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LITERATURE-BASED DESIGN OF A CLEAN BIOMASS COOKSTOVE FOR MULTIFUNCTIONAL RURAL AND INDUSTRIAL APPLICATIONS

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ABSTRACT
In India rural regions are still dependent heavily on traditional biomass cookstove which lead to significant issues like incomplete fuel utilization which lead to inefficient combustion indoor air pollutions and various health problems. Despite of Continuous efforts by various agencies and government policies, many improved biomasses stove still suffer from limited adaptability, single functionality, and poor real-world performances. This study presents a literature driven approach to design and optimize a multipurpose conceptual stove that integrates with the multiple pot cooking, baking (oven), water heating and thermoelectric power generation within a single compact system. Drawing upon an extensive review of academic and policy literature, the study identifies critical gaps in existing models and utilizes the proven design strategies to develop complete user centric cooking solutions for off grid rural communities. As a part of the conceptualization process, a comprehensive 3D CAD model was prepared using Ansys Space claim 2024 R1. The Model Clearly depicts the key functional Zone involving primary combustion chamber, an integrated baking oven and flue gas driven water heater. A forced and natural draft hybrid system, supported by thermoelectric generator (TEG) integrations of sensors for IOT based monitoring and control to ensure maintaining constant efficiency in real life environment.
The proposed stove offers a promising pathway toward scalable, low-cost advanced clean cooking technologies aligned with sustainable development goals (SDGs). This work serves as a model for deploying literature-based design innovations to support rural energy requirements and reduce indoor air pollution and promote sustainable fuel practices.

Keywords:
Biomass stove, Clean cooking, Thermo Electric Generator (TEG), multifunctional stove, Waste heat recovery, Rural energy access.

I. Introduction
The global energy demands are increasing day by day and its landscape is in transition with increasing attention towards clean and decentralized solutions to fulfil the demand of under resourced population[1–3]. In India, a major portion of rural areas are directly dependent upon traditional biomass fuels such as wood, crop residues and dung for cooking and heating[4–6]. Local availability and familiarity of such fuels lead it to use in inefficient stoves[5,7,8] that emits high level of carbon monoxide, black carbon, and fine particulate matter (PM 2.5) [9–12], Contributing to deformations and adverse health outcomes particularly among women and children[13–16].

II. Literature Review and Design Basis
The evolutions of biomass have been extensively studied and documented, its transitioning from open fire, three stone to modern improved cookstoves[6,30,36]. The Traditional Cookstoves used in India are shown in **Error! Reference source not found.**

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Figure 1 Traditional cookstoves used in rural India

Cooking and Heating using biomass fuel like wood, crops residue and dung are early ages practice [6]. Traditional stoves are inefficient and produce high levels of smoke and pollutants [37], leading to health risks and environmental damage [38]. To mitigate these issues Improved Stove are introduced which is shown in Figure 2.

