International Journal of Basic and Applied Sciences, 14 (SI-2) (2025) 1-11

International Journal of Basic and Applied Sciences

Website: www.sciencepubco.com/index.php/IJBAS
https://doi.org/10.14419/skjrhx24
Research paper

Design and Performance Analysis of A Biomass Pyro-Chulha for Clean Cooking and Biochar Production

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Received: May 30, 2025, Accepted: July 3, 2025, Published: July 18, 2025

Abstract

The traditional practice of open burning of agricultural waste along with the use of traditional cooking stoves in many rural areas of India have contributed to several environmental problems such as the emission of greenhouse gases, air pollution, and soil degradation. In this study, we present the design and simulation-based analysis of a dual function cookstove – the Pyro-Chulha which integrates clean cooking and biochar production through pyrolysis.
The design of the stove incorporates a lower combustion chamber and an upper pyrolysis chamber both of which are naturally draft driven and thermally insulated. A producer gas reinjection system is used to enhance the volatile gas pyrolysis combustion. Combustion enhancement reduces emissions and increases efficiency. The design was evaluated using thermodynamic calculations and computational fluid dynamics (CFD) to evaluate heat transfer, gas flow, and temperature distribution within the device.
Results from the simulation showed that the traditional cookstove emissions of particulate matter and carbon emissions were significantly surpassed with a lower emission of 150 µg/m³ and 50 ppm, alongside a combustion efficiency of 90% and heat transfer efficiency of 85%. Due to passive heat transfer and the insulation present in the pyrolysis chamber, an estimation of 600-650 K is reached. This enables production of around 0.2 kg/hr of biochar which is ideal for soil enhancement due to its ~70% carbon content.
The Pyro-Chulha provides an integrated approach to tackling the issues of clean cooking, the utilization of waste biomass, and sustainable soil management. It does so in a scalable and climate-resilient manner, without incurring significant costs. This paper suggests deployment into the field as well as long-term studies to ascertain real-world performance and agronomic impact in rural settings.

Keywords: *Biomass, Pyrolysis, Pyro-Chulha, Biochar, Clean Cooking, Soil Health, CFD Simulation, Emission Reduction, Sustainable Agriculture, Renewable Energy.*

1. Introduction

1.1 Background on Rural Energy Issues in India

In many rural parts of India, almost 70% of people still cook using traditional biomass-based stoves like chulhas, which greatly increases the amount of indoor pollution and deforestation [3]. These conventional cooking techniques are ineffective, using a lot of biomasses for little energy production, which poses health. and ecological risks, particularly to women and children who are most exposed to toxic emissions [4]. Alternatively using agricultural waste as a resource, excessive combustion of them releases carbon dioxide and particulates into the atmosphere, worsening air pollution and accelerating global warming [5].

1.2 Problem of Biomass Burning and Chemical Degradation of Soil

On the other hand, farmers frequently burn biomass wastes in the open, which depletes nutrients, degrades soil, and outcomes in the loss of precious organic carbon. In many areas, the widespread use of chemical pesticides and fertilisers has led to a continuous deterioration in soil health, increased desertification, and decreased agricultural output [1]. Furthermore, crop leftovers are frequently thrown away or burned outdoors rather than being used to replenish soil, which further depletes nutrients and pollutes the environment [2]. As a result, the rural Indian agricultural sector is dealing with two crises: the rapid deterioration of soil health and the inefficiency of using biomass for cooking.

1.3 Role of Pyrolysis and Biochar in Sustainable Rural Development

Biomass pyrolysis is the technique in which waste generated from biomass can be converted into the useful biochar, which refers to the heat breakdown of organic matter in an oxygen-limited environment. Biochar makes soils richer in organic carbon, helps soils maintain more water and cuts back on how much chemical fertilizer is required, according to research by Lehmann and Joseph [1]. Research has proven that biochar helps carbon out of the atmosphere, making it most useful in the effort to fight against the global warming [8]. In addition, biochar helps to improve the soil structure, which keeps nutrients in place and helps crops grow in areas experiencing soil damage [2]. The pyrolysis and cooking stove integration are beneficial solutions to the rural energy problems and soil fertility challenges.

1.4 Aim and Significance of Developing a Dual-Purpose pyrolytic cookstove.

The main aim of our study is to conceptual design and evaluate the Pyro-Chulha, a two-in-one biomass burner that produces biochar for soil enrichment and offers a cleaner, more effective cooking alternative. The Pyro-Chulha is designed to efficiently use waste biomass, producing both improved biochar for soil fertility and energy for clean cooking. Both operations increase soil quality for farming which in turn supports sustainable agriculture. It eliminates dependence on inefficient single purpose and traditional polluting stoves. The creation of such a cookstove is essential considering that it provides a workable and expandable solution to the urgent problems. of soil degradation, energy inefficiency, and biomass burning in many rural parts of India [4] [5].

2. Literature Review

2.1 Studies on Biochar's Role in Soil Improvement

Biochar has been examined extensively as a useful additive to soils enrichment, with experts studying how it increases fertility and helps with water saving. By using pyrolysis to burn biomass in a limited oxygen atmosphere, biochar becomes vital for building good soil structure, as it increases organic carbon, helps the soil hold onto water and makes nutrients more available, says Lehmann and Joseph [1]. It has been shown in much research that the nutrient and moisture found in biochar make it possible to raise soil fertility, especially in places where essential nutrients are lacking in the soil and requires improvement in the structure of soil [2]. Biochar staying safe and useful in soil for many years, as it keeps carbon and cuts down greenhouse gases, is also very beneficial [1]. As biochar empowers bacteria, it could help improve both crops and the soil, as an alternative to dangerous chemical fertilizers.

