



Development of a Top-Lit Up Draft Biomass Stove with a Combustion Chamber Level Adjustment Mechanism

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Abstract: This project aims to develop adjustable-depth TLUD (top-lit updraft) biomass stove combustion chamber technology to enhance stove performance during operation. Three conditions must be met for stove performance testing. The TLUD biomass stove was available in fixed depths of 7" (FS-7) and 11" (FS-11), as well as adjustable depths of 7 and 11" (AS-7/11) during operation. The evaluation of the biomass stove's performance used the water boiling test (WBT) methodology to assess thermal efficiency (η), burning rate (BR), power (P), and water boiling time (BT). The test results indicated that the FS-7 exhibited the maximum thermal efficiency ($18.60 \pm 0.14\%$), whereas the AS-7/11 showed the highest burning rate and power output (50.05 ± 1.07 g/min and 12.91 ± 0.27 kW, respectively). The AS-7/11 required the shortest duration to boil water (6.83 ± 0.69 min). The AS-7/11 was appropriate for applications necessitating high firepower and speed for thermally demanding tasks and was compatible with various containers.

Keywords: Biomass stove; combustion chamber adjustment; renewable energy

1. Introduction

Domestic energy consumption is expected to rise. Economic growth will stimulate increased energy consumption across several sectors. The government has promoted the use of several renewable energy sources, including biomass, solar, wind, hydropower, and geothermal energy [1, 2]. The goal is to reduce the importation of fuel energy from foreign sources and lower the community's expenses. Renewable energy sources can utilize a wide range of waste products from the agricultural and forestry sectors. It also supports community firms in the comprehensive production of biomass fuel, including biomass material aggregators, processors, and users [3, 4].

Biomass, as a renewable energy source, can be replenished naturally. Biomass may be used as an energy source to replace the finite supply of fossil fuels. Biomass is an organic material derived in substantial amounts from living organisms. Biomass sources include wood chips, rice husks, bagasse, corn cobs, eucalyptus wood chips, and palm waste [5, 6]. A biomass stove is a device that converts the thermal energy generated by biomass combustion into usable energy. Various types of domestic biomass stoves include protrusion stoves, high-performance stoves, high-performance braziers, conventional braziers, rocket stoves, and top-lit updraft (TLUD) biomass stoves. The TLUD biomass stove combusts fuel from the top while facilitating gas movement from the bottom to the top [7, 8]. The geometry of the combustion chamber in the TLUD

biomass stove directly influences combustion efficiency and the quality of the producer gas. Within the combustion chamber, three reaction zones are arranged along the chamber height: the pyrolysis zone, the incomplete combustion zone, and the reduction zone [9]. The depth of the combustion chamber influences the thermal efficiency of the biomass burner. A biomass stove featuring a shallow combustion chamber will yield superior thermal efficiency compared to one with a deep combustion chamber. A deep combustion chamber yields greater power than a shallow combustion chamber [10]. The implementation of a forced draft system enhances combustion efficiency during the ignition phase [11].

These restrictions made the stove unsuitable for applications requiring variable thermal output during operation. A stove with a fixed combustion chamber depth cannot be adequately modified to meet such needs. This project aims to address limitations of conventional biomass stoves by designing and developing adjustable combustion chamber depths that can be fine-tuned during operation. The goal is to improve the adaptability and effectiveness of firepower regulation for a variety of applications.

2. Materials and Methods

A TLUD biomass stove with a leveling mechanism for the combustion chamber operates in two depths as follows.

2.1 Development of a TLUD-type biomass stove that can decorate the combustion chamber

The development of TLUD biomass stoves used a 2 mm-thick steel plate as a component. The beam system was engineered to level the combustion chamber via the foot mechanism. The stove performance test had three conditions: a fixed biomass stove with a 7" deep combustion chamber (FS-7), a fixed biomass stove with an 11" deep combustion chamber (FS-11), and an adjustable biomass stove with 7" and 11" deep combustion chambers (AS-7/11).

