to produce dehydrated products of vegetables and fruits along with performance is brought out. That these could be a game changing approach to the diffusion of biomass-based combustion technologies is emphasized.

The work the present author was involved in, namely, teaching and research in combustion science related to rocket engines and industrial developments had a welcome intrusion in a persuasive conversation with Prof. A. K. N. Reddy in 1981 and is described in detail in chapter 13 of[1]. Prof. Reddy wanted the present author to take interest in biomass gasification to operate diesel engines on replacing at least 75% diesel by producer gas so that the rural farming operations dependent on diesel engine-based water pumping would get less stressed and the farmers would get benefitted. This became the author's long period of interest in biomass-based conversion science and technology. Also uncovered were the fundamental questions on biomass combustion process itself and the questions as to what limited the water boiling efficiencies in biomass stoves vis-à-vis kerosene stoves.

The work on biomass gasification between 1982 to 2003 is documented in refs.[2,3]. During the latter half of this period, the role of gasification to generate high grade heat for industries became a relevant option and these have been documented in[4]. While the work on gasification system development, technology transfer, the resolution of field related problems with the licensees, and international projects and training programmes were all being carried out even beyond this period, the decline of biomass gasification route to electricity and high-grade heat began in 2014 significantly when the central Government started large scale implementation of solar photovoltaics for power generation. While this development was taking place, the Government decided to supply LPG as clean cooking fuel to the underprivileged in a massive program over a 8 year time frame giving nearly 80 million families with a free LPG stove and one cylinder in the first stage. But the number of refills went up to 4 during later periods. A discussion of these appears in[5]. Thus, the most important research as well as developments on biomass energy that were continuing from 1981 needed a change in direction.

Sometime early into the study on biomass conversion in combustion systems, it became clear that both the fuel and the combustion device are important even though it was expected that biomass combustion device should work with biomass fuel of any shape size and possibly, moisture fraction. *It may sound overstated if it is brought out that a gasoline engine cannot be run on diesel as it is well known and therefore the nature and quality of fuel are important.* But it appears that it is *yet to be realized* that one cannot get much out of a biomass combustion device unless the feed stock quality is controlled *in addition to air flow rate*.

While the importance of moisture may be considered to have been generally understood even if not rigorously taken care, it must be emphasized that most people including professionals do not recognize that a stove meant for 20 mm sized biomass will give much lower power if 40 mm size biomass is used (in fact, one-half or one-fourth the power depending on whether the pieces are long or short exposing the fuel surface for combustion) and a 10 mm size biomass will give much higher power (two to four times the power). And, in reality, with the stove fed with logs as well as fine sized pieces of say, coconut leaf (found on the frond) or waste banana leaf as a bunch, expecting any meaningful performance would be unjustified since the burn rate and the air-to-fuel ratio required for good combustion become deviated from the nominal value both ways—high and low and either soot or smoke could be significant accompaniments to the combustion process. Thus, the whole approach of use of any fuel with even improved cook stove *is a contradiction to reality* as the fuel quality is as important as the combustion device itself for proper operations. And further, people (educated included) and professionals still carry an impression that biomass combustion is synonymous with smoke and *feel surprised* if it is stated that it is possible to have smokeless ignition and combustion of biomass when the fuel is prepared and the combustion device appropriately engineered.

Much work on this has been conducted along with students and colleagues over several decades[6–14] and most significantly in the last decade and these are discussed here from the perspective of the implications of these for the future. The rest of the article is arranged as follows.

Section	Subject
4	Continuous combustion system
4.1	The principles of the technology
4.2	Biomass processing for tree and agricultural crops
4.3	Urban solid waste-vegetable waste—food-waste based fuel
4.4	The continuous combustion systems in the field
4.4.1	An important application
4.5	Efficiency of and emissions from combustion systems
5	Combustion system in aid of drying fruits and vegetables
6	Concluding remarks

2 The Development Strategies

It is important to provide an appreciation for the development of stoves and combustion devices. The era in which the early developments took place was in which electric supply in the rural areas was very erratic and could not be depended on for enabling cooking using electricity-based support systems. This led to natural convection as the only alternative. Even when electricity became available, the low power fans (a few watts capacity) were available, they were so expensive that one could not contemplate using them except in laboratory environment. This is why one branch of effort at IISc that was in the chemical engineering department[15,16] was based on free convection arrangement. The air flow could be induced by using chimney and if the hot gases were led out of the kitchen into the atmosphere towards the top region, the indoor environment could be cleared up of smoke. In addition, most rural cookstoves were mud based with low efficiency. The scientific effort was therefore to enhance the energy of combustion captured in the cookpot and hence reduce the fuel use. While the primary fuel was firewood, the usage was extended to agricultural residues available during the season. Some of the fuel was admittedly not dry and since the stove functioned anyway and the nuisance of smoke was thrown out of the kitchen, users felt uninhibited in the usage of many fuels with wide range of size, shape and moisture. There are statements indicating that combustion was performed to generate highest temperature, but no formal data seems available. Since the nature of the fuel, size and shape are not a part of the specification, ensuring the best combustion performance would be impossible. Hence, it must be inferred that the primary aim of the design exercise would be to extract as much of heat into the cooking pot and users invariably cooked at least two kinds of food—rice and dal, two cooking pots were considered essential. To extract all possible useful heat a third pot also was provided. This led to the traditional 3 pan Astra-ole. There was much debate whether two pan version was adequate or even more appropriate and the stove Sarala-ole constituted the two-pan version. Beyond this, Prof. Lokras[15] took the responsibility for the design of combustion systems for a number of other applications that include community cooking, bathwater heating, areca processing, jaggery making, ayurvedic medicine preparation, silk reeling, dyeing of yarn, steam curing of lime stabilized mud blocks, vegetable drying, tobacco curing and cremation furnace. The fact that he was brave enough to take on many different kinds of projects and carry them out has been admirable and must be a matter of immense gratification.

As different from the above approach, the approach at CGPL (combustion, gasification and propulsion laboratory) was to deal with single pan metal stoves and combustion devices without and with air supply. This was guided by the fact that manufacture at scale would be better served with portable metal-based systems. The early version called SWOSTHEE an acronym for Single pan WOod SToves of High EfficiEncy was developed after significant effort into a thermochemical investigation of the operation of the stove[6]. Subsequently, many fan-based systems, namely, Oorja as a batch system, EIGAS, HERS, E-HERS, HC^{3}D continuous systems that are also forced convection-based systems were developed over a time, all of which have been patented with technology transfer to several industries. One of the key points of the fan-based development is to bring down the emissions of undesirable gases from the combustion system to the minimum since transferring emissions through the chimney would only move it into the atmosphere contributing to green-house gases, an important point that was made by Smith[17] that a stove with incomplete combustion generates more green-house gas emissions than a clean burning LPG stove. Hence, avoiding emissions of incomplete products of combustion through the chimney or indoor is a worthwhile aim in the design of combustion systems for biomass.

A question was raised in the early period as to whether technologies relevant to rural environment should even be patented, because patenting has the connotation of "commercialism", a word considered generally bad in rural support.

It is to be recognized that rural trade has been in existence ever since excess products have been exchanged for other necessities through barter or traded in currency terms. Thus, any new product, say, an advanced combustion system will have value in the minds of rural folk—a value that may be beyond their means at that time and if it is way beyond, gets ignored.

The question of how the advanced combustion solutions of portable metal hardware with fans can form the basis of sustainable rural cooking solutions becomes a question. Such solutions need the maintenance support for breakdown of passive or active system elements—grate that has to survive high temperatures, fans and power supply via battery. Providing the support system over a wide geographical environment needs financial back up. Further, the fact that the use of as-available biomass with varying shapes and sizes with uncertain moisture should be eliminated in terms of proper sized dry fuel, a subject that will be discussed in Sects. 4.2 and 4.3. It is suggested that prepared biomass should be supplied much as gaseous fuels like LPG and natural gas and gasoline and diesel are supplied. Storing biomass is much safer than the other fuels and can be supplied like others. *This is in fact a huge rural job opportunity—production of such "standard" fuels based on wide range of seasonally available wastes and "commercial" supply so that the combustion process is clean as well as efficient. This will "mainstream" biomass as a fuel in the country and this can be made available to all the users appropriately in a commercial way.*

Efforts are to be made by the state to subsidize the hardware for the financially underprivileged groups (like the below poverty line groups) after ensuring that biomass is available for use. This is what the central Government did in the case of LPG. They provided the stove freely and one cylinder of fuel to begin with. Surveys showed that a significant fraction of the served population did not return for a refill as it was expensive from their view point. The surveys also showed that the LPG stoves were used sparingly for important occasions and the users depended on the usual mud stove for the heavy daily cooking. Slowly the support of LPG cylinders went up to four an year and the current status is that improvement in local economic conditions may allow regular commercial supply of the LPG cylinders. *The Government is still to recognize that biomass is a true renewable source of local fuel and advanced combustion devices will have value in offering clean cooking solutions to rural people and can at least be allowed as a back-up solution*.