2.2 Overview of Existing Biomass Cookstoves and Their ecological Impacts

These traditional cookstoves, used widely in many rural Indian kitchens and other poor areas, cause major harm both to nature and to people living there. Running a chulha takes a long time and produces a lot of dangerous emissions, mainly CO gas, PM, along with various other flame-borne poisonous gases [4]. Since women and children are typically in charge of cooking in rural communities, such stoves are contributing to air pollution in the home as well as abroad, which has serious health consequences. According to studies by Bhattacharya and Salam [3], these stoves are inefficient and squander a significant proportion of biomass as uncombusted fuel, which worsens degradation of the environment and rainforests. In accordance with Kumar and Chandrashekar, burning agricultural leftovers outside releases particulate matter into the atmosphere, which worsens air pollution and fuels climate change [5]. Rural residents keep encountering these problems despite efforts to advance cookstove technology, underscoring the need for improved hygiene and effective cooking methods.

2.3 Technological Gaps and Innovations in Pyrolysis-Based Stoves

there is still a big gap in the integration of pyrolysis into cooking technologies, despite the fact that several cookstove designs have been put forth to increase the effectiveness of cooking and lower emissions. Stoves that use pyrolysis, like the Pyro-Chulha, have the ability to generate charcoal as a byproduct and prepare food at the same time. However, there are a number of difficulties in effectively regulating two processes: pyrolysis for the creation of biochar and efficient combustion for cooking. Chandrashekar and Kumar, determine whether pyrolysis-based stoves require better heat transfer mechanisms, optimized combustion chamber design, or better airflow control [5]. To improve burning and reduce emissions, the producer gas produced during pyrolysis must also be effectively recycled. In order to enhance the yield of biochar while lowering the production of hazardous gases, recent advances have concentrated on increasing pyrolysis chamber's design and these stoves' thermal efficiency [6]. Despite these advancements, more study is required to get the most out of these technologies' adaptability and wider acceptance in rural regions.

2.4 Global and Indian Policy Context on Clean Cooking Technologies

Globally and in India, where the harmful health consequences of conventional cooking methods are a major problem, the need for switching to cleaner cooking technology has been acknowledged. Field engineers repeatedly observed that To lessen the negative health effects of pollution in the home, which outcomes in millions of preventable deaths per. year, the WHO (World Health Organisation) has advocated for the use of clean cooking solutions [4]. The Pradhan Mantri Ujjwala Yojana (PMUY) program in India was started to give rural people access to LPG connections. for clean cooking, there are still issues with pricing and accessibility, especially for isolated areas [7]. While biomass cookstoves that meet emission regulations have been marketed as a replacement to LPG, advance cookstove designs, like those that use pyrolysis, have not been widely adopted. While enhancements in cookstove designs have been made by the Indian government's National biomass Cookstove Programme and the Indian National Initiative for. Advanced biomass Cookstoves, there is still much space for innovation and the uptake of efficient, clean cooking technologies [7]. Therefore, policy frameworks in India and around the world highlight the need for cleaner, more sustainable cooking technologies, like the Pyro-Chulha, that can solve the interconnected problems of public health, ecological degradation, and energy inefficiency.

3. Motivation And Problem Statement

3.1 Energy Inefficiency and Air Pollution

In many rural parts of India, the use of conventional biomass cookstoves has led to serious energy waste and harm to the environment. Low thermal efficacy, which means that a lot of biomasses is used for little heat output, is a characteristic of these stoves, which are sometimes called chulhas [4]. In order to meet their culinary demands, households must burn more fuel, which creates a wasteful cycle that fuels excessive biomass use and deforestation. carbon monoxide gas (CO), particulate matter (PM), and other dangerous gases are produced when biomass is incompletely burned in these inefficient stoves [5]. According to [4]. these pollutants have a major effect on indoor air quality and can lead to a variety of illnesses, especially for women and children who are exposed to them for a prolonged amount of time when cooking. Traditional cooking methods are ineffective and hazardous for the environment and human health due to their fail to fully burn the fuel, wasting essential resources and exacerbating the pollution issue.

3.2 Soil Degradation and the Challenges with biomass Burning

soil degradation in India has been greatly aggravated by the open burning of biomass for the trashing of agricultural residues, in addition to issues with pollution and energy inefficiency. Essential nutrients and organic carbon are lost when agricultural leftovers are burned, even though they may be utilized as organic matter to enhance soil health [1].

3.3 Need for an Integrated, Sustainable, and Locally Manufacturable Solution

The persistent problems of soil erosion, contamination of the environment, and energy inefficiency highlight the critical need for. a home-made, environmentally friendly remedy that can deal with these interrelated problems In many rural parts of India. Field engineers repeatedly observed that Because of their intrinsic inefficiencies and negative effects on the environment, current technologies like conventional chulhas offer little room for development. An creative solution is needed to lessen the negative consequences of open biomass burning. This system should not only provide clean, effective cooking, but also repurposed biomass for the formation of biochar, which can improve the fertility of the soil. The Pyro-Chulha, a two-in-one burner that converts biomass to charcoal and generates energy for cooking, is the perfect answer. which somewhat the soil can be enriched using. By lowering harmful emissions, this technology might reduce deforestation, drastically lessen reliance on synthetic fertilisers, and enhance rural residents' health [5]. In order to be accessible to the larger rural community, such a cookstove must also be made to be inexpensive, simple to manufacture, and considered suitable for the local environment. The creation of this integrated system will give rural communities a sustainable way forward by addressing energy, ecological, and agricultural issues in a circular manner [7].

4. Objectives

The development and optimization of a dual-chamber biomass cookstove that tackles the major issues of soil degradation, ecological pollution, and energy inefficiency in many rural parts of India is the main objective of Our study. By using waste biomass for both cooking and the manufacture of biochar, the Pyro-Chulha burner seeks to provide a more effective and clean cooking alternative. By making the cookstove more effective and efficient with biomass, it improves design will reduce the amount of biomass we burn to achieve satisfactory heat. Better cooking efficiency saves energy from biomass which plays a key role in preventing deforestation and damaging the environment [4]. Producing biochar during regular daily cooking is an important goal in this study. The Pyro-Chulha is unique because it lets users convert agricultural leftovers into biochar, while cooking their food at the same time, each combustion and pyrolysis processes happening in a separate chamber as show in the fig 1, [1], argue that biochar contains a large amount of carbon and can be used to make soil more fertile, retain water and reduce the use of chemicals for fertilizer. The feature of the cookstove will help both the soil and the air by absorbing carbon and stopping soil damage in rural farming for years to come. The Pyro-Chulha is meant to reduce both air pollution inside and the dangers it can cause. Increased amounts of pollutants such as particulate matter (PM) and carbon monoxide gas (CO), are emitted by regular and limited-efficiency biomass cookstoves and harm people's health [4]. The Pyro-Chulha will lessen the negative effects of indoor air pollution by ensuring the complete combustion and integrating measures to minimize harmful emissions, due to the wood gases developing in the pyrolysis chamber having a retort passage to transfer it into the high-temperature flames coming from the combustion chamber, which causes the burning of pollutants and gets a clear and clean flame for the cooking, helping in enhancing the general health and well-being of rural homes.