2.2 Performance Test of TLUD Type Biomass Combustion Chamber

The stove performance evaluation used the water boiling test (WBT) with 5 kg of water [9, 10]. Rubber wood fuel had a lower heating value (LHV) of 15,472 kJ/kg and was 15 cm in length. Dry the fuel at 108°C for 24 hours to evaporate the steam contained in the fuel. The Fluke 54-IIB thermometer and the Fluke 80PK-22 temperature probe measured the water temperature. The test was conducted within a fume hood to protect against external wind impacts. Experiment AS7/11 began with leveling an 11" combustion chamber. After prolonged use, the flame decreased, necessitating adjustment of the combustion chamber to 7". We adjusted the combustion chamber level to 11" to facilitate refueling. The low flame required it to be set at 7". FS7 and FS11 were fixed at combustion chamber levels of 7" and 11", respectively, during the test. The performance evaluation of the TLUD 3 biomass stove started with the addition of 1 kg of fuel. Subsequently, the stove was ignited from above, the air was released from the force draft system, and a container of water was positioned for testing purposes. Upon reaching the boiling point of the water, stop the force draft system. The evaluation of the stove's performance is detailed below, as illustrated in Figure 1.

2.2.1 Thermal efficiency (η)

Thermal efficiency (η) was the proportion of thermal energy derived from biomass stoves used to boil water and generate steam. It is calculated from equation (1) [12, 13].

$$\eta = \left[\frac{4.186m_W(T_f - T_i) + 2260m_V}{f_d \times \text{LHV}} \right] \times 100 \quad (1)$$

η represents thermal efficiency, expressed as a percentage. m_W represented the mass of water, quantified in kilograms (kg). T_i represented the minimum temperature of water, expressed in degrees Celsius (°C). T_f represented the maximum temperature of water, expressed in degrees Celsius (°C). m_V represented the mass of water vapor generated during the TLUD biomass stove performance test, quantified in kilograms (kg). F_d was the total mass of fuel used in the test, expressed in kilograms (kg). LHV was the lower heating value of biomass fuels, expressed in kilojoules per kilogram (kJ/kg). High thermal efficiency results in fuel savings for the biomass stove.

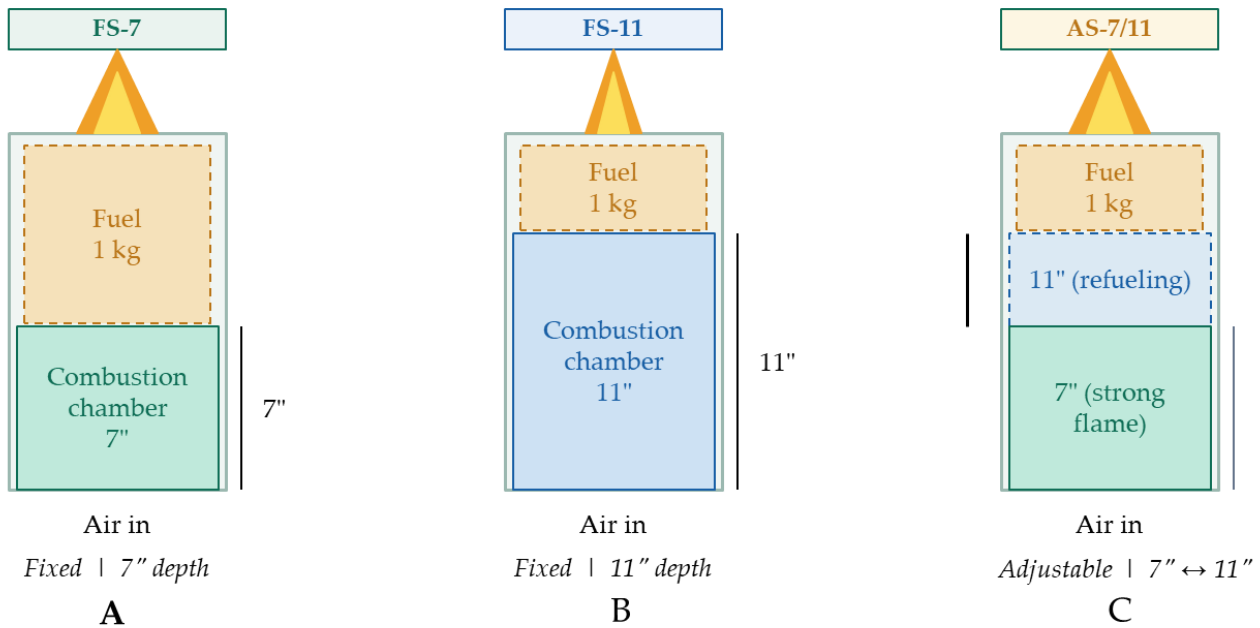


Figure 1 Schematic Diagram — Combustion Chamber Comparison A) Fixed 7" depth B) Fixed 7" depth. C) Adjustable 7" ↔ 11"

Note: AS-7/11 sequence: ① Set 11" → ② Flame decreases → ③ Adjust to 7" (stronger flame) → ④ Refuel → reset to 11"

2.2.2 The Burning Rate (BR)

The Burning Rate (BR) meant the quantity of biomass fuel combusted per unit of time, as determined from equation (2) [14]. The combustion rate reflects fuel consumption associated with the biomass stove's operation.

$$R_b = \frac{f_d}{\Delta t_m} \quad (2)$$

R_b represented the combustion rate in grams per minute (g/min). f_d represented the fuel's mass. It is quantified in kilograms (kg). Δt_m represented the duration of combustion in minutes. It was quantified in minutes (min).

