

Design and Development of a Batch Waste Biomass Stove for Sustainable Cooking in Rural Kenya

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Dependence on fossil fuels and wood in rural Kenya, which contributes to deforestation and increased greenhouse gas emissions, must be addressed immediately. Waste biomass is being investigated as a viable alternative, providing a potential fix for the urgent wood reliance issue and climate change. However, common biomass stoves still have shortcomings in that they discharge more flue gases into the environment due to incomplete combustion, and use charcoal as fuel. This study proposes the development of a unique batch biomass stove in the pursuit of cleaner, more effective cooking methods. Various biomass materials are investigated under different stove configurations that involve variation of primary and secondary air holes. High thermal efficiency of 67.1% for bagasse pellets and 68% for coconut husks was achieved during a standard water boiling test. A noteworthy byproduct of the stove is valuable biochar, which may be used to improve soil fertility, effluent color and odor removal, and promote sustainability. These results not only demonstrate the potential of waste biomass as a substitute energy source but also signal the beginning of environmentally friendly cooking methods and soil improvement in rural Kenya. In essence, this research represents a crucial step toward balancing human needs with environmental well-being and paves the way for a day when efficiency, environmental consciousness, and soil enrichment naturally combine.

Key words: Sustainability; Biochar; Bagasse pellets; Coconut husks; Greenhouse gas emissions Subtheme: climate change

I. Introduction

The ubiquity of biomass as a waste in rural Kenya is unrivaled (Masinde, 2020). For instance, coconut wastes are abundant to the people living in the coastal region of Kenya (Pole F.N. et al., 2014). Similarly, in the western region of Kenya, there are numerous sugar factories, whose byproduct is bagasse (UNEP, 2019). These wastes have been partially used as fuel in homesteads. However, their full potential is yet to be realized. Kenya, among other Low- and Middle-Income Countries (LMIC), has been reliant on firewood and unprocessed biomass for decades, which is considered a polluting fuel (Ministry of Energy - Republic of Kenya, 2019). A summary of polluting fuel usage distribution according to regions is shown in Figure 1. However, this trend is projected to change, and the adoption of biomass is relatively decreasing as summarized in Figure 2 (UNSD, 2021), in quests to provide clean cooking and curbing climate change. It is projected that most of the population will be using gas regardless of its cost, due to its efficiency (Abbas & Ermakov, 2023).

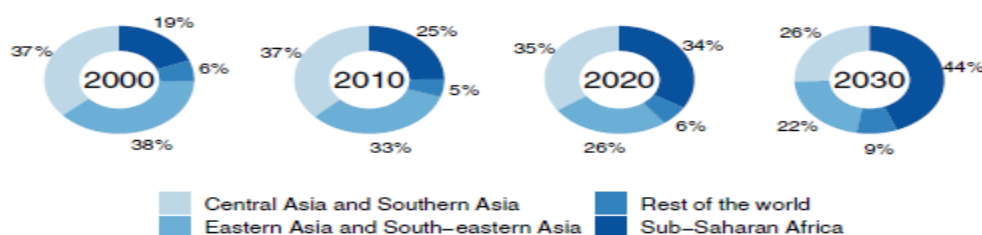


Figure 1 population using polluting fuel (Stoner et al., 2021)

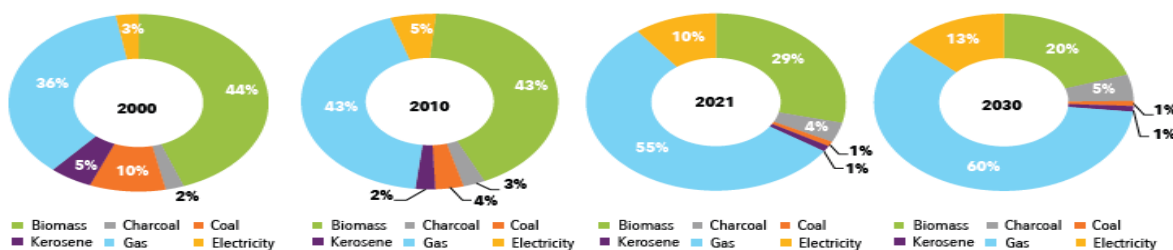


Figure 2 Comparison of the percentage of people in LMICs using various fuel types in 2000, 2010, and 2021, with a projection for 2030 (UNSD, 2021).