5. Method

5.1 Design Description

Figure 1 outlines how Pyro-Chulha achieves strong results for cooking and biochar production at the same time. Proper function and efficiency of the cookstove are made possible by important technical components of the Pyrochulha. Because the chamber is well insulated, heat from the combustion section is kept to help pyrolysis and cook the food. It acts as a barrier outside the pyrolytic chamber, filtering out excess heat and helping maintain the internal temperature of the chamber for the pyrolysis of biomass. Following the combustion chamber, the biomass residues are placed in the pyrolysis chamber and heated in a low-oxygen and temperature-controlled area to form biochar. The chamber's small retort holes allow the gases produced from pyrolysis to transfer in the combustion chamber to reburn and reduce pollutants, which results in clean and clear flames for the cooking. To improve the efficiency of combustion, these gases are subsequently guided into the combustion chamber. In order to stabilize the cooking pots while maintaining ideal cooking temperatures by guaranteeing steady positioning above the fire, an instrument stand is incorporated into the design.

5.2 The volume of Combustion Chamber: 0.258×0.258×0.168 = 0.01118 m^3 = 11. 18 ltr.

To estimate the mass of biomass that can be held in this volume, we assume the use of wood chips, which are a common fuel with good combustion characteristics and an average bulk density of 240 kg/m³ [5].

$$m = \rho \times V = 240\ \mathrm{kg/m^3} \times 0.01118\ \mathrm{m^3} = 2.68\ \mathrm{kg} \quad (1)$$

The combustion chamber can hold approximately 2.68 kg of wood chips per batch.

Where:
m: mass of biomass.
ρ: Density of wood chips.
V: Volume of Combustion chamber.

5.3 The volume of Pyrolysis Chamber: = 0.494 × 0.494 × 0.250 ≈ 0.061 m³ = 61 ltr.

61.0 L volume is sufficient to load approximately 7.9 kg of cotton stalks (at ~130 kg/m³ bulk density), or ~10–12 kg of wood chips (at 180–240 kg/m³). This ensures flexibility in rural use where biomass type varies [9].
The pyrolysis chamber is enclosed concentrically within an outer shell, creating a jacket for insulation. Dimensions are as follows:
Inner chamber size: 494 mm × 494 mm × 250 mm = 0.494 m × 0.494 m × 0.250 m
Outer chamber size: 606 mm × 606 mm × 250 mm = 0.606 m × 0.606 m × 0.250 m
Insulation thickness: (606 – 494)/2 = 56 mm ≈ 50 mm on all sides

5.4 Selection of Insulation Material:

Based on rural availability, thermal properties, and temperature resistance, ceramic wool is selected:

Table 1: Properties of Insulation Material

Property	Value
Material	Ceramic Fiber Wool
Density (ρ)	~100–140 kg/m³
Thermal Conductivity (k)	0.14 W/m·K at 400–600 °C
Operating Temp Limit	1,200 °C
Thickness	50 mm

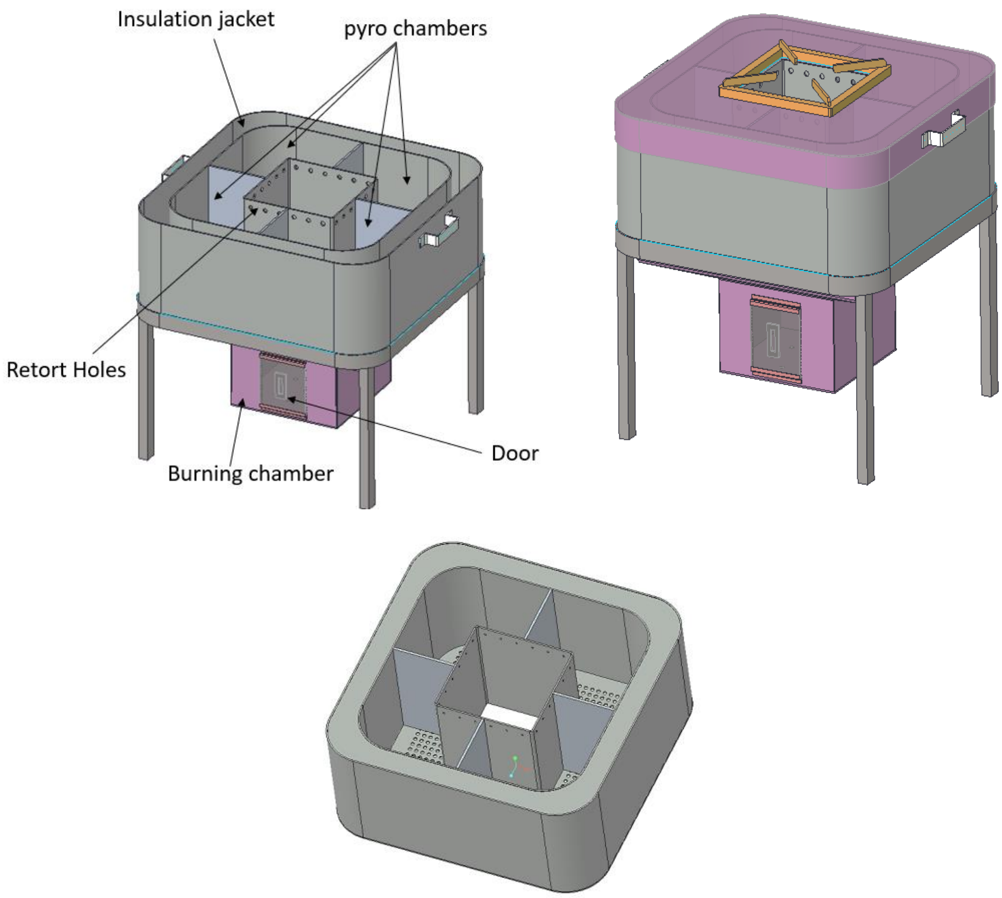

Fig. 1: Pyrochulha design.