3 Batch Biomass Combustion System and Carbonizer

3.1 Batch Combustion System

The study on stoves with clean combustion have been discussed in detail in ref.[7]. The essential idea is to reverse the operation in a normal open top gasifier. In the reversed arrangement, air is supplied from bottom and the biomass bed is lit at the top. Under these conditions, the flame front moves down against the air flow and the volatiles are released from the surface of the biomass fuel. The burnt gases react with the char above the biomass bed and get converted to a combustible gas. This process occurs over a thickness of a few particle thicknesses. This design was called reverse downdraft system (REDS) at CGPL. It was termed as top-lit up-draft system (TLUD) by Anderson and Reed (see references in[7]). The specifications for this stove were derived from our earlier work[6]. The fact that air supply made a difference to the performance of REDS could be actualized when computer fans of low capacity (~ 1 L/s at 4–5 mm water gauge) were available at affordable cost form the year 2000 onwards. The basic principles of the operation of this combustion device are set out in Fig. 1.

Fine pieces of biomass about 10–20% size of the container (10–20 mm for a 100 mm diameter vessel with some pieces smaller or slightly larger acceptable) are loaded over a grate in the container as shown in Fig. 1a. With air supplied from the bottom at velocities termed at superficial velocity (V_s) implying the mean air velocity in an open cross section at 0.03–0.1 m/s and the top lit by spreading kerosene/diesel or gel fuel and lighting it, one gets combustible gases from the top. Combustion air is supplied laterally at the top to obtain complete combustion and the flame that spreads over the surface as shown in Fig. 2 is obtained after about five minutes. The flame is found between the air injection holes and one can see bright char zones below the flame in Fig. 2a. A weak flame is seen over the char in Fig. 2b. This flame is weak and the CO emissions much higher than in Fig. 2a. This is because char bed is far more porous and combustion process is weak. One can enhance this by increasing the air flow in this regime and reduce the CO emissions. The bottom and top air flows are also called primary and secondary air. Primary air serves to gasify the fuel and the secondary air to burn it. For most applications, the bottom air is to be supplied at

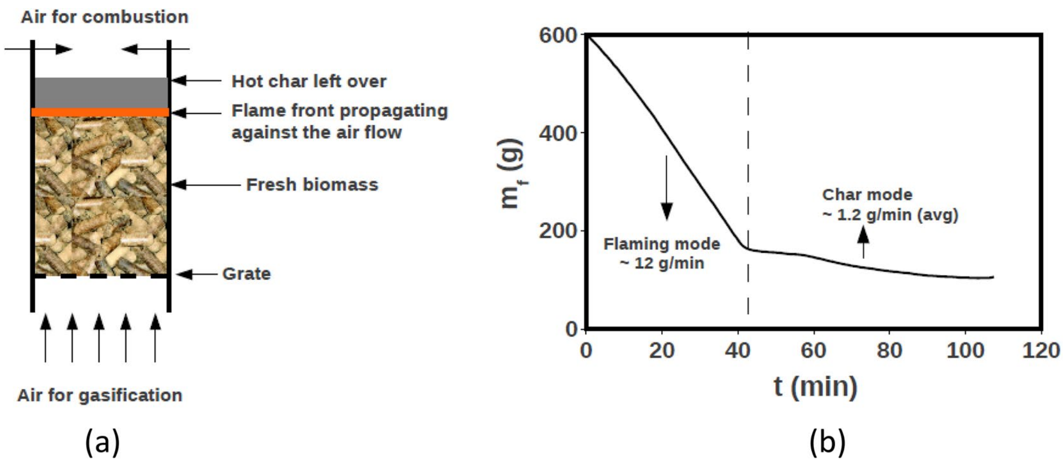

Figure 1: **a** Operational principle of the combustion device, **b** mass loss vs time curve of the stove in operation.

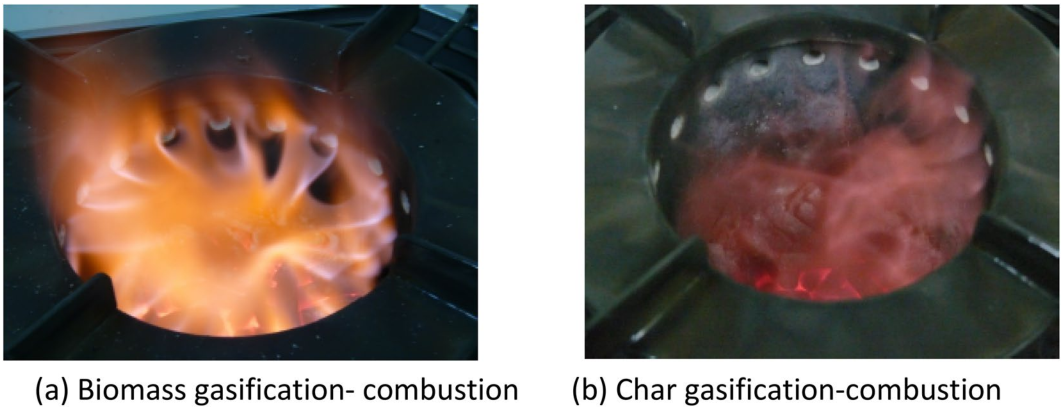
(a) Biomass gasification- combustion (b) Char gasification-combustion

Figure 2: The flame over the combustion device on the left with a burn rate of 12 g/min largely with volatiles and 1.2 g/min largely with char at the same air flow rate (or same V_S).

1.5 times the biomass burn rate to ensure "gasification" mode. The top air will be about 3 to 4 times the biomass burn rate so that the stoichiometric air-to-biomass burn ratio of 5.5–6.5 is achieved.

It can be noted from Figs. 1b and 2a that correspond to each other that the burn rate is near constant at 12 g/min that translates to about 2.8 kWth (at the volatile calorific value of 14 MJ/kg) for 40 min and the char burn is at 1.2 g/min for which the burn behaviour is shown in Fig. 2b. In this case, the thermal power is low—0.5 kWth (at calorific value of the char of 24 MJ/kg) for 20 min.

The combustion behaviour with increasing superficial velocity is *an important design and development result uncovered in*[9] and is set out in Fig. 3 and Table 1. Increasing the superficial velocity will increase the power levels linearly, but result in larger emissions of particulate matter (PM2.5 in particular). For these reasons, V_s is set at 3.5 cm/s and it is ensured that the design value does not exceed 5 cm/s. The conversion behaviour and the performance parameters are depicted in Fig. 3. The fuel burn flux increases with the superficial velocity, somewhat linearly to begin with and saturates at a superficial velocity of 0.17 m/s at a burn flux of 250 ± 30 kg/m^{2}h.

The variation is primarily due to the density of the fuel. Higher densities like for coconut shell pieces or tamarind wood pieces permit higher fluxes. Since larger superficial velocities lead to higher gas speeds over the bed and so, *particulate emissions*, the domestic combustion systems without chimney are designed with a low value of V_s of 0.035 m/s, certainly not more than 0.05 m/s. This design choice helps in limiting the particulate emissions, particularly PM2.5, which is often argued as a serious pollutant.

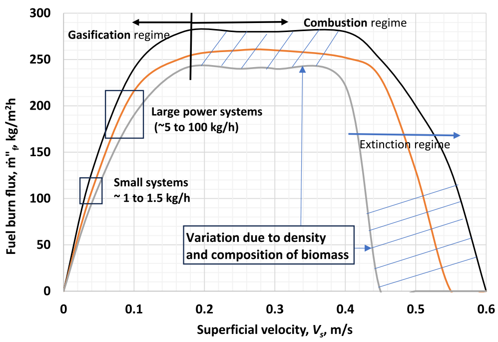

Figure 3: The results of fuel burn flux (burn rate per unit cross sectional area) with V_s, the key control parameter and regimes of conversion.

When V_s increases beyond 0.4 m/s, the combustion behaviour is erratic because of differences in surface area of individual particles experience both heat release and heat carry over by the air flowing around. The fact that the burn flux saturates around 250 ± 30 kg/m^{2}h is inferred to be due to a balance of heat flux from diffusion limited heat release due to char-air reaction and the heat flux drawn away due to convection. When the latter overtakes the former, something that begins around 0.4–0.5 m/s, the resultant burn flux becomes lower and lower till extinction occurs. This segment has more scatter because the precise details of the surface area of various particles, the possible catalytic role that some inorganic ingredients play in the heat release will are responsible for the heat “loss” rate to overtake the heat generation rate with passage to local extinction that spreads over the fuel bed leading to overall extinction. Hence, most acceptable operational regime for clean combustion is restricted to $V_s < 0.17$ m/s. The measured gas phase composition of the combustible gas and surface temperature over the fuel bed are set out in Table 1. Included in the table are data for pyrolysis (at $V_s = 0$) that is endothermic and so needs heat from outside and the output depends on the maximum temperature of operation. At lower temperatures (600–700 K) more heavy tars are generated and at higher temperatures (1000 K) lighter tar and more gases. Only when air is introduced, the process becomes exothermic and one gets combustible gases up to V_s of 0.17 m/s and the energy from these gases will get released in the localised combustion process at larger values of V_s. The magnitude of char obtained is the largest in the non-oxidative mode at low heating rates. With air flow at lower V_s, the char obtained is about 30% and decreases as V_s increases. This is due to rate of oxidation being higher with increasing access of oxygen to the char surface.