2.2.3 Firepower (P)

Firepower (P) was the rate at which biomass fuels were converted to thermal power per unit of time. It is calculated from equation (3) [12]. High firepower is appropriate for rapid boiling, such as steam generation, but low firepower is ideal for stewing and simmering.

$$P = \frac{E}{\Delta t_s} \quad (3)$$

P represented the power output of the biomass stove, measured in kilowatts (kW). E represented the energy measured in kilojoules (kJ). Δt_s represented the duration of combustion in seconds. It was measured in seconds (s).

2.2.4 Boiling Time (BT)

Boiling Time (BT) is the time, in minutes, required for 5 kg of water to reach its boiling point. Signifies a decrease in the operational duration for biomass stove users. The test results were compared among FS-7, FS-11, and AS-7/11. The performance evaluation of the three types of biomass stoves was conducted in duplicate repeatedly. The experimental data were analyzed using analysis of variance (ANOVA), and mean differences were evaluated using Duncan's multiple-range test at a significance level of 0.05. The AS-7/11

biomass stove addresses the constraints of stoves with fixed combustion chambers by allowing the depth to be set to 11 inches, thereby enhancing the stove's firepower for rapid initial water boiling. Subsequently, the depth of the combustion chamber is reduced to 7 inches to reduce the biomass stove's firepower in accordance with application requirements, thereby enhancing thermal efficiency and conserving fuel. It may be readily adjusted to the operational conditions. A deeper combustion chamber will have a greater volume of pyrolysis and combustion zones, thereby enabling producer gas at a higher rate over the same period. This results in an elevated heat release rate, directly influencing the firepower output [15].

3. Results and Discussion

3.1 Development of TLUD-type biomass stove with adjustable combustion chamber level

The TLUD biomass stove has been improved and advanced to allow for the adjustment of the combustion chamber's height using the pedal plate shown in Figures 2A) to 2B). The TLUD biomass stove developed is made of thick steel plates (2 mm thick) joined together to form a rectangle. 1) The stove body supports the combustion chamber, covering 12" in width, 12" in length, and 20.5" in height. 2) The combustion chamber is 7.5" in width, 7.5" in length, and 12" in depth. 3) The ash tray functions to contain ash produced by biomass combustion within the combustion chamber. 4) The force draft system regulates air release and directs airflow into the lower section of the combustion chamber. 5) The choke ring functions to minimize flame dispersion at the stove aperture. A rail is there to facilitate the introduction of biomass fuel into the combustion chamber, along with a 2.5" container supporter. 6) The pedal plate and grate lever mechanism function to modify the depth of the combustion chamber during the operation of a TLUD biomass stove. To adjust the combustion chamber depth from 11" to 7", the user presses the "pedal plate," which transmits force to the "grate lifting rod" via the grate lever. Using the lever principle, the grate is raised. The "lever support" is then rotated by the user to support the "grate lever" and lock the grate level. To adjust the combustion chamber depth from 7" to 11", the "lever support" is rotated away from the "grate lever," which changes the grate position from 7" to 11", as illustrated in Figure 3. Figure 2C) illustrates that the base of the combustion chamber features a grate linked to the grate lifting rod, accompanied by a guide slot that ensures the grate lifting rod remains stable during operation, thereby adjusting the combustion chamber's level.

3.2 Comparison of stove performance at different conditions

Performance test results for the three TLUD biomass stove varieties: FS-7, FS-11, and AS-7/11. The test maintains control over external variables, including energy loss due to wind, by conducting experiments within the fume hood, as illustrated in Figure 4. Figures 5A) to 5D) present the test results of the three TLUD biomass stoves.