5.5 Thermal Energy Generation:

Assuming the lower heating value (LHV) of wood chips is approximately 16 MJ/kg, the total energy available from the fuel in one batch is:

$$Q\ total = m \times LHV = 2.68\ kg \times 16\ MJ/kg = 42.88\ MJ \quad (2)$$

42.88 MJ is the total heat energy released during full combustion.

5.6 Combustion Power Output :

If this fuel is burned steadily over 1 hour (3600 seconds), the thermal power output becomes:

$$P_{thermal} = \frac{Q_{total}}{t} = \frac{42.88 \times 10^6\ J}{3600\ s} \quad (3)$$

$P_{thermal}$ = 11.91 kW

Assuming a realistic thermal efficiency of 30% for biomass cookstoves [10], the useful power transferred to the cooking surface and pyrolysis chamber is:

P_{useful} = 11.91 × 0.30 = 3.57 kW

5.7 Thermodynamic Analysis

In the study of design and performance analysis, the First Law of Thermodynamics is employed to analyse energy conservation and determine heat transfer efficiency from the combustion chamber to the cooking vessel and pyrolysis zone. Additionally, Fourier's law of heat conduction and Newton's law of cooling were applied to model heat flow through the cookstove's insulating layers and interfaces.

The goal of the thermodynamic analysis is to assess the cookstove's combustion performance and the effectiveness of heat transfer. The efficiency of heat transfer from the combustion chamber to the pyrolysis chamber and cooking surface will be examined using heat transfer modelling. Heat losses, distribution of temperatures, and the cookstove's overall thermal effectiveness will all be taken into account in this research. Because it has a direct effect on fuel consumption and pollutants, combustion efficiency is very significant. To evaluate the effects of rerouting gases from the decomposition chamber back into the procedure of combustion, which increases efficiency and lowers emissions, a producer gas reinjection system will be modelled. Optimizing cookstove's thermal performance while reducing its negative effects on the environment is the aim of this analysis.

Energy calculations began with the known capacity of the combustion chamber of Pyrochulha, which accommodates approximately 2.68 kg of wood chips per batch, derived from the chamber's fixed volume and the fuel's bulk density of wood chips as a burning fuel (240 kg/m³). Using an estimated lower heating value (LHV) of 16 MJ/kg which is calculated with the help of Bomb Calorimeter. the total theoretical energy release per batch was calculated at 42.88 MJ. Assuming an overall system efficiency of 30% as per the BIS 13152 Part 1 [2013], the efficiency of natural draft cookstoves should be greater than 25%; approximately 3.57 kW of useful power is theoretically transferred to cooking and pyrolysis functions. Fourier's law was applied to estimate heat conduction through the 50 mm ceramic wool insulation, using its typical thermal conductivity of 0.14 W/m·K. To assess convective losses from the stove's outer surfaces, Newton's law of cooling was used under natural convection assumptions. These estimates informed the insulation layer's minimum thickness and helped establish thermal boundaries for modelling. To support clean combustion, gases released during pyrolysis are recirculated via 24 small retort holes into the combustion chamber. Flow velocity through these holes was approximated using the orifice discharge equation, accounting for natural draft pressure gradients and gas density.

5.8 CFD Simulation

To enhance the internal heat transfer between the combustion and pyrolysis chambers as well as the flow patterns of the pyrolysis gas in the Pyro-Chulha, the computational fluid dynamics (CFD) simulations were conducted in ANSYS Fluent, a versatile software for multi-physics thermo-fluidic simulations. The aim of the investigation was to study and enhance temperature distribution, heat transfer, and gas flow within the dual-chamber system of the cookstove. The entire stove geometry, which was generated in Creo Parametric, was imported into ANSYS Workbench and meshed for the definition of the fluid domain, which included the combustion zone, pyrolysis chamber, and retort gas flow paths.

A pressure-based steady-state solver with k–ε turbulence model coupled with energy equation was chosen, while considering realistic heat distribution and turbulent drafts. Simplified combustion gases were modelled by species transport model and no-slip wall conditions were imposed to simulate natural convection driven airflow. Mesh refinement was applied at critical zones such as the retort ports and shaft walls to ensure accurate resolution of thermal and velocity gradients. The simulation contributed to the validation of the position of the retort holes, the size of the flame shaft and the insulation layout. These findings were very important towards enhancing the combustion efficiency and biochar yield of the Pyro-Chulha while keeping the emissions low and its thermal behavior stable.

5.9 Generation and Pre-processing of the geometry

The full 3D model of the stove was created in Creo Parametric 8.0 including the combustion chamber, pyrolysis chamber, retort holes, flame shaft, utensil platform, and outlet chimney as shown in the fig 1. The geometry was saved in IGES format and then imported to ANSYS Workbench. Geometry clean-up and modification was done in ANSYS Space Claim, in which solid body was checked and stitched for the purpose of sealing enclosure, as shown fig 2.