The reluctance to use biomass as a source of fuel by the local Kenyan population is championed by its presumed low thermal efficiency and pollution (Bolo et al., 2022; Timothy et al., 2022). The available biomass burners have failed to address these issues fully. Such stoves produce much smoke, and sometimes take a longer time to cook due to limited thermal efficiencies. Researchers have focused on trying to eliminate these inefficiencies, and by so doing, many stoves have been designed, redesigned, and improved (Hayyat et al., 2024). These stoves range from continuous feed stoves, rocket stoves, and batch stoves.

Traditional stoves, or "three firestone stoves," are being used by the rural inhabitants today. This is mostly impacted by geography and cultural traditions. LPG gas is also expensive, while electricity is both difficult to access and costly. Improved traditions have undergone a number of changes over time to increase their effectiveness. Three-stone open fires have evolved into many kinds of mud stoves, as well as other changes like the usage of chimneys, depending on local cultures, food choices, and fuel availability (J. M. Hafner et al., 2020). A more efficient mud stove called Chepkube was developed. (Wamalwa et al., 2022). This design emphasizes efficiency increases, faster cooking times, and less fuel consumption. However, this stove had certain drawbacks in terms of lowering the amount of flue gases released. Even so, many researchers still refer to these upgraded versions as conventional stoves. Later, more advanced stoves appeared. They were distinguished by the application of scientific improvements to the conventional stoves to increase their effectiveness (J. Hafner et al., 2018). Improved cookstoves are popular because they have complete fuel combustion, low fuel consumption, low emissions, and high thermal efficiency, as well as being inexpensive and easily accessible (Sharma & Dasappa, 2017). Traditional cookstoves typically have incomplete fuel combustion, high fuel consumption, high emissions, and low efficiency. The issue area was modified to reduce indoor air pollution as the threat of severe environmental pollution spread around the world (Gitau, Sundberg, et al., 2019). The "rocket stove" and "top-lit-up-draft (TLUD)" stoves were explored in an effort to address environmental concerns and lessen the amount of deforestation brought on by high fuel use, respectively (Energy Efficient Cook Stoves for Siaya Communities – Kenya UNFCCC). On the other hand, Saraswati aimed to enhance a TLUD. The research sought to ascertain the effects of the changes made to the stove by collaborating with the users to learn about their goals and emphasize their position as project stakeholders. It was based on Kwale, a county in southern Kenya, where most cooking is done with firewood. How simple the stove is to use was the main concern of users. (Development, 2018).

Regardless of the energy efficiency, improvements were further sought to provide cleaner cooking, and the results of gasifier stoves were explored (Bailis et al., 2020). According to (Njenga et al., 2016) small-scale farmers could benefit from the gasifier system by having access to more energy and having more time, while also breathing healthier in the kitchen. This may help underdeveloped nations create cleaner biomass cooking methods. Due to apparent advantages, those who used the gasifier to cook preferred it over traditional methods (Manoj Kumar et al., 2013). Thus, the gasifier is suitable for rural regions because it creates a cleaner cooking system that conserves fuel, makes charcoal for a subsequent cooking session, cooks quickly, and lessens indoor air pollution from cooking with biomass fuel. To make it more secure and safe, the design does need to be enhanced. Another significant advantage of these gasifier stoves, in addition to efficiency and ecological consciousness, is the production of biochar as a byproduct (Torres-Rojas et al., 2011). If the generated char is added to the soil, it can improve crop yields and sequester carbon (Jeffery et al., 2017). It has been shown that producing biochar using gasifier cookstoves can reduce emissions and fuel consumption, but more research is still needed to determine how their adoption will affect users. The need to chop fuel to the proper size, reloading fuel when charring occurs before the meal is entirely cooked, and lighting the stove are a few of the difficulties associated with the stoves (Gitau, Mutune, et al., 2019).

Even after many improvements, better cookstoves still have a number of drawbacks. They include the use of wood as biomass, which poses a growing threat to the forest cover, which is already at risk. Additionally, the added labor necessary to chop firewood to the required biomass size for the stoves is an issue. The construction of a biomass burner using bagasse and coconut husks, which are typically regarded as wastes, is the main goal of this work. The cookstove's ideal specifications will be found for each fuel in order to boost efficiency.