The next question that was to be addressed was how to convert the idea into a cooking solution. The burn rate of the stove was set at 0.75 kg/h with a fan that supplied the bottom air at 1.2 m^3/h and top air at 3.5 m^3/h to enable the overall air-to-fuel ratio at about 10% more than stoichiometric value. It was necessary to do this since the fuel composition could vary slightly and allowance was to be made for the fuel demanding the largest stoichiometric ratio (which varied from 5.5 to 6). The burning zone of an LPG stove and a domestic 10 burner kerosene stove is about 100 mm. Thus, it was intended to release the heat at this diameter so that the energy utilization in a 250 to 300 diameter vessel would allow realization of high overall efficiency. The value of V_s

Table 1: Thermochemical parameters during reverse downdraft operation ($\dot{m}''_f$ = fuel burning rate per unit cross sectional area, HHC = higher hydro-carbons also termed tar, * = conditions in a stationary reactor heated to the 600 K).

Sup vel m/s	$\dot{m}''_f$ kg/m^{2}h	CO %	H_2 %	HHC %	CO_2 %	T_s K	Char %	Comment
0*	–	10	15	30	5	650*	40	Pyrolysis, to be heated
0.035	100	10	16	3	14	900	32	Gasification
0.05	130	12	14	3	15	1000	28	Gasification
0.10	230	15	14	2	12	1300	15	Gasification
0.17	250	15	9	1	13	1500	10	Gasification
0.25	260	10	3	0	20	1800	0	More local combustion
0.30	250	2	1	0	23	1800	0	Combustion
0.40	250	1	0	0	5	1000	0	Combustion
0.50	150	0	0	0	0		0	Extinction

Figure 4: The reverse downdraft stove: fixed volume loaded pellet fuel (largely), gasification air supply from the bottom, combustion air from the top holes both needing a fan of 1.5 We for 3 kWth power from the combustion system.

was chosen as 0.035 m/s. This led to a vessel inner diameter of 100 mm. To accommodate 0.75 kg in a duct of 100 mm and a reasonable height of say 140 mm, one needed a fuel with a packing density of 750 kg/m^3 and this needed a fuel with a density of 1000–1100 kg/m^3. This implied that the only fuel fulfilling the requirement was pelleted fuel. The fuel was intended to be produced using agricultural residues—bagasse, groundnut shells and other residues available seasonally at low prices for procurement. BP, India to which the technology was transferred by Indian Institute of Science set up a pellet factory at Islampur in Maharashtra and procured the waste fuels from about 50 km around the factory. Much development took place on the stove and power pack and fans, all of which are described in[7]. Figure 4 shows the air supply system schematically and the octagonally shaped stove. The ceramic wall with grate at the bottom and air supply holes at the top are visible. The elegance of the look was not lost on the buyers of the system. Many studies have been conducted on the efficiency and emissions from the stove. The results have been summarized in[7,11,12] and the aspects on efficiency and the emissions are discussed in Sect. 4.6.

Over 0.4 million stoves were sold in 2007–2010 period in a commercially subsidized venture by BP, India and it appeared to be scaled to larger outreach. The fuel was initially sold at Rs. 5/kg, generally in 25 kg bags. The stove was extensively used in various villages in 2007–2009.

Subsequently, due to issues of agro-residue shortage—largely, bagasse and groundnut shells, the prices of fuel went up from about Rs. 5/kg to Rs. 10/kg in 2 years. The affordability of the fuel came into serious question and the program was to be shut down. BP, India got transformed into an Indian company, First Energy Private Limited (denoted as FEPL from now on), Pune who sought sustainable markets for the stoves and pellet fuels. They expanded into hospitality industry and supplied far-more improvised and advanced solutions for cooking keeping the essential fundamental ingredients much as in the early design. Systems with power levels of 0.75 kg/h (3 kWth) to 3 and 6 kg/h (12 and 24 kWth) were built and marketed with much success in several metros—Bangalore, Hyderabad, Chennai, Coimbatore, and other places. An interesting commercial strategy that they employed was to let know the users, mostly in the hospitality industry, that the combustion system will be installed and operated for the cost of the fuel that they will need to obtain from them after letting them know that the cost of manpower services to maintain and if necessary, operate the combustion system would be factored into the cost of fuel that they would pay. Typically, this cost was 12–15 Rs/kg. A total of 1500 tonnes per month of agro-residue pellets are being sold over 4 years in Hyderabad, Mumbai, Bangalore and Chennai. The domestic market demanded a fuel price pitched against liquefied petroleum gas of no more than Rs. 7/kg at this time when the LPG prices had not increased as they normally would. Hence the stove availability and use in the domestic segment in fact plummeted. Around this period, FEPL also wanted the present author to try and develop continuous combustion fan-based stoves based on the feedback of over fifty of the users in the hospitality industry. These efforts are described in Sect. 4.

3.2 Batch Combustion System as Carbonizer

Biochar has been a hot topic with a large number of enthusiasts entering the arena, building biochar cylindrical reactors from waste hardware and demonstrating that one can get biochar. But there are issues. Lehmann[18] presented an important study that brought out that the properties of biochar with appropriate features of high internal surface area and cation exchange capability could be obtained when the char was produced at temperatures in excess of ~ 500 °C. The surface temperature of the char is 600–650 °C and meets the requirement of the char being processed under conditions under which the internal surface area would be very high and has the requisites for qualifying to be a good biochar. The flame propagation process naturally produced char by extracting the volatiles from the biomass though in this process, some carbon would also be pealed-off so that the char fraction left behind follows the values indicated in Table 1. Operating the reactor to produce char was straightforward. Thermocouple would be welded to the steel grate and the output monitored. It would show ambient temperature till a point when the flame reached the grate at which stage the temperature would shoot up to 600–650 °C. This implied that the biomass in this region would have become char. After allowing for about 10–15 s to ensure the temperature in the entire region reached the same condition, the air blower would be switched off. One would have an option at this stage to cover the top with a ceramic cloth to ensure that the char cooled down under conditions without air around. Alternately, one could switch in nitrogen for about a few minutes till the char cooled down. Then, the char could be extracted. Studies conducted on producing biochar are discussed in[10].

The fuels that were considered are set out in Fig. 5 that also shows that where the requirement of the char was for higher end applications, one would benefit by drying, pulverising and producing pellets before use for biochar production. One could expect to get uniform and good properties.

It was also required that a few other wastes be considered for char production (in the case of rice straw the demand was significant). The experiences in handling these wastes are described in[10]. Figure 6 shows two simpler designs of reactors with controlled supply of air from the bottom, both ensuring that the conversion from biomass to char occurs at temperatures in excess of 500 °C. The properties of char produced in these reactors is listed in Table 2.

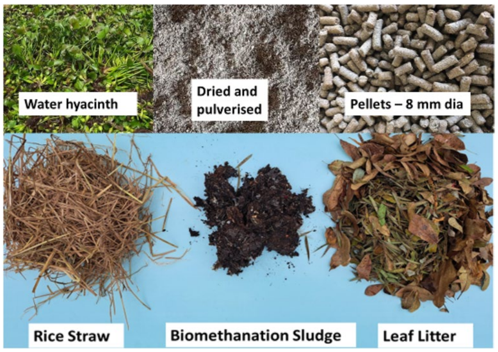

Figure 5: The various biomass considered for biochar generation.

The choice of superficial velocity, V_s is between 0.05 and 0.1 m/s and it can be seen that Increased V_s results in lower char output. The amount of char yield varies between 22 to 25% of the initial feedstock with light residues and is 28% for organic solid waste. The pH is largely in the basic range and the more interesting result concerns the Iodine number. It is a parameter that indicates the level of internal pore area of the char that has the ability to absorb chemicals in solutions. The value is around 100 mg/g for light residues and around 600 mg/g for pellet fuels. Thus, if this parameter is to be optimised, it is important that the light residues be made into pellets to enable achieving higher internal surface area.

4 Continuous Biomass Combustion Systems

4.1 The Principles of the Technology

There was expectation and demand from FEPL that continuous combustion systems be developed as they were what the users' expectations were. What they had done to provide a "continuous" system using batch system hardware was that they would allow the deployment of two batch systems so that after one system had burnt up the fuel, it would be replaced by another similar system and the system that would be hot with exhausted fuel would be allowed to cool down in an hour and then refilled with fuel and prepared for the next operation. After having observed the problems in reality, a serious examination of the approaches to approximate the outstanding quality of combustion in packed bed batch combustion systems was started. The initial attempt was to look at larger power combustion systems—systems with power levels of more than a few kg/h, as these were the class of systems that the hospitality industry was needing.

Figure 6: The *simple biochar production systems*—a 0.56 m diameter, 200 L waste diesel drum based reactor on the left for many light residues and the brickwork based reactor on the right for bales of rice straw.

Table 2: Summary of the results of char produced at the laboratory (*procured from outside, see[10]).

No	Material	V_s m/s	Yield %	pH (25 °C)	Iodine No mg/g
1	Rice Straw	0.05	24.6	10.0	120
2	Rice Straw	0.10	20.4	10.0	95
3	Leaf Litter	0.05	24.0	9.3	102
4	Biomethanation sludge	0.05	22.0	8.5	100
5	Water hyacinth*	0.05	28.5	9.0	616
6	Organic Waste pellets	0.05	28.4	9.0	600
7	Rice Straw (large scale)	0.05	22.0	10.0	120

Once the system size is larger, one could afford to deploy blowers—the cheaper of these was a ring blower at 200–400 W and provided enough pressure head of 1000 mm water gauge (compared to 12–50 mm water gauge for small fans/blowers) to get jet speeds of 50–60 m/s. The early designs to explore the idea were both vertical and horizontal combustion system designs using ejector-based principle.