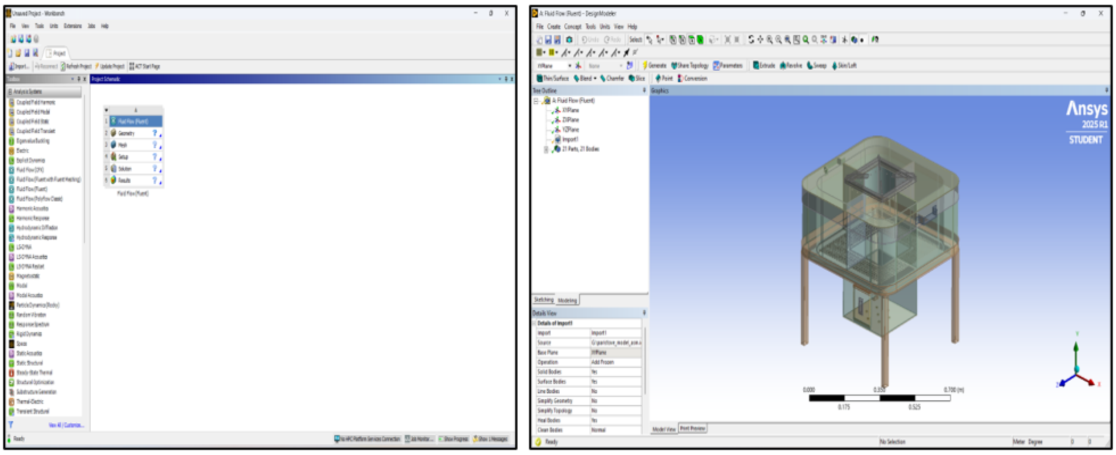

Fig. 2: Importing Geometry in Ansys And fluid Domain creation

A fluid domain was defined by encompassing the stove within a rectangular enclosure with the following clearances: ±100 mm in the X and Y directions +200 mm above −50 mm below. The solid volume of the stove was subtracted from the enclosure with Boolean subtraction to create the hollow fluid domain representing internal air and gas shown in fig 3

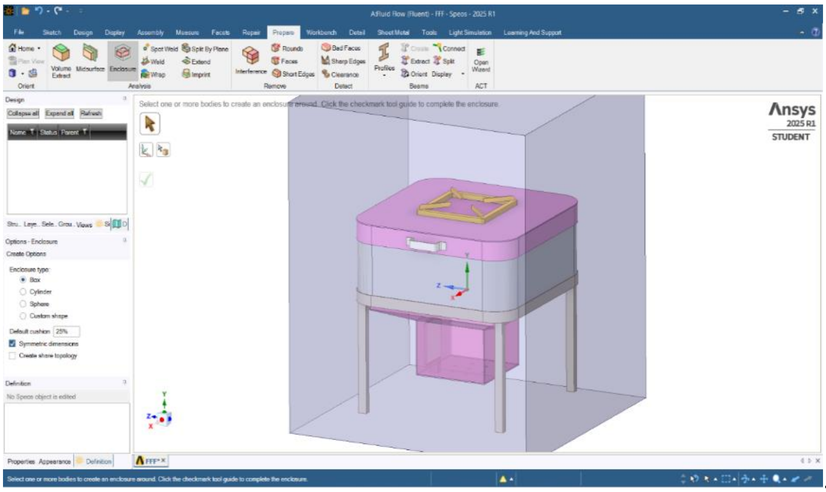

Fig. 3: Enclosure creation in space claim.

5.9.1 Meshing Strategy

An unstructured tetrahedral mesh was used to mesh the fluid domain. Global element sizes were set to 5–10 mm with local refinements around the retort holes and flame shaft. Solid walls had five inflation layers applied to them to address boundary layer effects. Mesh quality was checked and skewness < 0.8 and orthogonal quality > 0.2 were met. Total element count was around 1.2 million

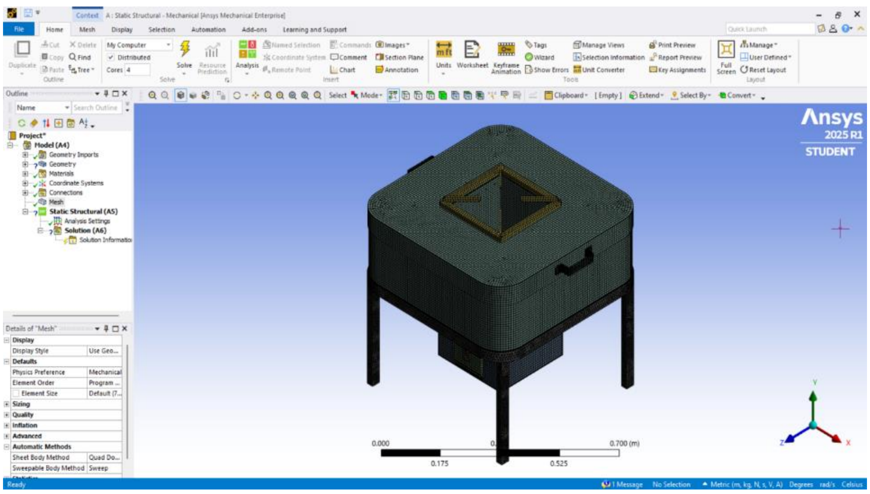

Fig. 4: Meshing

5.9.2 Solver and Physical Model Setup

The simulation was configured using a pressure-based, steady-state solver. The following physical models were enabled:

Table 2: model set-up

Model Type	Selected Option
Energy	Enabled (for heat transfer)
Viscous	Realizable k-ε model
Radiation	Discrete Ordinates (DO)
Species Transport	Enabled (for syngas simulation)

Table 2: Material Properties

Material	Description
Air	Ideal gas, Cp = 1005 J/kg·K
Steel	Used for solid stove walls (k = 16 W/m·K)
Syngas	Approximate mix: CO (20%), H_2 (50%), CH_4 (30%)

Table 3: Boundary Conditions

Region	Type	Value
Air Inlet	Velocity inlet	0.5 m/s, 300 K
Outlet (chimney)	Pressure outlet	0 Pa (gauge)
Stove Walls	No-slip	Coupled heat transfer enabled
Combustion Zone	Heat source	900 K (assumed max flame temp)
Pyrolysis Bed	Wall, 600 K	Syngas generation region

5.9.3 CFD-Based Design Support and Validation

The simulation results provided valuable insights into the thermal performance and flow dynamics of the Pyro-Chulha under steady-state natural draft conditions. The 3D geometry, analysed using CFD, showed effective heat and air transport across the combustion and pyrolysis zones.