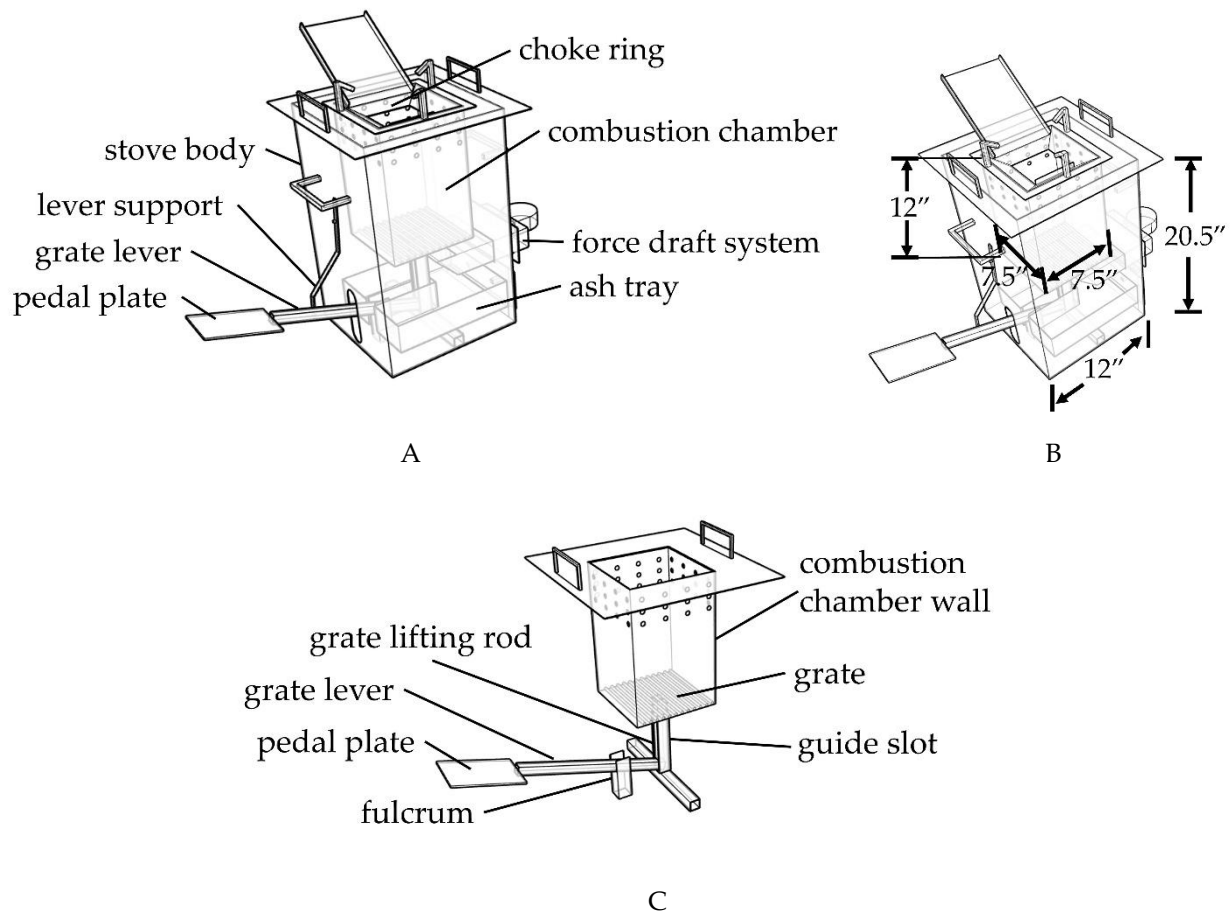


Figure 2. A) Diagram of a TLUD biomass stove, which includes an adjustable combustion chamber
 B) Observations of TLUD biomass stoves, including an adjustable combustion chamber
 C) Illustration of the combustion chamber and the apparatus used to level the grate

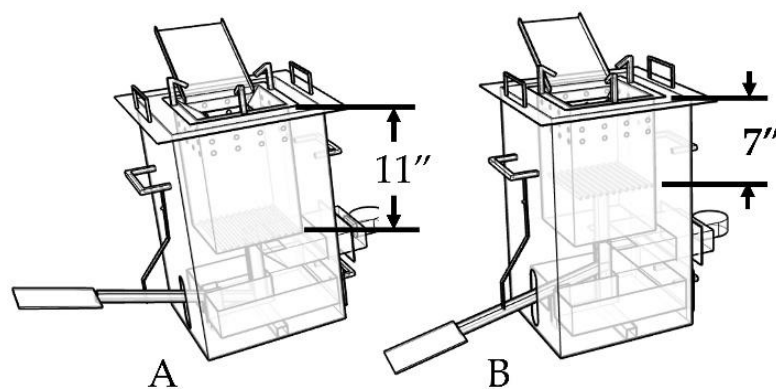


Figure 3. A) Biomass stove with 11" deep combustion chamber leveling and B) Biomass stove with 7" deep combustion chamber leveling