Figure 7 (left) shows the design of a continuous stove that was described in the patent application no 1365/CHE/2005. This design uses a horizontal leg for feeding the biomass in the form of fire wood, could be other briquettes of sawdust or other agro-residues as well. This would enable accessibility of the fuel feed port for introducing fuel when needed, the aspect of continuous combustion system. Air was introduced in the form of fine high velocity jets (velocities of 50 to 60 m/s) at the bottom region of the vertical combustion chamber over the grate (this needed blower with power demand of 400 We).

The air jets were located about 100–200 mm away from the fuel bed. *The ejector action caused suction in the zone below the air nozzles*. This enabled air being drawn from the sides and the bottom region with the bottom of the grate region being kept open. This air drawn through the horizontal bed of fuel through an ejector action caused a flame front to propagate through the solid fuel bed *much like in a gasification system when the fuel bed was lit*. This process generated combustible volatiles that burnt in the vertical combustion chamber after mixing with the high-speed jets of air. The hot charcoal that fell on the grate was also get converted into a combustible fuel in terms of carbon monoxide or completely oxidized to carbon dioxide or a mix of the two depending on the amount of air drawn through the bottom region. Conditions were created in the chamber for a "mild or flameless" combustion mode to dominate thereby ensuring the lowering of emissions (of CO).

Figure 8 shows the bright flame from biomass combustion at 10 kg/h, the power for operating this system drawn from a two stage DC fan of Sunon make operating at 15,000 rpm drawing only 12 W power at 12 V.

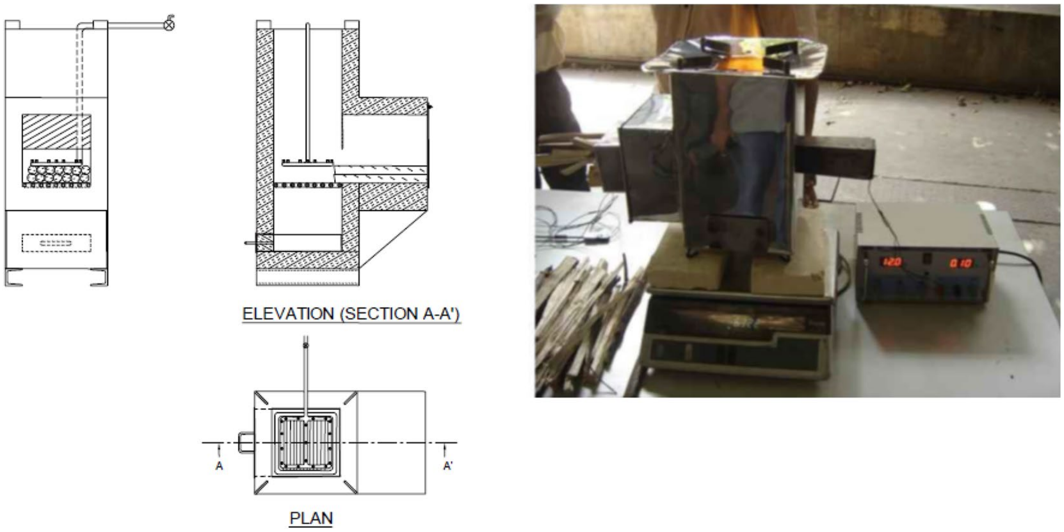

Figure 7: Ejector Induced Gasification system (EIGAS) evolution—left—10 kg/h, right—1.5 kg/h version.

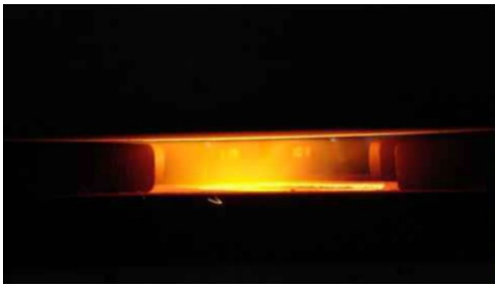

Figure 8: Clean combustion in EIGAS at 10 kg/h dry biomass operated with air supply from a 12 W, 12 V two stage fan.

Building larger power systems was simpler and systems of 10–120 kg/h were built over a time. It was then thought that it was important to build domestic clean combustion systems for a range of biomass. Therefore, attempt was made to embed the principles in a small power combustion system using ejector-based principle except that the ejector velocities were set to 8–12 m/s instead of 50–75 m/s in the larger power systems; this needed limited electric power of the order of 1.5 We for a 3 kWth cook stove. They were largely aimed at both at firewood and other fuels. The principles of the combustion process are set out in Fig. 9 for both horizontal and vertical combustion devices. The essential difference between the early developments at high power as illustrated in Fig. 7 and these devices is the relative location of the fuel bed and primary air. While in the earlier design, there was no specific primary air flow, but was induced by the secondary air flow, in these designs, the primary and secondary air flows are directly provided for in amounts that can be controlled. Lower primary flow implies lower conversion rates of char and this condition arises at low power levels. Providing larger amounts than needed causes some excess air flow via fuel port and the fuel starts burning in the fuel port with flame coming out. This is obviously undesirable and it can be corrected by increasing the secondary flow implying larger power. If larger power is not needed, the primary air flow must be turned down. It is also possible that the size of the biomass is so much larger than acceptable that the resulting char is not converted by the bottom air flow and so a pile up of char occurs over the grate and the fuel cannot enter the combustion zone.

This problem is absent when the fuel size is controlled to about 10–20% grate size of combustion space dimension. Typically, a 1 kg/h system has $0.1 \times 0.1 \times 0.1$ m sized combustion chamber and the mean fuel size should be 10–20 mm with about 10% larger sizes being acceptable. On the lower side, this fraction could go to a few mm as well. A 3–5 kg/h system with $0.15 \times 0.15 \times 0.15$ sized combustion chamber (note that the fuel burn flux is about 130–220 kg/m^{2}h) can have 15–30 mm sized fuel. One can use firewood of this dimension with length of 50–60 mm in the case of HC^{3}D. In the case of VEBCOD, the length restriction is absent.

One of the key relevant questions is whether the continuous stove design in its final form approaches the behaviour of the batch stove design *in terms of quality of combustion*. In the case of the batch system, the flow of gases is

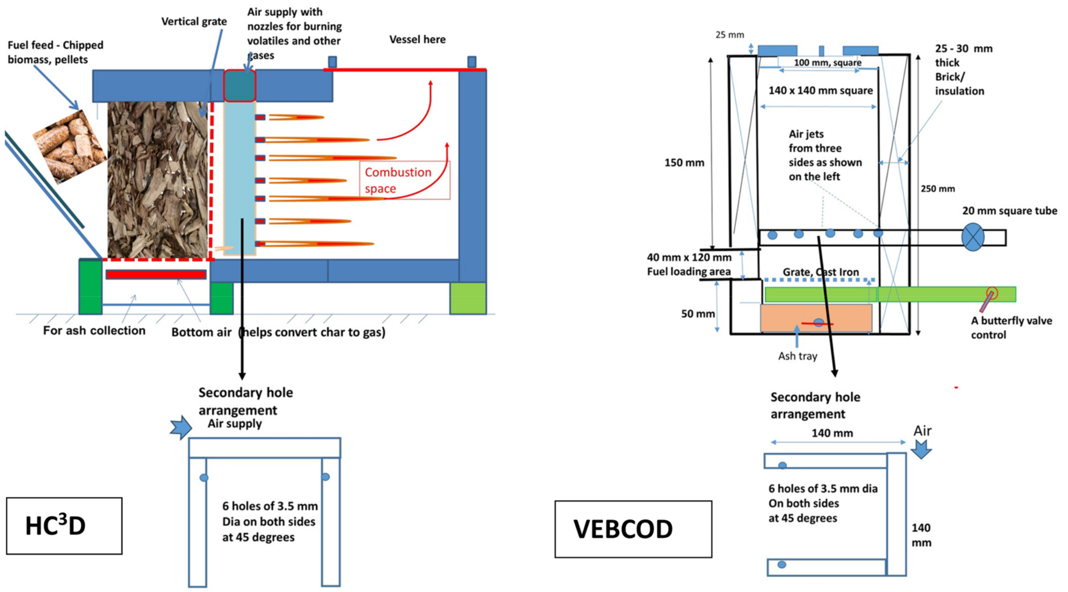

Figure 9: Schematic presentation of the Horizontal Clean Continuous Combustion Device (HC^{3}D) and Vertical Ejector Biomass Combustion Device (VEBCOD).

linear—air flows through the packed bed in the open spaces between the particles/pieces of the biomass, burns with the volatiles released from the surface of the biomass (typically at 600–650 K) to reach temperatures between 950–1800 K and moves up in the bed to pass through char particles. The reduction reactions absorb a part of the heat to convert water vapour and carbon dioxide to hydrogen and carbon monoxide as shown in Table 1. The flow of the gases is along the same upward path.