Design of the biomass stove

The science of heat transmission, combustion, and the notion of fluid flow are all applied in the design of the biomass stoves to achieve complete combustion. The transfer of fire to the cooking vessel with the least amount of heat loss results in the maximum heat transfer (Sutar et al., 2015). The design of each component will best utilize these considerations. Table 1 lists the design's constituent parts.

Table 1 constituent parts of the proposed biomass stove

Part	description
Combustion chamber/cylinder	The stove's essential part is the combustion chamber. In this area, combustion takes place
Air holes	Due to the ability of the air-fuel combination to evenly distribute air to the bottom of the fuel, the air holes in the stove increase combustion efficiency. This speeds up combustion by reducing heat loss through the wall.

Exhaust	The exhaust on the stove's design will assist in getting rid of flue gas. Due to the temperature differential, hot gas will escape up the.
Fire regulator	The airflow passage on the stove can be opened and closed by this flame regulator, which is a plate. This plate is useful for controlling the air flow inside the stove, which in turn controls how much heat the stove produces. Its layout can be found in either the inside end of the chimney or the mouth of the combustion chamber.

The improved stove, on the other hand, mainly utilizes mild steel in its components. Besides its cheaper cost and suitable conductivity factors, it is usually available in the community, sometimes as scrap waste. Therefore, its utilization helps reduce solid waste by reusing the otherwise wasted mild steel. Figure 3 is the drawing of the proposed stove's parts in their working position.