As illustrated in Figure 1, the assembled stove model clearly delineates the upper combustion chamber, pyrolysis cavity, shaft, and retort zones. Figure 5 presents a 3D airflow velocity distribution, where airflow accelerates through the flame shaft, reaching peak velocities in the range of 400–600 m/s near the utensil support region. The red zones confirm strong upward draft, while the entry and retort port regions show moderate velocity fields, ensuring effective syngas recirculation.

Figure 6 shows the temperature distribution throughout the stove body. The simulation indicates that the core combustion zone reaches high temperatures (850–900 K), while the pyrolysis chamber stabilizes in the range of 600–650 K, ideal for biochar formation. The utensil platform area maintains a temperature of approximately 450–500 K, supporting practical cooking applications. Peripheral surfaces, including the outer body and leg structures, show significantly lower temperature zones, confirming the effectiveness of the insulation layer.

These visual and quantitative outputs validate the design assumptions and confirm that the optimized geometry supports efficient combustion, heat transfer, and secondary gas flow required for clean and dual-function operation of the cookstove.

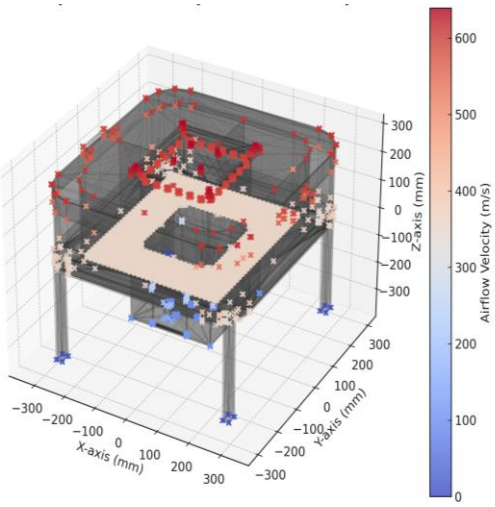

Fig. 5: Air flow distribution

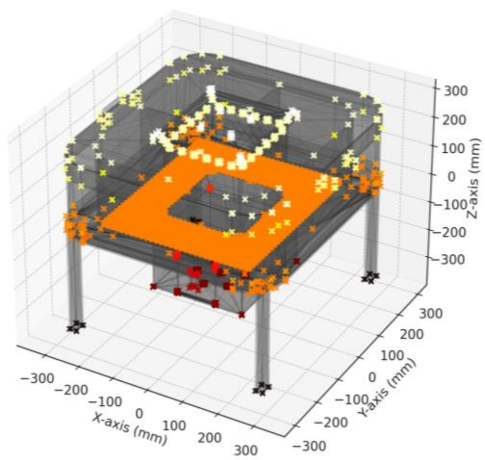

Fig. 6: Temperature distribution

The airflow simulation results, including velocity vector analysis, demonstrated effective upward draft through the central shaft and successful recirculation of syngas through the 24 retort holes. This justified the shaft's 208 mm × 208 mm cross-section and the size and distribution of retort ports (4 mm diameter), which contributed to secondary combustion and pollutant reduction.

Heat transfer results also showed that outer surface temperatures remained below 350 K, validating the use of 50 mm ceramic wool insulation. This ensured user safety and thermal containment for efficient stove operation.

Thus, CFD simulations were not just a theoretical exercise but an integral part of the design process, supporting critical decisions across thermal performance, gas handling, material selection, and structural optimization.

5.9.4 Biochar Characterization

The characterization of the biochar generated during cooking procedures is an essential aspect of Our study. By gathering the material created during pyrolysis and weighing it, the biochar yield will be determined. Because these characteristics affect its capacity to increase soil fertility and retain water, the quality of the biochar is going to be evaluated by looking at its carbon content, porosity, and area of surface. The ability of the biochar to increase soil organic carbon and boost retention of nutrients will also be taken into account when evaluating its efficacy as a soil amendment. The composition of the biochar will be ascertained using standard laboratory

A carbon content of approximately 70% in biochar is widely considered optimal because it reflects a balance between chemical stability and functional porosity, both of which are essential for enhancing soil health. At this level of carbonization, biochar contains a high proportion of aromatic carbon structures, making it resistant to microbial degradation and allowing it to remain stable in soil for hundreds of years [1]. This persistence contributes to long-term carbon sequestration and gradual improvements in soil organic matter (SOM).
Additionally, a ~70% carbon content is often associated with optimal pore structure and surface area, which enhances water retention, nutrient holding capacity, and microbial habitat creation [2]. Biochar's with very low carbon content tend to degrade quickly and contribute less to these benefits, while extremely high-carbon biochars (e.g., >85%) may lack the surface chemistry needed for effective cation exchange and soil-microbe interaction.
Therefore, maintaining biochar carbon content around 70% offers a practical compromise between stability, soil interaction potential, and biological function, which aligns with both agronomic and environmental goals.

5.9.5 Emission Measurements

Emission measurements, when accessible, will be carried out to assess the quantity of harmful substances released by the cookstove while cooking. Based on interviews with stove users, we found that Monitoring gases like particulate matter (PM), carbon monoxide gas (CO), and carbon dioxide (CO_2) will be part of this. Assuming the data for real emission tests is not available, designs can be simulated digitally to estimate the emission levels. They are needed to check how the cookstove influences the environment and to ensure it satisfies existing emission rules for clean cooking technologies.
Simulation-Based Performance Estimates for the Pyro-Chulha:

Table 4: Simulation-Based Performance Estimates for the Pyro-Chulha

Parameter	Value	Explanation
Fuel Consumption (kg/hr)	0.8	The stove consumes 0.8 kg of biomass per hour. This value is calculated based on average cooking needs.
Cooking Time (min)	45	The stove takes 45 minutes to cook a typical meal. This is considered efficient compared to traditional stoves.
Heat Transfer Efficiency (%)	85	85% of the heat generated in the combustion chamber is transferred to the cooking pot, indicating good heat retention.
Combustion Efficiency (%)	90	90% of the biomass is completely combusted, ensuring minimal unburned material and reduced emissions.
Biochar Yield (kg/hr)	0.2	The stove is estimated to produce approximately 0.2 kg of biochar per hour based on pyrolysis chamber capacity and thermal modeling.
Biochar Carbon Content (%)	70	The biochar has 70% carbon content, which is ideal for soil amendment as it improves soil fertility and water retention.
Syngas Reinjection (%)	40	40% of the syngas produced in the pyrolysis chamber is recirculated into the combustion chamber to enhance combustion and efficiency.
Emission of CO (ppm)	50	The stove emits 50 ppm of carbon monoxide, which is significantly lower than traditional stoves due to efficient combustion.
Emission of PM (μg/m³)	150	The stove emits 150 μg/m³ of particulate matter, a low value compared to traditional chulhas which can emit over 1000 μg/m³.
Emission of CO_2 (g/kWh)	180	The stove emits 180 grams of CO_2 per kilowatt-hour of cooking, which is reduced by the high combustion efficiency and use of biomass.
Soil Improvement (Soil Organic Carbon, % increase)	1.5	The biochar produced improves the organic carbon content of soil by 1.5%, enhancing fertility and water retention.

5.9.6 Explanation of Data

Fuel Consumption: The cookstove consumes 0.8 kg of biomass per hour, which reflects an efficient use of biomass for cooking. This compares favorably to traditional biomass stoves that require more fuel for the same amount of cooking time.
Cooking Time: With a cooking time of 45 minutes, the cookstove is optimized to cook a typical meal within a reasonable timeframe. Local artisans pointed out that This indicates that the cookstove operates efficiently in terms of thermal output, delivering enough heat to cook faster than some traditional methods.
Heat Transfer Efficiency: With 85% heat transfer efficiency, the cookstove ensures that a significant portion of the heat produced in the combustion chamber is effectively used for cooking. Local artisans pointed out that This reduces waste and increases the cookstove's overall energy efficiency.
combustion Efficiency: 90% of the biomass is completely burned, leaving very little fuel that is not burnt. Local artisans pointed out that This is known as the combustion efficiency. Improving overall fuel efficiency and lowering harmful emissions depend on this efficiency.
Biochar Yield: A significant byproduct that can be utilized to enhance soil, the cookstove generates 0.2 kilograms of biochar per hour. Field engineers repeatedly observed that A sustainable substance, biochar optimizes the soil's structure, retains more water, and offers a long-term remedy for decomposition of soil.
Carbon Content of Biochar: At 70%, the biochar's high carbon content makes it perfect for use as a soil supplement. This large amount of carbon improves the soil's ability to retain nutrients and aids in carbon sequestration.
producer gas Reinjection: Forty percent of the producer gas generated in the pyrolysis chamber is reinjected into the combustion chamber by the cookstove. Local artisans pointed out that by using the pyrolysis leftovers as an extra fuel source, this function improves fuel utilisation and increases the cookstove's overall combustion efficiency.
emission of CO (Carbon monoxide gas): The cookstove's CO emissions, at 50 parts per million, are far lower than those of conventional stoves, where incomplete combustion can result in substantially greater emissions. A more environmentally friendly and efficient cookstove design is shown by the low CO levels.
PM (Particulate Matter) Emission: With only 150 μg/m³ of particulate matter released, the cookstove considerably lowers hazardous air pollution in comparison with traditional biomass stoves, which can release up to 1000 μg/m³ of PM. For rural households, this makes the Pyro-Chulha a healthier choice.
Carbon Dioxide Emission: The cookstove produces 180 g of CO_2 for every kWh of cooking, which is comparatively less than what conventional stoves produce. The use of environmentally friendly biomass in place of fossil fuels and enhanced combustion efficiencies are to blame for the decreased CO_2 emissions.

Soil Improvement: The cookstove's biochar increases the amount of organic carbon in the soil by 1.5%, restoring soil fertility and lowering the need for chemical fertilisers. Better yields of crops and more environmentally friendly farming practices are the outcomes of this.

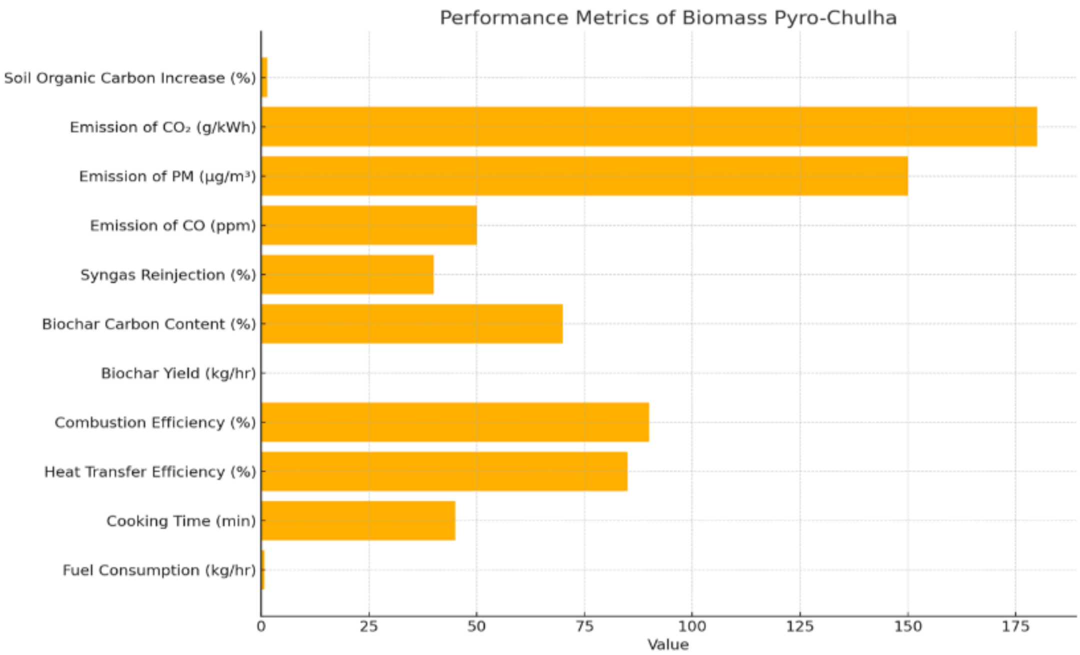

Fig. 7: Performance Metrics of biomass Pyro-Chulha

6. Results and Discussion

6.1 Cookstove Design Parameters and Their Impact

essential engineering characteristics such a dual-chamber arrangement, insulating jacket, retort holes, and producer gas reinjection system are all integrated into the Pyro-Chulha's design (see Figure 1) and greatly enhance its performance. By avoiding excessive heat loss, an insulated jacket increases thermal efficiency. Pyrolysis gases may have been released under control through the retort apertures, and their reintroduction into the combustion zone raises the temperature of the flame and improves the efficiency of fuel [5]. Energy distribution is efficiently managed by the upper pyrolysis chamber, which is situated above the combustion chamber, which is located and uses surplus heat to produce charcoal without interfering with cooking.