Figure 4. Performance evaluation of TLUD biomass stove with the WBT method

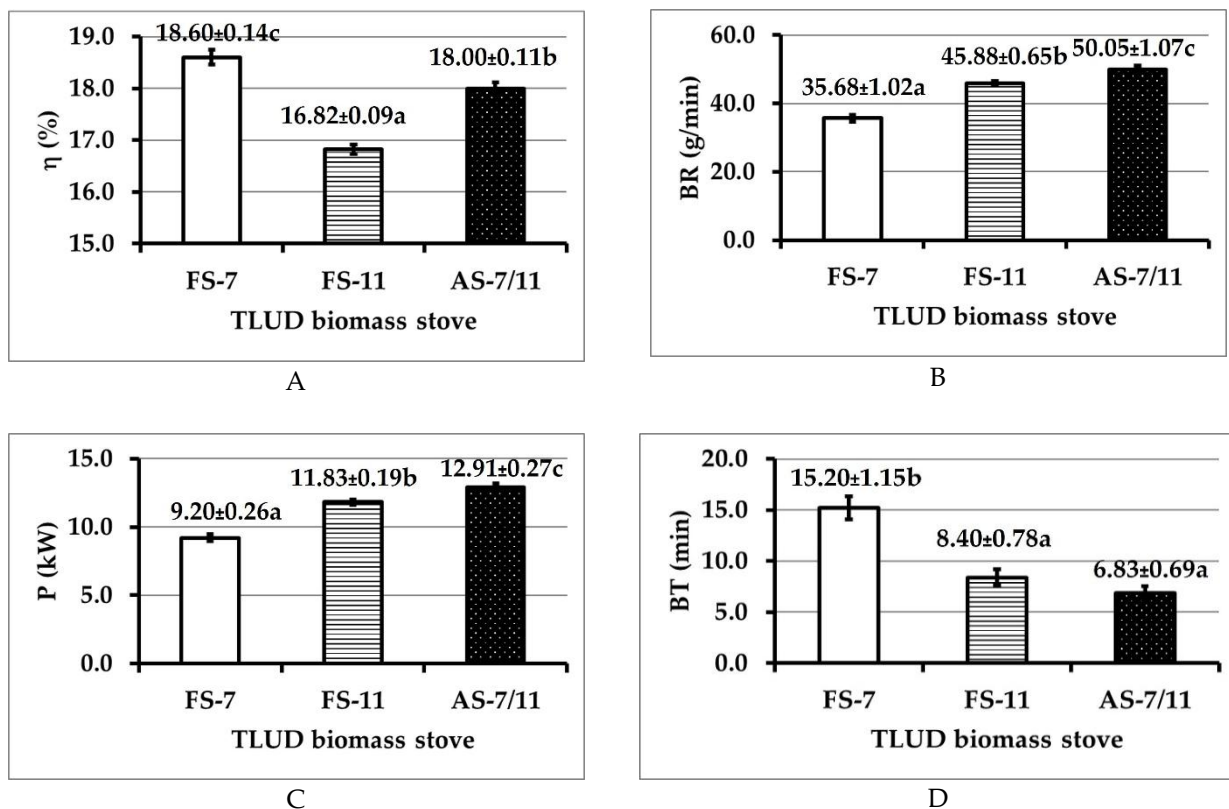


Figure 5. A) Comparative analysis of the thermal efficiency (η) of a TLUD biomass stove. B) Comparative analysis of burning rate (BR) in TLUD biomass stoves. C) Comparative analysis of firepower (P) in TLUD biomass stoves. D) Comparison of boiling time (BT) for water using a TLUD biomass stove. Notice: For identical letters, no statistical difference was observed at the 0.05 significance level.