The continuous stove design does not have a single pathway. There are two pathways. The flow from the bottom of the grate is one. The second one is the one induced by the secondary air flow that causes a flow from the fuel feed port, the magnitude of the flow depending on amount of fuel present in the space over the grate at any point of time. The bed on the grate initially made of biomass will become a char bed due to the behaviour much like in the batch system. The char bed continues to be consumed because of oxidation with the bottom air and generates combustible gases with good to weak composition depending the bottom air flow. Weaker composition implies higher temperature since some part of hydrogen and carbon monoxide would have burnt up with air.

In addition to this flow of partially burnt gases, volatiles from the top region consisting formaldehyde, acetic acid and other oxygenated components will also issue out of the bed. The oxygen for this process is supplied by the flow of air through the top portion of the bed induced by the secondary air jets.

These volatiles get mixed with the combustible gases from the bottom region and are drawn by suction due to the ejector effect of the secondary air flow through individual holes (shown in the bottom portion of Fig. 9) and meet the air issuing as jets in the high temperature zone just downstream of the air tubes. The combustion proceeds much in the way it happens in batch mode combustion process. If the air flow rate is slightly larger than required for stoichiometric combustion, the products will be much cleaner than in the stoichiometric combustion since the carbon monoxide experiences an environment of oxygen to more completely oxidise.

The air flow is provided through tubes/ducts in which holes of the requisite size are drilled at the right orientation. What is shown in Fig. 9 is one such arrangement used in most large power systems to ensure longer life of the air delivery tubes whose life otherwise is about 1000 h of usage with stainless steel material used for them. The share of secondary-to-primary air flow rates varies between 50:50 to 70:30 depending on the char left behind on the grate which itself depends on the volatile fraction of the fuel (as obtained from the proximate analysis). If the char fraction is larger, a larger primary air flow is needed. Since the range of the values is not large, the valve controls provided will help take care of this problem.

It must be remembered that fuel used in combustion systems can come from many sources and *it is inconceivable that the composition can be controlled like in the case of liquid petroleum fuels*.

An important question that may arise is: Which system, HC^{3}D or VEBCOD is superior? How should one choose either of them?

Both HC^{3}D and VEBCOD will discharge the function of providing high utilization efficiency. HC^{3}D is built to use smaller sized biomass. Hence it functions like a packed bed. The thermal conversion process occurs with greater mixing between fuel vapours and air and hence one gets better combustion. One may therefore infer that it is easier to get more complete combustion in HC^{3}D than in VEBCOD. In the case of VEBCOD, the fuel is usually firewood. The space for interaction between fuel vapours and air is more limited and the secondary jets are arranged at an angle to the vertical to create the needed completeness of combustion. Both the designs provide water boiling efficiencies of 36–40% for burn duration of 60 min and above. The choice of either of them depends on the space available for including the combustion system. It has been found that there are height restrictions that will allow the use of only HC^{3}D and in some instances, firewood is the only available fuel and VEBCOD is the favoured design. There are also occasions when the application is more simply handled with HC^{3}D, but firewood more easily available fuel. In such cases, it is suggested that the user has a cutter to bring down the size of the firewood to enable its use in HC^{3}D or use cut pieces from wood processing plant where available.

To reduce the cost of the power pack—fan/blower and DC power supply and charger, the smallest system needed to carry out the combustion well (implying an air flow rate of 1.6 g/s for air-to-fuel ratio of about 6), a blower that provides 1.6 g/s at a pressure head of 12 mm water gauge with measured jet velocities from a 3.5 mm orifice of 10 m/s in the mean (generally obtained from Sunon make) was considered satisfactory. For higher power systems, a range of high-speed DC fans of high speed and superior performance were/are available.

It is important to ask a question as to why this issue is not important for REDS (batch system, Sect. 3.1), but so for continuous operating system. The air supply system in the batch system has to overcome the pressure drop of the bed which is less than 1 mm water gauge that result in velocities of 10 cm/s and 50 cm/s for the intended flow rates. In the case of continuous systems, the flow has to be induced through the momentum of air in the secondary jets and this requires 10 mm water gauge to get to 10 to 12 m/s of jet speeds that causes an ejector action to maintain air flow rates required for burn rates up to 1.5 kg/h. For higher power systems, fans with pressure head of 50 mm water gauge would be required. Rest of the system design is based on standard engineering principles.

4.2 Biomass Processing for Tree and Agricultural Crops

It has been brought out that for the technology to be meaningfully assimilated into the society, it is crucial to use fuels of the right sun-dry material of the appropriate size and shape with minimal ash content. While it is recognized that biomass available to a user in rural environment is different in different seasons (with some of them like coconut leaves that are generally left behind as they leafy or used in ways that produce large amount unburnt volatile hydrocarbons implying smoke and soot as well), to imagine that that fuel as available is the most appropriate for direct use is incorrect. In many regions, bovine dung is available at homes and these are converted to cakes and allowed to dry.

The use of cow dung cake leads to very smoky combustion and releases heat very slowly quite different from what happens with coconut tree leaves. It is therefore appropriate to combine these residues to produce a reasonable density fuel.

Figure 10 shows many naturally available and prepared fuels for use in small combustion system—domestic and community applications. The fuels in inset **a** and **b** are chipped and chopped biomass of low density (200–300 kg/m^3) of packed density and can be used in HC^{3}D system. Unlike REDS system, continuous feed system does not have the limitation of density for combustion. But lower density implies higher volumetric loading rate for the same mass burn rate. This implies that the users have to be feeding at higher frequency or alternately adopt a top self-loading arrangement. The insets **c** and **d** refer to corncobs and cashew shell wastes from processing industries. These can be directly used in the small combustion systems to be discussed subsequently. Inset **e** refers to prepared fuels using cow dung along with sawdust to enable obtaining a structure to the fuel. It has a low density. It was obtained by manually making balls of the mix and drying them. If very light material is in abundance, it would be appropriate to pulverise it, mix it with a binder—almost any waste wet food stock

Figure 10: Fuels for small combustion systems: **a** cut tree droppings along with bark, packing density of 200–210 kg/m^3. **b** Causarina chopped pieces, packing density of 240–280 kg/m^3, **c** corncobs, packing density of 200–210 kg/m^3, **d** cashew shell waste—90–100 kg/m^3, **e** processed sawdust-cowdung balls, 60–80 kg/m^3, **f** pellets of a mix of seasonal agro-residues, packing density = 600 kg/m^3; ash content < 5%, drawn from[11].

(like waste fruits, banana and waste cooked rice, and others) to the extent of about 10%, pass the mix through a screw press not very different from what is used in food industry and dry it.

Once dry, it can be used in continuous combustion systems of the kind discussed later since the systems do not depend on the fuel density for the operation. The only issue is that these fuels cannot be stored for long time as they would be affected by fungal attack. Also, the density of the fuel affects directly the periodicity of the fuel feed. The highest density fuel needs to be fed at nominal power perhaps once in an hour but the lower density fuels every ten minutes or so.

Larger systems meant generally for industrial need will have automated feed system. The domestic system at 1–1.5 kg/h throughput is in a sense more difficult to realize since the expectations are different. Clean combustion and continuous operation have to be coupled with reducing the initial cost of the device to ensure affordability of the community benefiting from it. For the fuels shown in Fig. 10, the cost has the same trend as density since lighter fuels are found more easily and the densification process adds to the cost of the fuel. Typical cost of firewood might vary between 4 and 6 Rs./kg, the cost of pellet fuels would be about double this value. Without automation, the limitation is that those who wish to use a combustion system with the low-density fuel (that may be very cheap) will need to pay much larger attention to fuel feed and ash extraction than with higher ash fuels. Inset **f** is the standard pellet fuel with seasonal agro-residues (bagasse, groundnut husk, coffee husk, sawdust, sal, celery waste, marigold waste, rice bran, and others, the choice being made to balance the cost and quality of the pellets.

4.3 Urban Solid Waste-Vegetable Waste: Food-Waste Based Fuel

Urban solid waste is a much talked about subject over the past three decades and many waste-to-energy projects were started at humongous investments with bank loans, and capital subsidy from the central government, and systems built half way (most of the time) and closed due to many reasons. The projects were based both on bio-methanation and combustion-boiler-electric power generation approaches. Land close to waste dump yard) was usually given as the equity of the state and the cost of the processing and infrastructure and power generation was about the same. Some projects failed because it was claimed that the waste quality as received at the dumpsite

Figure 11: The in-feed waste material received from M/s carbon masters and the processed cakes that can be used as combustible material in domestic or industrial combustion systems.

was lower than promised by the local municipality at the beginning of the project, some because of increased hardware and construction costs during the project, some not meeting the environmental considerations on the emissions, etc.

While not dwelling much on the contentious issues that have plagued the subject, a simpler approach to dealing the problem is outlined. It is understood that recyclables, plastics, metals should be taken out of the system. While removing the recyclables is easy to appreciate, it is also not difficult to note that plastics have multiple uses explored in India, including production of liquid fuels and as a part of road construction, we infer that a large part of the material is biomass based. These can be in various shapes and sizes. Where the biomass material of distinguishable and large size can be separated for use, the small sized material can often be crushed with a heavy crushing equipment along with wet wastes to produce a dough like material. This material may have moisture fraction of 20–30%. It can be extruded into cylindrical pieces 20–50 mm size and sundried for small throughputs or dried at large throughputs by hot air generated by using the processed material as a fuel in the combustion system of the kind discussed here along with a large air supply system to dilute the combustion gases to 100–120 °C. These are simpler engineering practices not discussed in detail here.