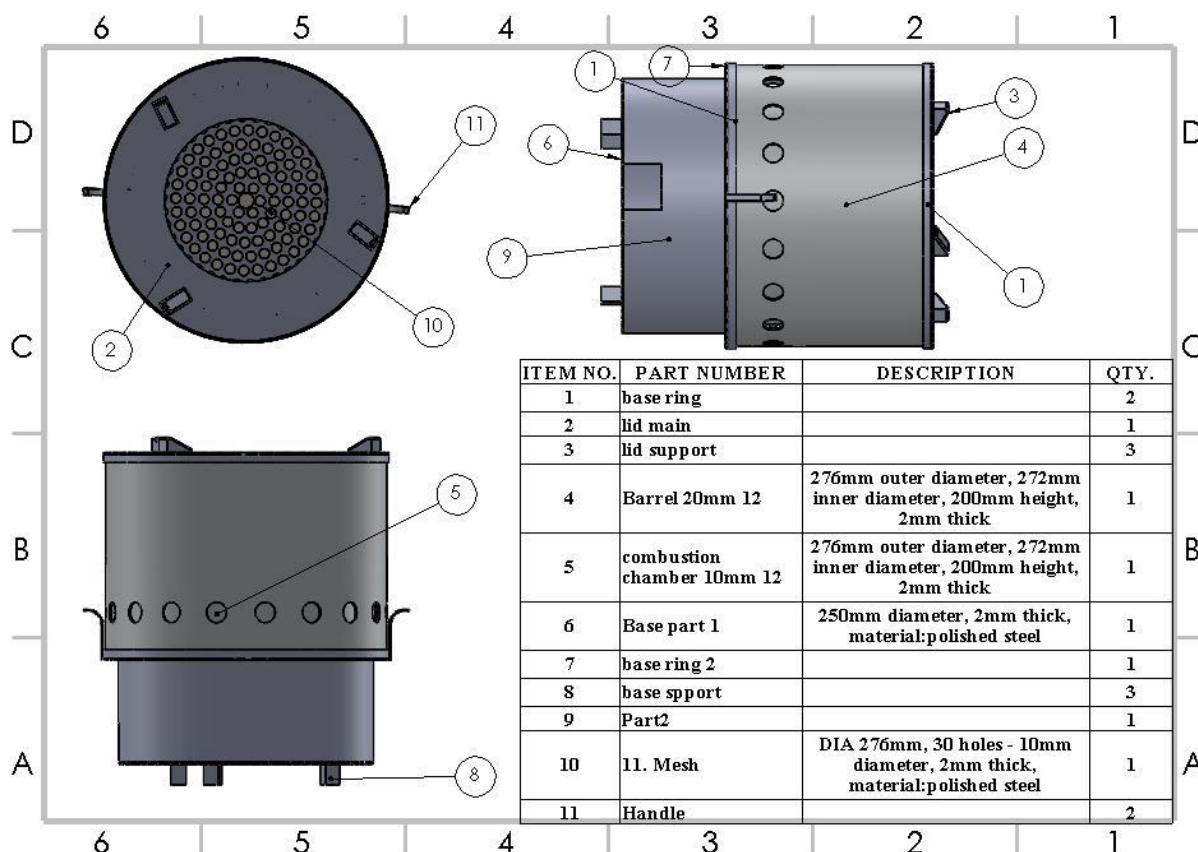


Figure 3 Drawing of the proposed stove

Complete combustion is encouraged in order to attain maximum thermal efficiency (Performance Evaluation Biomass Cooking Stoves Used At, 2019). This design uses both primary and secondary air openings. In addition to providing a percentage of the combustion air, primary air also regulates the maximum amount of fuel that can be burned. The primary air holes are shown in Figure 4. Secondary air, on the other hand, encourages the fuel to burn all the way through, which increases combustion efficiency. In most cases, supplemental air is not necessary for power burners. The secondary air holes are shown in Figure 4 The flame and flue gas temperatures are diluted by air entering through access/clean-out doors, burner mounting flanges, boiler sections, etc., which lowers operating efficiency and impairs our ability to precisely monitor combustion conditions.

Two cylinders are used to enclose the cooking fire in the design. These cylinders are separated from one another by 20 mm on either side, as shown in Figure 4. The secondary air is allowed to flow through the space between these cylinders. The furnace and barrel are represented by these cylinders. The furnace is the inner cylinder utilized as the combustion chamber, and the barrel is the outer cylinder. Applying the fluid dynamics principle, a fuel input area with the appropriate modifications to account for fresh air flow caused by the pressure differential. The holes at the barrel's lower end serve as a secondary source of air as well.

The intake of fresh air supply from below the fuel helps the fuel burn completely (Kshirsagar & Kalamkar, 2014). The air entry on the base allows for this. In the combustion chamber, the fuel is supported by a mesh. The mesh assists in separating the ash and unburned fuel. This helps prevent the buildup of an insulating coating of ash, which would otherwise limit the amount of fresh air that can enter the fuel and inhibit complete combustion.

Radiation and convection losses should be prevented for improved cooking by keeping the space surrounding the pot and burner to a minimum. This made it necessary to alter the rectangular design that is typical of many current structures. In order to reduce the cross-sectional area through which the gases depart, the proposed design consequently adopted round cylinders with a small lid hole for the exit of flue gases. Additionally, by lessening flue gas turbulence, the amount of heat energy reaching the cooking vessel increases, meaning that the least amount of heat energy is lost. Additionally, this configuration makes it easier and more natural for chilly flue gases to exit. The fuels needed to put this concept into practice are inexpensive and easily accessible. The minimum compliance requirements and intrusion into people's lifestyles and cooking habits are also features of this cookstove.