Figure 5A) presents a comparison of the thermal efficiency of the TLUD biomass stove in all three conditions, which shows a statistically significant difference at the 0.05 level. FS-7 shows the highest thermal efficiency (18.60 ± 0.14%), followed by AS-7/11 (18.00 ± 0.11%) and FS-11 (16.82 ± 0.09%). The test results indicated that the depth of the biomass stove's combustion chamber was inversely related to thermal efficiency, as a deeper chamber lost thermal energy before reaching the water container used for the test. Depth-adjustable combustion chambers offer greater operational flexibility, but they exhibit higher thermal energy losses than shallow or fixed combustion chambers [10, 16]. TLUD biomass stoves using a shallow combustion chamber

(FS-7) exhibit superior thermal efficiency compared to those with deep combustion chambers (FS-11), as heat loss through the chamber walls escalates with the distance traveled by the hot gases. A small combustion chamber with a short gas flow path minimizes conductive and convective heat loss, thereby enhancing the efficiency of energy transfer to the container [15].

Figure 5B) illustrates that the burning rate of the TLUD biomass stove showed a statistically significant difference at the 0.05 level, with AS-7/11 recording the highest rate (50.05 ± 1.07 g/min), followed by FS-11 (45.88 ± 0.65 g/min) and FS-7 (35.68 ± 1.02 g/min). It was shown that AS-7/11, a stove with an adjustable combustion chamber level, achieved the highest burning rate compared with FS-7 and FS-11, which maintained a fixed combustion chamber level during the test. As the combustion chamber was leveled, ash fell from the grate, facilitating increased airflow from below into the combustion chamber [17]. This results from the impact and vibration of the grate during combustion chamber leveling. Consequently, the ash descends from the grate, creating an opening that allows increased air intake into the combustion chamber from below, thereby enhancing the stove's firepower. Figure 5C) illustrates that the firepower output of the three TLUD biomass stoves exhibited a statistically significant difference at the 0.05 level, with AS-7/11 showing the highest value (12.91 ± 0.27 kW), followed by FS-11 (11.83 ± 0.19 kW) and FS-7 (9.20 ± 0.26 kW), respectively. Figure 5D) illustrates that AS-7/11 (6.83 ± 0.69 min) and FS-11 (8.40 ± 0.78 min) show no different values; however, FS-7 (15.50 ± 1.15 min) is statistically substantially greater than both AS-7/11 and FS-11 at the 0.05 significance level. The size of the combustion chamber influences the rate of biomass energy transfer from the chamber to the container and the water used in the experiment [16]. A deeper combustion chamber could heat 5 liters of water to its boiling point faster than a shallower one [18]. Test results indicate that the AS-7/11 is optimal due to its ability to adjust the grate level of the combustion chamber during operation. This represents a trade-off between achieving satisfactory thermal efficiency, high firepower, and a fast boiling time.

3.3 Comparison with other biomass stoves

The AS-7/11 biomass stove is distinguished by its high output and short operating time, making it ideal for quick tasks or high-power applications such as steaming. It is suitable for boiling large quantities of water or deep-frying. The AS-7/11 features a forced draft system. The AS-7/11 offers increased firepower, a higher combustion rate, and improved boiling times for water. The AS-7/11 features a forced-draft system that allows more air to enter the combustion chamber than other stoves. The AS-7/11 provides increased firepower, a higher burning rate, and improved boiling times for water [19-21].

Table 1. Comparative analysis of biomass stove performance

Biomass stoves	η (%)	P (kW)	BR (g/min)	BT (min)	Highlights
AS-7/11	18.00	12.91	50.05	6.83	Highest firepower & lowest operating time
Development TLUD [20]	25.78	7.19	27.89	12.86	Save fuel and moderate power output.
Standard TLUD [20]	24.87	6.64	25.76	20.64	Save fuel and moderate power output.
Traditional TLUD [20]	18.92	8.57	33.23	16.69	Easy to build
Protruding stove [20]	21.96	5.52	21.41	34.16	Releases heat slowly
TLUD 9-holes [19]	10.85	-	-	-	Easy to build
Heavy rocket [21]	35.1	4.8	-	20	Most of the savings in fuel

4. Conclusions

The AS-7/11 TLUD biomass stove features an adjustable combustion chamber depth of 7" and 11" during use. The AS-7/11 biomass stove is designed for applications that require power modulation during operation, overcoming the constraints of conventional biomass stoves that deliver fixed firepower via an adjustable combustion chamber depth mechanism. This adaptability addresses the requirements of processes that require various levels of continuous heating, such as rapid cooking followed by simmering, or applications that demand high or low heat throughout operation, eliminating the need for multiple biomass stove types, as the combustion chamber's depth can be adjusted to match the task's needs. This study

demonstrated the AS-7/11 biomass stove's effective performance and flexibility; however, it did not quantify emissions such as PM_{2.5} or CO. Consequently, future research should test emissions and analyze the consequences of using alternative biomass fuel types.

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