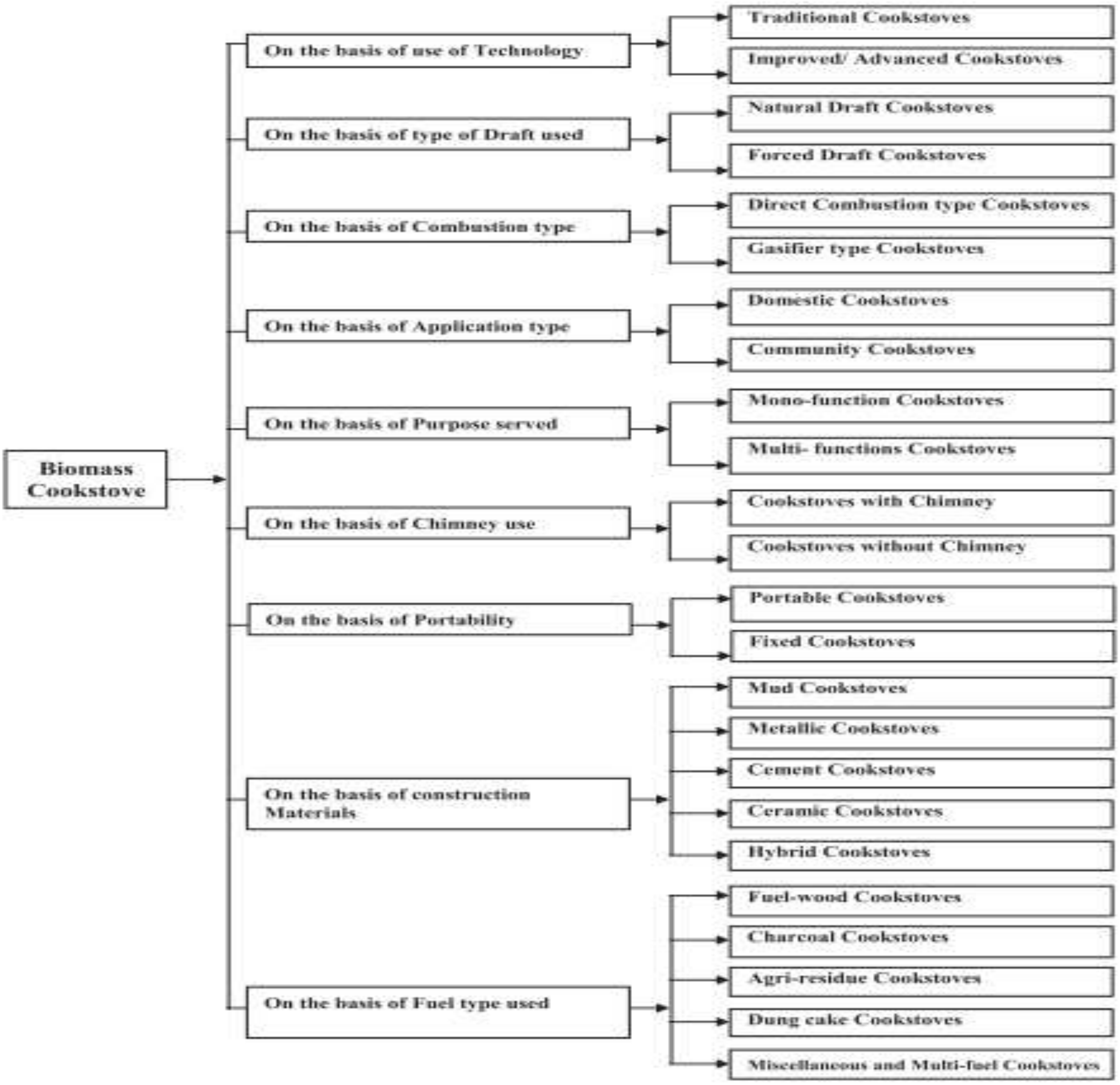

Figure 1 Classification of Biomass Cookstoves by Kshirsagar et al.[18]

Biomass stoves are classified by Kshirsagar et al [18] as shown in Figure 1.

All Initials design were focused on combustion efficiency [39] and pollutants reductions [40], with more recent models are now integrating the thermoelectric generators (TEGs) [8, 27, 41–45], waste heat recovery systems and hybrid air draft configuration [46–50]. Many researches emphasized the environmental burden of biomass combustion and identify household stoves as major contributor to the black carbon emissions in India [10], [11, 20, 51–55]. Some studies link traditional stoves to health risk including respiratory illness and cardiovascular diseases and other mental effects to the people who are exposed to it [14-17].Some researchers used to optimized the air fuel ratio [56] and positioning of the air inlet.

Figure 2 Improved Biomass Stoves image from Jetter et.al [57]