A vegetable market waste bio-methanation process that was commercial implemented by M/s Carbon masters headquartered in Bangalore with bio-CNG and organic fertilizer as products came to our attention. While the larger segment of the feedstock was vegetable waste, there was always a mix of lignaceous feed stock like broken coconut shells and other material that could be handled only by thermochemical conversion. Such material if not separated during the daily feeding would end up in waste sludge.

Handling this waste sludge and separation of plastics almost always mixed up with the vegetable waste was another issue. In addition, waste water had to processed and handled as a supply to fields along with the fertilizer. The variable quality of the sludge to be supplied as fertilizer needed attention to help maintain quality. As an alternate strategy, the procedure outlined in the earlier paragraphs was tested with about 50 kg of *the infeed material* used in bio-methanation plants was procured from M/s Carbon masters and processed at FCRC[13].

After initial examination to separate large sized material, the material, both dry and green waste were together processed in a hammer mill. This led to fine sized material with dough-like consistency. This material could be processed into cylindrical shapes through a low energy extrusion system. An even simpler system of spreading the material over a flat surface to produce dry cake like product was used. Figure 11 shows the pictures of the infeed material and the cakes left for drying. These cakes that contain much less lignin than biomass burn with flames more transparent than with cut pieces of wood. Simple estimates of first cost of installation is that it is about a third of the costs involved with bio-methanation plants.

Figure 12: HC^{3}D—single pan (**a**) and two pan (**b**) versions with chipped wood. Many other fuels in Fig. 10 acceptable for operation.

Figure 13: VEBCOD—Examples of single pan 1 kg/h system (aa), two pan version of 1 kg/h each (bb) and 3.5 to 6 kg/h (cc) largely for use with long sticks—split coconut or palm frond, firewood, corncob, etc.

The product can be sold to domestic or commercial users of combustion system.

4.4 The Continuous Combustion Systems in the Field

Figure 12 shows two examples of the use of the single pan and two pan HC^{3}D systems both operated by 12 V battery based sun on blower working at 1 and 1.4 kg/h both operating with sized dry wood pieces about 15 mm lateral size and 30–50 mm long.

In the case of two-pan system during the operation, the heat received in the second pan is about 30% higher than in the pan closer to the combustion area. This is due to the flaming jets moving with speeds of 35–40 m/s (due to the gases being of high temperature and so of lower density) and reaching the outer zone. Both the systems were produced to ensure aesthetic quality and most observers have had found them attractive.

Ignition of the fuels was also a question that was to be addressed. Traditionally, sprinkling of used cooking oil or kerosene/diesel with a match stick would be adequate to start the ignition process. This would need to be allowed for about a minute before the air supply can be switched on with the flow rates at the minimum. Over the next two/three minutes, the power can be raised. Full power delivery will begin only after 10–12 min because the hardware has to get heated up. The ignition process is shorter with finer pieces of fuel wood that the normal pieces (10–20 mm size).

Three examples of VEBCOD are shown in Fig. 13. The system shown in Fig. 13aa is for long stick class material like firewood. The system shown in Fig. 13bb is an arrangement of two single pan stoves with the power pack in the middle. Either of the stoves can be can be used separately. The system shown in Fig. 13cc is a VEBCOD operating at 3.5–6 kg/h. It can be used for larger scale cooking as well. Many of these combustion systems have been marketed by partners in Karnataka, Kerala and Manipur.

A number of systems have been in the field for over two years at this time. These are, 150 of 1.5 kg/h domestic system are in various parts of Kerala, 30 of 3.5–6 kg/h system in Karnataka and Kerala, 15 kg/h and 30 kg/h systems two each and one of 100 kg/h system. Those

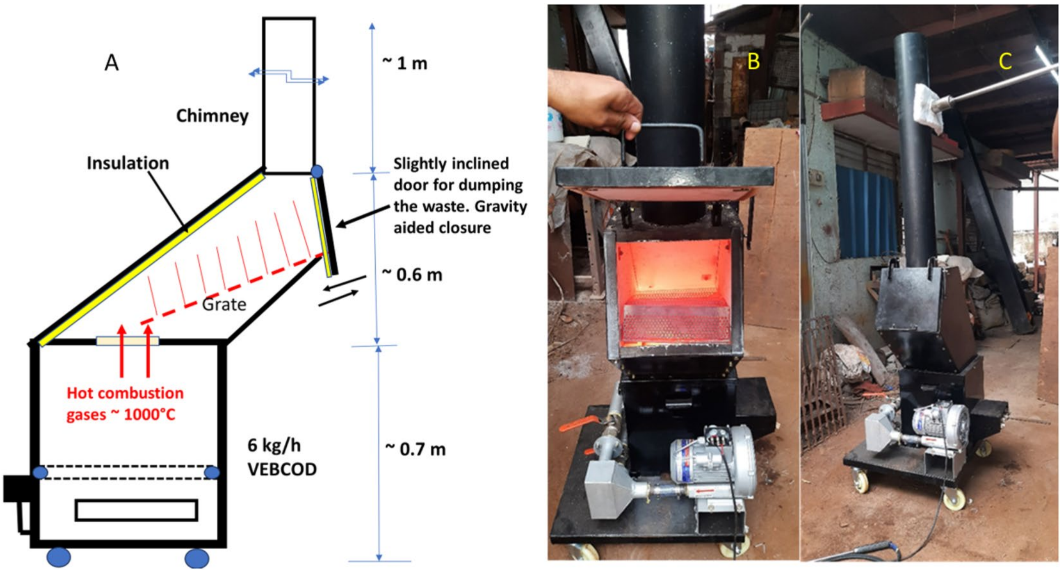

Figure 14: The 3.5–6 kg/h VEBCOD system arranged for the combustion of sanitary pads and diapers. Inset **A** shows the schematic of the system and **B** shows the system in combustion mode and inset **C**, the set up for emission measurements.

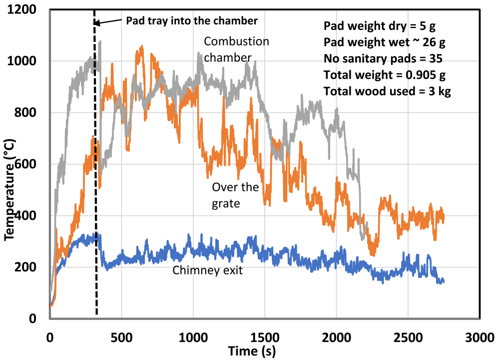

Figure 15: Measurements of gas temperature of the high temperature gas, the grate carrying the sanitary pads and exhaust during the operation.

which are used for cooking have been extensively used for 4–6 h a day. Industrial use has been for at least 6–8 h a day. The larger systems have crossed over 4000 h of operation and have needed the refurbishment of the inner bricks and secondary air nozzles.

4.4.1 An Important Application

One interesting and important application of the combustion system is the handling of diapers and sanitary pads. This problem does not appear to have been handled with the due care even though publicly accessible information indicates that the magnitude is humungous. The general suggestion that thermal treatment is the most appropriate comes through the regulations of the central pollution control board, CPCB: https://cpcb.nic.in/uploads/plasticwaste/Final_Sanitary_Waste_Guidelines_15.05.2018.pdf

Having assessed the current status of the technology, the 3–6 kg/h VEBCOD system was considered for application to ensure clean combustion of the sanitary pads and diapers. Figure 14 shows the details of the system. The approach for burning the sanitary pads and wet diapers is set out in the schematic of Fig. 14A. The 3.5–6 kg/h system when operated at 6 kg/h biomass can burn 30–40 sanitary pads or 10–15 baby diapers with a cycle time of 15–20 min. The combustion zone into which the sanitary pads/diapers are placed is shown in Fig. 14B and the system being readied for emission measurements is shown in Fig. 14C.

The sanitary pad/diaper loading is based on an open metal basket with intermediate separators. Once the combustion system has stabilized to high combustion rate with hot gas temperatures of ~ 1000 °C that comes about in about 10 min from the start, the metal basket containing 25–30 diapers/sanitary pads is introduced into the system. To test the performance of the system, 35 sanitary pads with 5 g dry mass and ~ 26 g wet mass was introduced into the system 6 min from start as shown in Fig. 15. The temperature data of the hot gases from the combustion system operating at 6 kg/h firewood, the temperature at the

Table 3: Measured emissions on wet diapers.