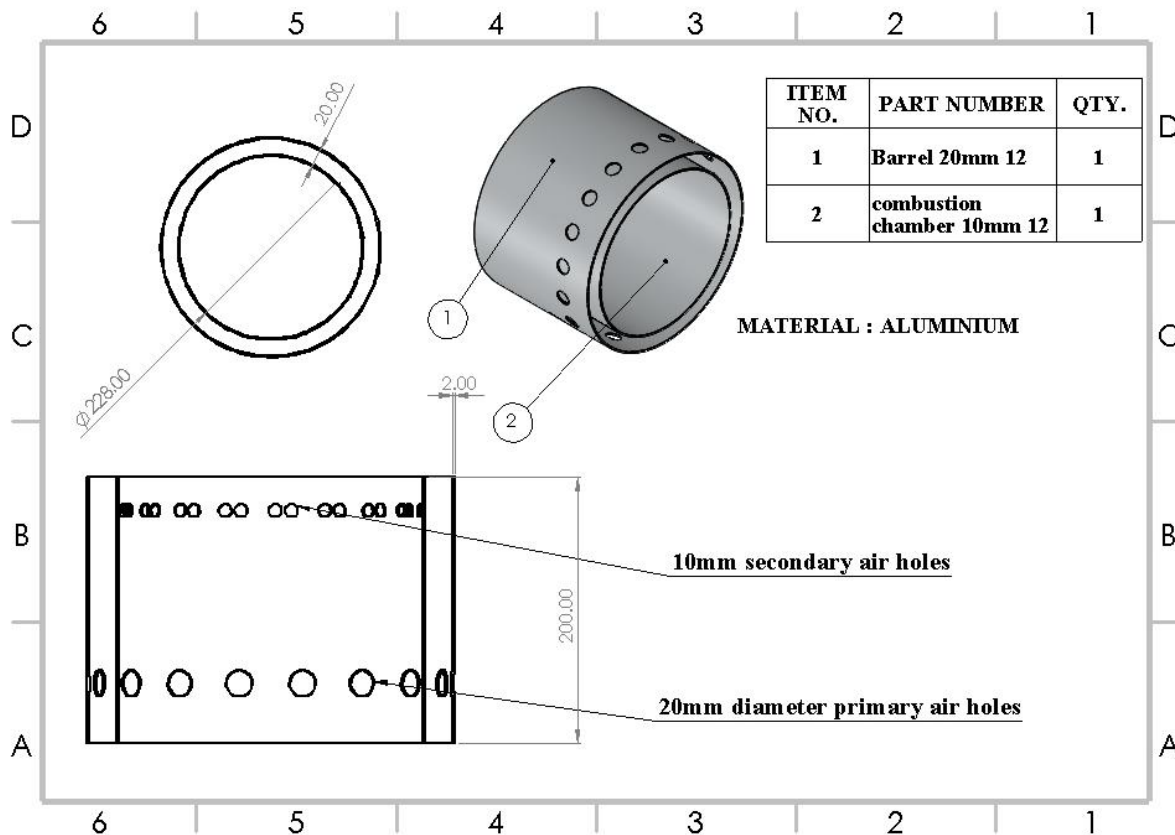


Figure 4 Barrel Assembly Design

Fuel properties

Table 2 The properties of the fuels used to test this stove are shown in table

Parameters	Bagasse Pellets	Coconut Husks
Calorific value(J/kgK)	1428000	2120000
Ash content (%)	3.6-4.8	6
Toxicity	No	No
Bulk density of dry pellets(kg/m3)	600	726
Cost/kg(Ksh)	21	Yes
Carbon credit	Yes	5

Table 2 demonstrates the characteristics of the particular fuels used to test the stove. The effectiveness of burning is impacted by such qualities. The variations in outcomes might be seen during testing.

Testing of the stove

Testing is essential to the creation and application of biomass burners. The various parameters were assessed using the standard water boiling test.

1.5 kg of bagasse pellets and 1 L of water were weighed and measured in a heating pot. The combustion chamber of the built biomass stove was then filled with bagasse pellets, and a matchbox and some kerosene were used to start the fire. The amount of

time the fuel burned was timed using one stopwatch. After the fuel had started burning evenly, 1L of water was added to the heating pot on the stove, and a second timer was used to begin timing the time it took for the water to boil. When the water started to boil, the stopwatch was paused, and the duration of the boiling process was noted. Additionally, the duration it took for the fuel to totally burn out and turn into biochar was continuously tracked. The stopwatch was then stopped, and the time was recorded. When it came to coconut husks, the entire process was repeated, with a 1kg mass for the husks.

Various parameters like heat input rate, thermal efficiency, fuel flow rate, gasification rate and firepower were calculated for different primary and secondary air holes configurations.

Heat input rate

The quantity of heat energy given to a system or process per unit of time is measured by the heat input rate, which is often expressed in watts (W). It measures the rate of heat addition to a system, which could be a heating appliance, a manufacturing procedure, or any application where heat transmission is crucial. Heat input rate may relate to the rate at which heat energy is supplied or released by the burning fuel in experiments or research involving combustion, as illustrated by Eq. 1. It's an essential variable for comprehending and evaluating the effectiveness of heating techniques and systems.

$$\text{Heat_input_rate} = 2(m_{f1} - m_{f2}) * CV * \frac{60}{Rt} \quad \text{Eq 1}$$

Where m_{f1} the initial mass of pellets/husks in kg, m_{f2} is the final mass of pellets/husks after burning in kg, CV is the caloric value of pellets/husks in J/kg and $Rt(\text{Runtime})$ is the time taken to burn the fuel.