Some important study done in understanding the air flow distribution in the biomass stove ratio of 4:6 for the primary and secondary air inlet get lowest CO and PM 2.5 emission and Higher efficiency as suggested by the Deng et al and Himanshu et al[62,63]. Meanwhile M. Holubčík et al find that for Wood stove (primary /secondary /tertiary) air distribution ratio 25/50/25 or 0/100/0, Emphasis on secondary air reduces emissions; all three air types important for complete combustion [64]. The use of a Hybrid draft biomass cookstoves (HDBC), which combine natural and forced draft for air supply, consistently achieve significant reductions in CO and PM2.5 emissions, often reaching Tier 4 or higher emission standards, outperforming standard natural draft stoves these are findings by Suraj S Ghiwe et al. and Kshirsagar et al. [46-48, 65–68]. Some study focus on findings the heat recovery TEG + Water Heater Heat Exchanger recovers up to > 80% finding by Sakdanuphab et al. [44, 36, 44, 61, 27]. Medina et al. [69] finds Improved Combustion Efficiency using the plancha Modified combustion efficiencies (MCE) are higher in plancha stoves (97–98%) than in traditional open fires (93–95%), indicating more complete fuel burning and fewer harmful emissions. Plancha stoves provide more consistent heat distribution and allow for multi-pot and sequential cooking, which can save 35–44% in fuelwood and further reduce emissions when cooking tasks are integrated. Heleria et al. [70]. Faisal et al. [71,72] studies using both experimental and computational methods found that chimney height significantly affects stove performance. For double-pot stoves, a height of 1.65 meters yielded the highest pot temperatures and thermal efficiency (up to 37.66%).

Advance modelling tools like CFD are now are used in stove design allowing engineers to simulate combustion and understand various fields like heat transfer rate, fluid flow etc. [58, 59, 60]. Literature reviews show a strong consensus around the need for multifunctionality, with integrated features such as baking ovens, water heaters and charging ports gaining attentions. However, gaps remained in implementing all these features in a single unit also implementing heat distributions, durable material and smart sensors integrations. This study addresses these gaps by synthesizing established design strategies into a unified stove model.

III. Problem Statement

Most of the available improved biomass stove in India suffer from a lack of multifunctionality and poor fuel adaptability [17, 6, 18–23]. Existing designs often prioritize the laboratory and technical efficiency only instead of user experience which results in low adoption rates [21, 24, 25–30,8,17, 21, 26, 28,31–33,34,35].

Key Issues with Traditional Biomass Stoves:

Incomplete Combustion: Leads to higher emissions of pollutants like CO, PM2.5, and unburnt hydrocarbons.

Unutilized Excess Heat: Significant amount of generated heat escapes unused, reducing overall thermal efficiency.

Blackening of Utensils: Due to soot formation from inefficient burning, affecting hygiene and user satisfaction.

Single Pot Usage: Limited to only one cooking task at a time, reducing productivity for households with multiple cooking needs.

Lack of Integrated Features: Absence of useful add-ons like, Oven (for baking), Water heater (for sanitation/cooking), Electricity generation (for lighting/charging).

IV. Objectives and Scope

This study aims to design a conceptual advance multipurpose biomass stove based on best practices and findings from existing literature. The proposed stove integrates.

- A heat recovery oven
- Water heating compartment
- Hybrid (natural and forced draft) air inlet
- TEG for forced draft operations and small appliances charging
- IOT enabled sensors for future real time monitoring applications.

The scope includes CAD model development of conceptual design, Parametric optimization based on the literature review, with a focus on practical, Rural implementation which will serve as a complete cooking solution in typical Indian rural family.

V. Proposed Stove Design and Functionality

The final conceptual design integrates several components derived from the literature available, a rectangular combustion chamber, internal baking oven, hot water jacket with chimney, cooking surface and thermoelectric generator integration. The combustion chamber uses a dual zone airflow design for enhanced oxygen supply. Secondary forced air inlets improve volatile combustion and reduced smoke [19, 25, 46, 47, 54, 57–59,60].

The oven is embedded parallel to the combustion chamber and harnessing heat from the excessive heat generated during combustion and from the top surface flue gases through conduction and thermal radiation. A water heating cylindrical tank is located concentric at the chimney for capturing residual heat from the flue gases. The chimney is vertically aligned to facilitate the natural draft which is also supplemented by the TEG driven fan. A CAD modelled in Ansys Spaceclaim 2024 R1 ensured accurate representation, while exploded views helped map individual subcomponents for the potential fabrication.

5.1 Conceptual design CAD model and parts explanations

A CAD model was prepared using Ansys Spaceclaim 2024 R1 to visualize the conceptual model for better understanding an exploded view is shown in Figure 3, the primary target of this conceptual model was user centric, multi-fuel, multifunctional, and portable design it clearly depicts each subpart their explanation are as follows-

Cooking surface – It will provide area to keep multiple pots over it for cooking simultaneously multiple dishes at a time it is also removable for cleaning and direct open fire cooking purposes.