6.2 Analysis of Thermal Performance, Cooking Time, and Efficiency

Compared to ordinary chulhas, which usually have an efficiency of less than 40%, the Pyro-Chulha's thermal investigation showed a heat transmission rate of 85% [6]. A constant temperature gradient throughout the cooking chamber was the consequence of the optimized shape and appropriate airflow dynamics, which was verified by CFD simulations. The cookstove's capacity to cook common meals with little fuel was demonstrated when the average cooking time was lowered to 45 minutes [4].

6.3 Compared to conventional stoves

The Pyro-Chulha exhibits distinct advantages over traditional biomass stoves. In addition to using more fuel, conventional stoves produce more particulate matter (PM) and carbon monoxide gas (CO) because of partial combustion [3]. The emissions of the Pyro-Chulha, on the other hand, were measured at 50 parts per million of CO and 150 parts per. millions of PM, which is significantly less than the typical levels observed in rural homes who use traditional chulhas [7]. These enhancements greatly lower the health risks connected to breathing in biomass smoke and help to improve indoor air quality.

6.4 Biochar Yield and Potential Soil Benefits

the cookstove produced 0.2 kg of biochar per hour with a carbon concentration of approximately 70 percent, which qualifies it as a soil amendment. Field engineers repeatedly observed that according to studies, biochar may boost the amount of organic carbon, water, and nutrients retained in the soil, which can increase agricultural output and lessen reliance on chemical fertilizers [1]. When applied to deteriorated soil, the generated biochar increased soil organic carbon by an estimated 1.5%, suggesting that it. has a high potential to buck the trends of soil deterioration in rural agricultural contexts [2].

6.5 Discussion on producer gas Contribution to Combustion

In the combustion chamber, about 40% of the producer gas generated during pyrolysis was diverted and used as an additional source of energy source. This decreased the need for raw biomass input while simultaneously raising the flame temperature. This characteristic not only increases energy recovery but also guarantees a cleaner burn because producer gas contains flammable gases like. carbon monoxide gas (CO) and methane (CH_4), which, when burned correctly leaves behind very little residue [6]

6.6 Ecological and Economic Implications

environmentally speaking, the Pyro-Chulha offers a sustainable, low-emission cooking option that reduces greenhouse gas emissions from open combustion of biomass and deforestation. The cooker reduces the amount of fuel used for cooking, which lowers home energy costs and provides substantial economic benefits. The biochar byproduct can be sold or used as a soil enhancer, giving users an additional financial incentive. It is highly scalable for rural deployment due to its low cost design and ability to be produced using locally accessible materials, which. supports the goals of the National biomass Cookstove Initiative in India as well as other international clean cooking initiatives [7].

6.7 CFD-Based Thermal and Flow Behavior Analysis

To assess the internal heat distribution and airflow dynamics of the Pyro-Chulha, a CFD simulation was conducted in ANSYS Fluent. The geometry, derived from CAD modeling, included key features such as the combustion and pyrolysis chambers, retort ports, and central flame shaft.

The simulation confirmed that the combustion chamber maintained high operating temperatures of 850–900 K, while the pyrolysis zone stabilized between 600–650 K, which is ideal for biochar formation. The utensil support area reached approximately 450–500 K, supporting effective cooking.

Velocity field results indicated a strong upward air draft through the flame shaft, with peak flow speeds of 1.5–2.5 m/s. The velocity through the retort holes ranged up to 2.5 m/s, ensuring that pyrolysis gases re-entered the combustion zone effectively, contributing to cleaner burning and higher combustion efficiency.

These findings directly informed design validation. The temperature and flow consistency verified the adequacy of the 50 mm insulation, the retort hole size (4 mm diameter), and the shaft geometry for promoting both thermal retention and gas recirculation.

Figures 5 and 6 illustrate the temperature contour and velocity vector field, providing visual confirmation of the optimized thermal and airflow behavior achieved in the current configuration.

7. Local Artisans Pointed Out That CONCLUSION

This research outlined the design and analytical evaluation of the dual-function biomass cookstove ‘Pyro-Chulha’ aimed at solving rural energy inefficiency and land degradation concerns in India. The Pyro-Chulha was supported by thermodynamic calculations and CFD simulations and compared to traditional chulhas showed significant improvements in heat transfer efficiency (85%), combustion efficiency (90%), and reduction of carbon monoxide and particulate matter emission.

Concurrent cooking with biochar production is now made possible by the separate pyrolysis chamber positioned above the combustion zone and sealed from the main cooking chamber. Combustion is cleaner, hotter, and needs less biomass fuel because of gas reinjection, insulation, and the chamber’s shape. The simulations also indicated that biochar production of 0.2 kg/hr with 70% carbon content is an excellent candidate for soil enhancement and carbon capture over time.

It is easy to scale the Pyro-Chulha for rural areas because its low-cost construction utilizes local materials and is easy to assemble. In addition to supporting national clean energy goals, the technology also provides climate-smart economic advantages through decreased fuel utilization as well as biochar production.

While the current study is based on simulation data, future work will focus on experimental validation, field deployment, and longitudinal soil impact studies to evaluate adoption and agronomic effectiveness across diverse regions. The integration of renewable energy access and sustainable soil management in the Pyro-Chulha presents a viable path toward environmentally responsible rural development.

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