Fuel flow rate

The rate at which fuel is consumed or supplied to a system or device is measured as fuel flow rate, which is usually expressed in kilograms per hour (Kg/hr)(Jain and Sheth, 2019). As shown in Eq. 2, it calculates how much fuel is consumed or delivered in a certain amount of time. In many different applications, such as the operation of automobiles, power production, industrial processes, and heating systems, fuel flow rate is a crucial factor. It assists in determining energy usage, monitoring engine and equipment performance, and evaluating fuel efficiency.

$$Q_f = m_{f1} * \frac{60}{Rt} \quad \text{Eq 2}$$

Where Q_f is the Fuel flow rate in kg/hr. m_{f1} is the Initial mass of the fuel before combustion, and Rt is the time taken to burn the fuel in minutes.

Gasification rate

The rate at which solid carbonaceous materials, such as coal, biomass, or waste materials, are transformed into gaseous products is referred to as the gasification rate(Baruah and Baruah, 2014) . It is expressed in Kg/hr.m², as illustrated by Eq. 3. These solid materials are heated by the thermochemical process known as gasification in the presence of controlled amounts of oxygen, steam, or other gasifying agents. Syngas, also known as synthesis gas, is a mixture of gases, comprising carbon monoxide (CO), hydrogen (H₂), and methane (CH₄). The gasification rate can vary depending on factors such as the type of feedstock, operating conditions (temperature, pressure, and residence time), and the specific gasification technology being used. A higher gasification rate often indicates a more efficient and rapid conversion of solid feedstock into gaseous products, which can be important in various applications, including energy production, chemical synthesis, and waste management.

$$\text{Gassification_rate} = \frac{\text{fuel_flow_rate}}{\text{area_of_combustion_chamber}} \quad \text{eq 3}$$

Thermal efficiency

Thermal efficiency, which is often represented as a percentage, is a measurement of how well a system or equipment turns heat energy into meaningful work or output. It's an important factor in determining how well different thermal systems function, including engines, power plants, heating systems, and, as of late, biomass stoves.

The following is the general formula used to determine thermal efficiency:

$$\text{Thermal Efficiency (\%)} = (\text{Useful Output Energy or Work}) / (\text{Input Heat Energy}) * 100$$

For the biomass stove,

$$\eta_{th} = \frac{(Q_1 + Q_2)}{Q_4} * 100\% = \frac{Q_3}{Q_4} * 100\% \quad \text{Eq. 4}$$

Where Where Q_1 is the Heat absorbed by the water in the vessel, expressed as;

$$Q_1 = m_w * C_w * \Delta T$$

Firepower

The ability of a biomass stove to produce heat or energy from biomass fuel sources like wood, crop wastes, or other organic materials is referred to as the stove's "firepower" in this context. It is a gauge of how effectively a stove can turn biomass into thermal energy for uses such as heating or cooking. In places with limited access to conventional fuels like gas or electricity, the firepower of a biomass stove is crucial for cooking and heating. Maximizing firepower can help these sectors' cooking and heating processes use less fuel, emit fewer emissions, and operate more effectively overall. This is especially important in many underdeveloped countries because household chores are frequently completed using biomass burners.

$$E_F = \frac{m_f * C_v}{T_{boiling}}$$

Where, E_f is the fire power, $T_{boiling}$ is the time taken to boil 1kg of water.

II. Results

Table 3 Results for Bagasse Pellets

Gas air flow			Thermal efficiencies, %	Fuel flow rate, kg/hr	Firepower, W	Gasification rate, kg/hr.m2
Primary air holes diameter, mm				Secondary air holes diameter, mm		
20	10	3552.2	66.9	5.84	5795.5	142.4
14	10	3775.2	67.1	6.2	6945.5	151.2
20	6	3644.5	66.5	5.99	6891.9	146.1
14	6	3354	67.1	5.51	5675.7	134.4

Table 3 presents the results of Bagasse pellet stove testing with variations in primary air hole diameter and heat input rate. In one configuration, with a primary air hole diameter of 20 mm and a heat input rate of 10 W, the stove achieved a thermal efficiency of approximately 35.52% and a firepower of around 5,795.5 W. In another configuration featuring a primary air hole diameter of 14 mm and the same 10 W heat input rate, the stove demonstrated the highest thermal efficiency at approximately 37.75% and the highest firepower at around 6,945.5 W. When the primary air hole diameter was increased to 20 mm with a reduced heat input rate of 6 W, the thermal efficiency slightly decreased to approximately 36.44%, while firepower remained high at around 5,991.9 W. Lastly, a configuration with 14 mm primary air holes and a 6 W heat input rate had the lowest thermal efficiency at approximately 33.54% and a firepower of around 5,675.7 W.