		Concentration		
No	Species	**Measured**	**Limit**	Unit
1	O_2	9.9%		(v)
2	CO_2	5.5%		(v)
3	CO	53.5	100	mg/ Nm^3
4	SO_2	163	200	mg/ Nm^3
5	NO_2	345	400	mg/ Nm^3
6	Particulate Matter	9.2	50	mg/ Nm^3
7	CH4	32.6		mg/ Nm^3
8	C_2H_4, C_2H_6, C_3H_8, C_2H_2, C_4H_{10} n, iso; C_5H_{12}, n, iso; C_6H_{14}, C_7H_{16}	BDL—0.1%		(v)

All concentrations were measured as per IS 13270:1992 standard except for CO as per EPA 10:1999 method, SO_2 as per IS: 11255 (Part-2):1985, NO_2 as per EPA 7E:2005, PM as per IS: 11255 (Part-2):1985; subscript n, iso = normal and iso chemical structure; limit refers to the IS standards

BDL below detection limit

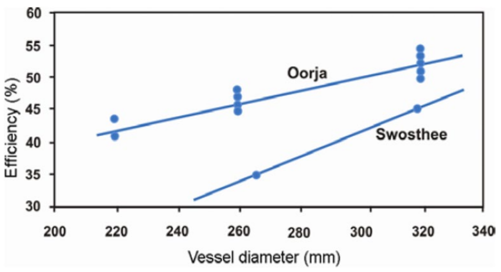

Figure 16: Water boiling efficiencies of free convection and forced convection systems with the vessel size.

grate and the exhaust at the top region. The gas temperatures around 900 °C and the temperatures at the grate upwards of 600 °C even up to 1000 °C. The measurements made by a third party in a field location with used sanitary pads are set out in Table 3. The results show that the emissions follow CPCB norms. Laboratory studies have confirmed that emissions follow CPCB norms even for diapers.

The designs of HC^3D and VEBCOD and variants (one of these is a self-feeding arrangement with 50 degrees slope described in[12]) have been deployed by partners in various locations and applications and many of them are described in[12]. Wider use of these technologies is dependent on market penetration being addressed by partners.

4.5 *Efficiency of and Emissions from Combustion Systems*

There have been discussions of the emissions and efficiency of this class of combustion systems in free convection-based systems (SWOSTHEE) in[6] and in forced convection systems in[7,11,12] for batch and continuous biomass-based combustion systems for domestic and industrial use. Figure 16 drawn from[7] shows the dependence of the water boiling efficiency with vessel size with water being taken to boiling conditions. It is clear that increased vessel size allows greater extraction of heat from the combustion system. It can be noted that the water boiling efficiency from 30 to 42% with vessel size increase from 240 to 320 mm even with free convection systems and from 42 to 50% with Oorja (REDS system) with vessel size increase from 220 to 320 mm. The efficiency is increasing because the heat transfer area is increased and greater amount of heat is extracted. Thus, it is nobody's benefit to promote smaller sized vessel as a standard for evaluating the water boiling efficiency. Defining the vessel size as in standards (like the BIS standard) for the water boiling test does not provide motivation to allow higher combustion efficiency to be explicitly brought out.

The issue arises because the utilization efficiency is the combined effect of combustion efficiency and heat transfer efficiency. If one were to look at combustion devices in gas turbine engines for instance, while combustion efficiency is still retained as one criterion for performance, a more appropriate one that affects the performance of the system is the temperature distribution at the exit of the combustor. This indicates to the possibility of separating the combustion efficiency from heat transfer efficiency. If one were to determine the temperature vs time in a zone where the flat bottom vessel will be located at one or several locations across the combustor, one can obtain a very good estimate of the combustion efficiency. What is more, even LPG efficiency measuring equipment provide data on combustion efficiency in addition to results of water boiling efficiency and hence, there is good reason to separate the two.

One interesting way to deal with the problem is to ensure evaluation of the *water boiling efficiency as a function of flat-bottomed vessel size*, perhaps at three vessel sizes, one at the nominal value and two/three meaningful larger sizes so that the asymptotic value of the efficiency of the system is obtained. *Any differences in the asymptotic value of the water boiling efficiency* between different designs will be reflective of the role of combustion efficiency, though indirectly.

While refs.[7,11,12] provide details of emissions, briefly stated, these are as follows: CO, particulate emissions and CO/CO_2 ratio from REDS class combustion system are about 1 g/MJ, 6 mg/MJ and 0.01 respectively. In the case of HC^3D system, these values are 0.6 g/MJ, 1 mg/MJ and 0.006 respectively. The PM2.5 data considered important over the last decade was recorded in the laboratory environment before, during and after the water boiling experiment was performed. These showed values of 100–120 mg/m^3 before and after the experiment and 130–150 mg/m^3 during the operation showing that the combustion process caused an increment of about 30 mg/m^3 of PM2.5 emissions. Thus, it is unclear if the PM2.5 contribution of the stoves can be considered problematic health hazard in view of the background itself being large.

In view of the fact that cookstove operates in a dynamic environment, meaning, the flow of air all around due to the movement of people, the inhalation of CO is governed by the local elevation and position of the cook with regard to the position of the cookstove. Hence, measurements were made of CO using a hand-held device to measure CO at 0.5–0.75 m from the position of the stove and these measurements showed that CO averaged over an hour of the combustion system was about 25 ppm. *The National Institute for Occupational Safety and Health (NIOSH), USA has established a recommended exposure limit (REL) for carbon monoxide of 35 ppm as an 8-h average and 200 ppm as a ceiling,* The observed values meet these expectations.

5 Combustion System in Aid of Drying Fruits and Vegetables

Though the combustion technology has reached maturity, *its commercial outreach is still limited*. Therefore, much thinking went into the approaches that could enhance the contribution in a more significant way. This turned out to be the use of combustion technology in relationship to the drying of fruits and vegetables, an important segment of food industry. It is known that India has limited infrastructure of cold chain infrastructure coupled strongly to transportation of perishable goods on time (see[13]). The need for drying has become more relevant in urban centres where the small and moderate hotels and similar establishments prefer to procure fruits and vegetables on demand if possible so that their own storage space is not demanded and any possible wastage due to longer storage is eliminated. This is particularly true of onions, garlic, and tomato. Since the packaging of the dried material constituting 15 to 20% of the mass of fresh material is lot simpler, hospitality industry benefits from procuring them *on demand*. Many other items like cabbage, raw banana, carrot, okra, bitter gourd also belong to this category. Food industry demands on drying of fruits like banana, pineapple, apple, papaya to meet the demands of the modern society also are opportunities to take advantage of. While many drying technologies such as osmosis, freeze, vacuum, spouted bed, fluidized bed, ohmic, microwave or the combination have been suggested or pursued, they are very expensive and so, have limited value for wider use by small and medium level operations (100–500 kg batch driers).

Lokras[15] has tried the indirect heating system for drying indicating that the use of the system they have developed delivers the performance with 40–50% of the fuel in classical driers in vogue, there are no technical data on the performance of the system. Recently, Sachin[13] has studied the problem of drying many of the perishable items described above using several drying techniques, the technological aspects of drying, the quality of the dried product and compared the processes for their performance. The important inference from this study is that convective drying in a tray offers a reduced investment cost for producing the product

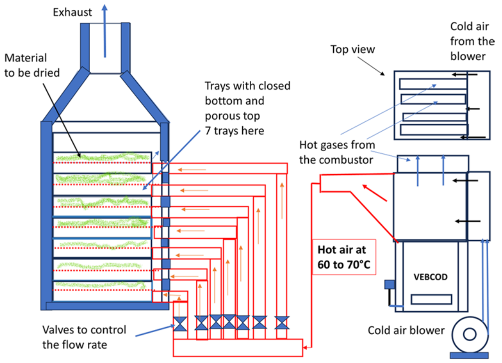

Figure 17: The schematic of a VEBCOD based high rate vegetable/fruit tray drier.

of high quality. To preserve the quality of the product, the maximum temperature to which the material must be subject to is 50–70 °C. In order to preserve the aroma, drying temperature should be in the lower range (50–55 °C) specially as in the case of cardamom. Many other products can be dried at temperatures between 60 and 65 °C. In all the food products, clear hot air is required for drying. Therefore, the heat from the combustion system should be used in a heat exchanger to draw clean air, raise it a temperature less than 70 °C and drive the air into the bottom of porous trays to enable the hot air to pass through the bed at a high enough convective velocity to allow faster moisture removal. The combustion system considered is the 3.5–6 kg/h VEBCOD system. The schematic of drier is set out in Fig. 17. The combustion gases can be mixed with 25 times the cold air to get air at a temperature of 60–70 °C. If the material to be dried is say, crumb rubber it is possible to mix the hot gases into the cold air directly. If what is intended to be dried is a food product, one needs to use a heat exchanger. The details of such an arrangement are shown in Fig. 17. Cold air from a blower passes laterally (horizontally) through a chamber that has channels through which the combustion gases pass from below to the top. Convective heat transfer takes place across the thin walls of the channels. The combustion system burn rate and the cold air flow rate are adjusted such that the hot air temperature is between 60 and 70 °C. This are passed through control valves into the tray drier. Each tray receives the same heat and hence the drying rate is nearly same in all the trays, typically 2–3 h. The hot air is designed to flow through a perforated SS sheet over which the material to be dried is placed. The moisture laden air goes out laterally into the chamber from which it goes out via the chimney. The number of trays shown here is 7. It can vary depending on the design that accounts for ease of operation. The system can be operated on a 24 × 7 basis to increase the productivity. Since the differential cost of drying is not high, one can expect high returns and there is motivation to operate it on a continuous basis (in batch mode). It is also possible to operate it to enable others to bring in material for drying at a certain price.

Its competitor namely, solar drier at medium scale is expensive and at small scale is good in some seasons, barely acceptable in a few other seasons and is quite poor in rainy seasons. This is because the drying time is so large—going up to 10–15 h that the product degradation over the drying period is a real problem. Systems using LPG are too expensive in terms of drying cost.