Chimney with water heater- allow user to get heated water for other applications and reduce indoor air pollution by attaching a long chimney to outdoor.
Fuel feed door and ash tray- It allows user continuous operation of the stove. Fuel feed area has shrouded parts to prevent flames reaching the user hands while feeding fuel.
Converging sheet and forced secondary Air inlet- Converging sheet act as directional guide for the intermediate natural draft air to the mid of the combustion chamber and Secondary forced air inlet provide excess oxygen for effective heat distribution and volatile fuel burning.

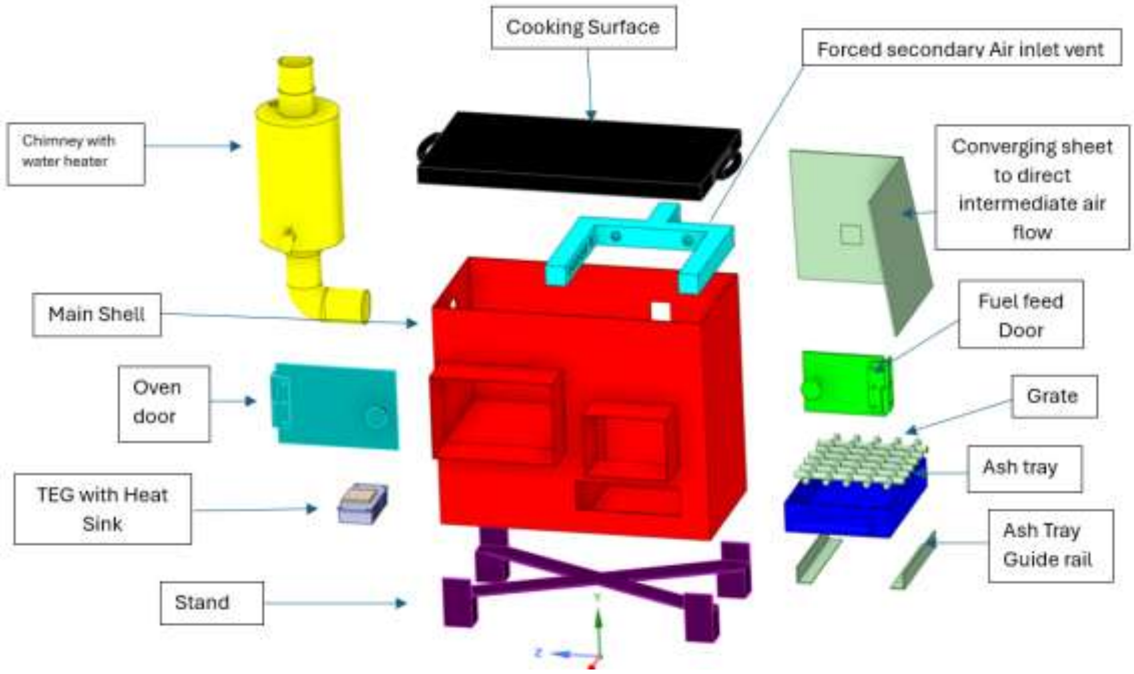

Figure 3 Exploded view of conceptual advance multipurpose biomass stove

Grate – Where fuel will be placed and combustion take place.
Ash tray guide rail- It keeps ash tray in its position's ash tray is little elongated toward front to allow under grate air for combustion to start up and maintain a good fire power.
Oven – It will allow users to cook traditional tandoori roti (Bread), and Insulated oven door prevent heat loss.
Main shell- It is an outer cover and a combustion chamber, and an oven is embedded inside it. Rectangular combustion chamber geometry allows to feed multiple kind of irregular fuel shape by providing more straight space. The shell has extra space below the oven where IOT devices can be fixed after proper insulations setup.
TEG with Heat sink- It will allow users to generate electricity for forced draft air inlet, to power IOT devices and charging small appliances like led bulbs, torch, and mobile phones during off grid.
Stand – Provide rigid base for holding the heavy utensils placed over the stove and provide the seating area to the main stove.