The implications of these variations suggest that the stove's performance is influenced by both primary air hole diameter and heat input rate. Smaller primary air holes (14 mm) appear to enhance thermal efficiency, potentially by allowing for more controlled air supply. Furthermore, a higher heat input rate (10 W) results in greater firepower, indicating the stove's ability to generate more heat. However, reducing the heat input rate while maintaining a smaller primary air hole diameter led to a decrease in thermal efficiency without a significant impact on firepower.

Table 4 Results for Coconut husks

Gas air flow		Initial water temperature, °C	Boiling temperature, °C	Time taken to boil water, min	Time taken to burn the fuel, min
Primary air holes diameter, mm	Secondary air holes diameter, mm				
20	10	27	95	5.31	11.35

14	10	27	95	4.54	11.12
20	6	27	95	5.32	11.38
14	6	27	95	5.25	11.48

Table 4 shows different stove designs that burn coconut husks as fuel, with modifications in the size of the primary and secondary air holes, the initial and boiling temperatures of the water, the boiling time, and the burning time of the fuel. All designs efficiently brought the water to a boil since the initial water temperature was maintained at 27 °C and the boiling temperature remained constant at 95 °C. The shortest measured boiling time was 4.54 minutes for configurations with 14 mm primary air holes, suggesting that a smaller primary air hole diameter may improve the efficiency of heating water. The time it took to burn the fuel, however, varied slightly between configurations, ranging from 11.12 to 11.48 minutes, with only very modest variances that didn't seem to directly correlate with variations in the primary or secondary air hole width. These findings imply that the size of the primary air hole may affect the effectiveness of water heating when coconut husks are used as fuel, but that the size of the air hole only has a little impact on the amount of time it takes to burn the fuel. Additional research might look into things like pollutants, thermal efficiency, and the usefulness of using coconut husks as fuel for heating or cooking.

Comparative analysis between Bagasse Pellets and coconut husks

In the stove testing, both bagasse pellets and coconut husks exhibited similar boiling times, ranging from 4.54 to 5.32 minutes, indicating their effectiveness at heating water to the boiling point. However, a notable distinction emerged in the time taken to burn the fuel. Bagasse pellets demonstrated a relatively faster and more efficient fuel burn, ranging from 4.54 to 5.32 minutes, while coconut husks exhibited a longer fuel burn time, spanning 11.12 to 11.48 minutes. Possible reasons for these differences include the composition, size, and preparation of the fuels. Bagasse pellets, being denser with a higher energy content, could burn more efficiently. Additionally, their consistent size and shape, as well as their compatibility with the stove's design and airflow requirements, likely contributed to the faster burn times. Therefore, based on these findings, bagasse pellets are suggested as the preferred fuel for this stove, offering quicker heating and reduced fuel consumption for similar results. Nonetheless, practical considerations, such as fuel availability and cost, should also be taken into account when making a final choice for a specific application.

III. Conclusion

In rural Kenya, abundant biomass waste resources like coconut husks and bagasse remain underutilized despite their ubiquity. Low- and middle-income countries, including Kenya, have historically relied on polluting fuels such as firewood and unprocessed biomass for cooking, contributing to environmental degradation and health risks. However, a shifting landscape aims to embrace cleaner cooking options to combat climate change, with increased adoption of gas anticipated by 2030. The evolution of biomass stoves, from traditional three-stone fires to advanced models like gasifier stoves, reflects ongoing efforts to enhance cooking efficiency and reduce environmental impact. Gasifier stoves offer cleaner cooking, reduced fuel consumption, faster cooking times, and decreased indoor air pollution, along with the valuable byproduct of biochar. In this context, our research focuses on designing a biomass stove optimized for bagasse and coconut husks, typically considered waste materials, aiming to improve efficiency through careful design and testing. Preliminary findings indicate that the current stove, when optimized for bagasse pellets, exhibits faster burning times and higher efficiency compared to coconut husks, making it a promising solution for clean and efficient cooking. These efforts align with global initiatives to promote clean cooking, environmental sustainability, and improved health outcomes. For future work, a User-Centric Design should be explored, research should involve end-users to ensure that stove designs align with their needs, preferences, and cultural practices. This can lead to more user-friendly and readily adopted solutions.

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