The results of drying tests in the early tests are set out in Table 2 for material with thickness of 2.5 mm. The moisture fraction of all the vegetables (f_w) is high ~ 0.85 or more excepting for banana (0.7). One of the important parameters is the loading flux = amount of food material loaded per unit area of the drier (drier area = 0.32 m^2). The drying flux which is the amount dried per unit time and area is directly related to the loading flux. The results show that loading an optimum quantity is critical to obtaining better performance from the drier. It was established early in the studies that reducing the size of the material is needed to improve the drying rate and it was finally arrived at that reduction to about 2.5 mm in the mean would be practical and necessary. The energy per unit feed stock is derived from the amount of biomass used and the calorific value taken as 16 MJ/kg (4.4 kWh/kg). This value becomes small with better loading density. The drying flux can be an important parameter for scaling the system. From the data in Table 4, 7–10 kg/m^2 would be loading density. The mean values from the table are that with a material size of about 2 mm or below, the drying rate is about 2 kg/h and the drying time of 4.5 h. The quality of the products so obtained have been analysed by the food technology department of the Jain university and found to meet the standards for dried food products.

Table 4: Results of the drying tests (Carrot1 = Chopped carrot, Biomass energy is taken as 16 MJ/kg), material size = 2.5 mm; $\mathbf{W_{in}}$ = Initial weight, $\boldsymbol{f_w}$ = moisture fraction, $\mathbf{W_f}$ = Final weight, $\mathbf{t_d}$ = Drying time; $\mathbf{r_d}$ = Drying rate.

Item	W_{in} kg	f_w	W_f kg	Yield	t_d h	r_d kg/h	Fuel used kg	Loading flux kg/m^2	Drying Flux kg/m^{2}h	Energy /feed kWh/kg
Onion	9.2	0.88	0.7	0.08	4.2	2.2	12.0	10.9	2.6	6
Potato	8.2	0.84	1.5	0.18	4.1	2.0	11.6	9.7	2.4	6
Bitter Gourd	9.1	0.93	0.7	0.08	4.1	2.2	12.6	10.8	2.6	6
Moringa Leaves	7.7	0.78	1.9	0.24	3.6	2.1	10.0	9.1	2.6	6
Raw banana	8.8	0.70	3.0	0.34	3.3	2.6	10.0	10.5	3.1	5
Carrot, chopped	8.4	0.92	0.7	0.09	4.0	2.1	12.0	10.0	2.5	6
Green chilly	5.7	0.80	1.3	0.23	4.1	1.4	10.2	6.8	1.7	8

6 Concluding remarks

This article is about novel combustion technologies developed largely over the last two decades using battery operated DC fans that have been tested in the field and have had limited commercial demonstration. Its basis is that even now a large part of rural India depends on biomass for large size cooking even when LPG is used for certain other situations. The considerations that demand the attention on science and technology of development are: efficiency, indoor emissions, emissions into the atmosphere, economics of both investment into the device and the cost of quality fuel.

There is definite progress on the understanding of the combustion process associated with batch and continuous operating systems at various power levels. The continuous combustion systems developed here are of pioneering nature and have no precedence.

The domestic systems are perhaps the most involved because of smallness of the power level and associated difficulty in achieving low emission, high efficiency while simultaneously making the stove *look aesthetically good* and *affordable*. The availability of small size efficient blowers at reasonable cost has made the development possible. Technologically, the availability of small size blowers at affordable costs even more than currently available (commercially) would make significant impact on the production of cost-effective domestic combustion systems. A total of 150 domestic biomass combustion systems and 30 larger systems for cooking and other applications, largely VEBCOD, and several based on HC^{3}D have been functional in the last two years.

The procedure to qualify stoves manufactured by industries is based on BIS/ISO standard. The crucial aspects of separating the overall efficiency into combustion efficiency and heat transfer efficiency are discussed. One simple approach to extract the information on combustion efficiency is to allow the conduct of water boiling tests with a number of flat-bottomed vessels with increasing diameter and *examining the maximum efficiency from them*.

Opportunity exists for producing quality biomass fuels and also deploying a range of combustion devices discussed here both for domestic applications as well as industrial needs. If the Governments consider providing support to the deprived and less privileged group to have start-ups that can acquire the combustion devices in significant numbers, the cost per system can come down and providing support for mainstreaming solid bio-fuels for domestic cooking applications will aid in enhancing the use of these fuels in modern combustion systems.

Dried, sized or chipped biomass is a cheaper alternative compared to pellets. Communities can afford to buy these at prices that are regulated, even if not subsidised. Forced convection based continuous combustion systems that perform on emissions better than efficiency are crucial to the new World. Of course, higher efficiencies are important, but reduced emissions far more important. This, it can be understood will reduce the magnitude of the use of biomass itself due to higher efficiency and replace correspondingly the fossil fuels. These will contribute positively to overcoming climate change problems and also improve the rural health quality.

Drying vegetables and fruits to the required quality with high productivity is made possible through the use of biomass combustion systems along with heat exchanger to get clean dry air at the requisite temperature to dry green items. This technology package that works at 100 kg/day and beyond can be an important aid in reducing the wastes of perishables in the country. The capability and availability of this technology even at low throughputs is of considerable interest to small farmers/producers as well.

Arrangements where a company owns the devices, maintains them through a network and is compensated by the families themselves through a support system for the deprived class, where needed would be useful. It is important that Governments and donor funding agencies concentrate on these aspects to create a self-sustainable cooking and drying solutions for India and the World.

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Declarations

Conflict of interest

There is no financial or other interests with any institution and hence no conflict of interest on the subject of this manuscript.

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References

1. Mukunda HS (2011) Understanding clean energy and fuels from biomass. Wiley, Chennai
2. ABETS, Biomass to Energy: The Science and Technology of the IISc Bio-energy Systems Combustion Gasification and Propulsion Laboratory, Dept of Aerospace Engineering, Indian Institute of Science (2003). https://books.google.ae/books/about/Biomass_to_Energy.html?id=X0c7NQAACAAJ&redir_esc=y
3. Sharan H, Mukunda HS, Shrinivasa U, Dasappa S, Paul PJ, Rajan NKS (1997) IISc-DASAG biomass gasifiers: development, technology, experience and economics, developments in thermo-chemical biomass conversion. Blackie Academic and Professional Publications, London, pp 1045–1057
4. Dasappa S, Paul PJ, Mukunda HS, Rajan NKS, Sridhar G, Sridhar HV (2004) Biomass gasification technology, a route to meet energy needs. Curr Sci 87:908–916
5. Rao S, Dahal S, Hadingham S, Kumar P (2020) Dissemination challenges of liquefied petroleum gas in rural India: perspectives from the field. Sustainability 12:2327. https://doi.org/10.3390/su12062327
6. Mukunda HS, Shrinivasa U, Dasappa S (1988) Portable single-pan wood stoves for high efficiency. Sadhana 13:237–270
7. Mukunda HS, Dasappa S, Paul PJ, Rajan NKS, Mahesh Y, Ravikumar D, Mukund D (2010) Gasifier stoves—science, technology and field outreach. Curr Sci 98(5):627–638
8. Varunkumar S, Rajan NKS, Mukunda HS (2011) Experimental and computational studies on a gasifier-based stove. Energy Convers Manag 53:135–141
9. Varunkumar S, Rajan NKS, Mukunda HS (2013) Universal flame propagation behaviour in packed bed of biomass. Combust Sci Technol 185:1241–1260
10. Mukunda HS, Payyanad S, Shivakumar A (2024) Challenges in pilot scale biochar production, to appear as Chapter 2 in Biochar and remediation. In: Nidheesh PV (ed) Taylor and Francis
11. Mukunda HS, Attanoor S (2018) New pathways in clean combustion of biomass and coal via partial gasification. In: De S et al (eds) Coal and Biomass Gasification, Energy, Environment,and Sustainability, Springer Nature. pp 455–472. https://doi.org/10.1007/978-981-10-7335-9_18
12. Mukunda HS (2022) Progress in biomass combustion and applications. Adv Energy Res 37(6):113–213
13. Payyanad S Application of biomass combustion systems in the dehydration of horticulture products, Ph.D. Thesis, FCRC, Jain (deemed-to-be-university), Bangalore

14. Mukunda HS (2015) Indian patent Sized multi-fuel horizontal clean continuous combustion device (SM-HCCD)
15. Lokras SS (2011) Development and dissemination of fuel-efficient biomass burning devices. J Indian Institute of Science 92:99–110; see also Jagadish KS The development and dissemination of efficient domestic cook stoves and other devices in Karnataka, Current Science, v. 87, 926 – 931, (2004) and Megha prakash, https://connect.iisc.ac.in/2017/10/it-took-many-years-to-develop-these-technologiesbut-today-they-are-helping-society/
16. Barnes DF, Kumar P, Openshaw K (2012) Cleaner hearths, better Homes, New stoves for India and the developing world. Oxford University Press, Oxford
17. Smith KR (1994) Health, energy and green house impacts due to biomass combustion in household stoves. Energy Sustain Dev 1:23–29
18. Lehmann J (2007) Bio-energy in the black. Front Ecol Environ 5(7):381–387

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