5.2 Design justification and Literature

Mapping Each design element has been validated through previously available literature. The complete detail is shown in Table 1.

Table 1 Literatures findings and Optimize version implementation

Features	Literature Findings	Design Optimization
Material Stainless steel	Stainless steel has high efficiency, lower emissions, resist corrosion and excellent durability and high heat retention capacity [48, 46, 76]	The material for the Combustion chamber uses Stainless steel with high heat-resistant coating.

Material Aluminium	Retain less heat cool down quickly, and very effective to transfer heat to TEG [43, 77]	Used to make the outer shell of the Combustion Chamber and at a small part below oven to place the TEG
Chamber Geometry	Rectangular Geometry share heat faster than the cylindrical or hexagonal shape [78] , reduces the dead spot zone or additional unutilized volume in combustion, Simple Fabrication and ultimately low cost.	It completely aligns with the Oven sharing maximum heat it with which are not utilized or otherwise go waste and increase overall compactness and rigidity of the stove.
Chimney	Reduces indoor air pollutions [79, 25, 80] and increase overall efficiency [81- 82] , faster cooking [83] and 1.65m height has excellent draft. Cooled Chimney exhaust reduces the particulate matter emissions as most of the matter stick in the chimney[74,84]	A smart move is done providing a splitable chimney half lower part is integrated with water heater to extract waste heat which cools the exhaust and other longer part can be attached according to need (Effects portability and allow to clean)
Cooking Surface	Reduce emissions up to 96% [85], improved baffles surface improve efficiency, may extend time for cooking but overall more benefits [86,87, 88]	An elongated cooking surface used to support multi pot cooking with removable features allowing users to use open flame when needed, but it prevents blackening of utensils and has many benefits
Air Inlets	Natural draft relies on chimney, Intermediate air inlet improve efficiency providing effective oxygen for burning, under grate air increases fire power and reduces cooking time and hybrid draft reduces emissions and increases efficiency achieving Tier 4 [73,47, 50, 56].	Under grate air inlet is provided using oversize ash tray, intermediate natural draft air inlet provides which will increase oxygen supply for effective combustion and below the cooking surface a forced draft TEG driven inlet provide which will reduce emission and ensure complete burning of volatiles and distribute heat to cooking surface and to the oven from top.
TEG (Thermoelectric generator)	Currently TEGs are less efficient but using multiple (2.5 -6 watt per module) enough for charging led bulbs, Fans and mobile phones, it recovers significant amount of heat wasted though walls.[27, 44, 8, 41, 27]	TEG integrated with a heat sink is placed just below Oven to extract excess heat from the oven bottom wall.

IOT (Internet of Things)	Realtime emission monitoring, automations for the air control and overall increase efficiency [31, 89]	Suggesting developing an application to control, monitor and check efficiency of the devices
Oven	Less or No Literatures are available	Traditionally it was used in some mud or fixed stove, implementing the same idea for the metallic compact stove ensuring the portability, thermal efficiency and complete heat utilization.

5.3 Broader Impacts and Sustainability Relevance

The conceptual stove directly addresses the SDG 3 (Good Health) by minimizing the emissions and indoor air pollutions which reduces women and children to the exposures to carbon monoxide and particulates. SDG 7 (Affordable and Clean Energy) is supported through self-sustained TEG powered fan operations and multifuel compatibility, while SDG 13 (Climate Action) is met because of reduced biomass consumptions and emissions.

Ultimately the stove multifunctionality leads to reduces the number of devices in a household needs, promoting efficiency and affordability. Along with it by accommodating agriculture residues and wood pellets, the system promotes circular local bio economy practices. The addition of sensors- ready slots enables potential real time monitoring and adaptive air flow control in future improvements work.

V Conclusions and Future Work

This study presents a comprehensive literature-based framework for need of designing a multipurpose biomass stove that fulfils real world rural energy needs. The model developed in CAD incorporates cooking, baking, water heating, and energy generation in a single unit, optimizing combustion and heat recovery.

Future work will focus on CFD simulations, physical prototyping, emissions testing, and optimizing the design by enhancing air inlets, TEG positions, understanding fuel compatibility, long term studies on durability and socio-economic adoption factors are recommended to ensure successful scaling and deployment in target communities.

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