Performance Evaluation of a Forced-Aeration Micro-Gasifier Stove for Rice Husk Gasification

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Abstract

Rice husk is a widely available agricultural residue used for energy generation in many developing countries. Its gasification in micro-gasifier stoves offers a practical method for clean energy production. However, the unique shape and bulk density of rice husk cause fuel bridging and poor flow, leading to incomplete gasification unless sufficient aeration is provided. In this study, design modifications were applied to an existing micro-gasifier stove, and a forced-aeration system was integrated to ensure adequate oxygen supply during combustion. A full factorial experiment was conducted to evaluate stove performance, with injection air velocity and fuel mass selected as experimental factors. Using a 3.97-litre micro-gasifier stove, three air velocities (0.6, 0.7, and 0.8 m s^{-1}) and three fuel levels (200, 300, and 400 g) were tested during the cold-start phase following the water boiling test protocol. Results were statistically analysed using factorial analysis within a completely randomised design. The findings showed that both air velocity and fuel mass factors significantly affect stove performance metrics ($p \leq 0.05$), including thermal power, thermal efficiency, fuel consumption rate, and boiling time. The highest thermal efficiency (51.7%) was achieved with 200 g of fuel at an air velocity of 0.6 m s^{-1}. The maximum thermal power (5420 W) occurred at an air velocity of 0.8 m s^{-1}.

Keywords: Biomass, Micro-Gasifier, Rice Husk, Thermal Efficiency, Thermal Power

Introduction

Rice (*Oryza sativa*) is one of the most important cereal crops extensively cultivated across the globe. In 2023, the worldwide annual production of paddy rice reached approximately 787 million tons (Mt) (Food and Agriculture Organization of the United Nations [FAO], 2024). Rice husk is one of the residues of rice post-harvest processes, considered agricultural waste (Tanpaiboonkul, Asavapisit, & Sungwornpatansakul, 2010). It has a hard surface, low density, and high silica content (Alvarez, Lopez, Amutio, Bilbao, & Olazar, 2014). Rice husk mainly consists of cellulose and hemicellulose in varying amounts ranging from 56% to 75%, along with lignin content between 13.6% and 34.8 (Nawaz *et al.*, 2023). Rice husk accounts for approximately 20% of the total weight of paddy rice (Mohammed *et al.*, 2024). Approximately 680 million tonnes of husked rice are produced annually, which results in the production of about 108 million tonnes of rice husk (Bodie, Micciche, Atungulu, Rothrock, & Ricke, 2019). Rice husk can be valuable; however, if not managed correctly, it may turn into hazardous waste (Fathurahman & Surjosatyo, 2022). In some regions, over 90% of rice husk is either burned in open spaces or disposed of in rivers and oceans (Quispe, Navia, & Kahhat, 2017). Additionally, rice husk is disposed of in landfill sites, posing serious environmental issues (Alvarez *et al.*, 2014; Pode, 2016). Furthermore, rice husk has various applications, including animal feed, fertiliser in plant nurseries, soil structure improvement, cooking fuel, colour enhancers, water purification, glassware cleaning, oil absorption, lightweight material production, cement, concrete, insect pest control in food storage warehouses, and more (Eliche-Quesada, Felipe-Sesé, López-Pérez, & Infantes-Molina, 2017; Pode, 2016). Due to the growing demand for converting waste into energy, significant research has been directed toward utilising rice husk as a fuel source. Approximately 2.4 billion people rely on wood, animal dung, charcoal, and other biomass fuels for cooking. Many of them use open fires or traditional cooking systems, such as two-wall stoves, which often lead to inefficient fuel use, low thermal efficiency, high pollutant emissions, adverse health effects, increased mortality, and deforestation (Lertsatitthanakorn, Jamradloedluk, & Rungsiyopas, 2014).

One way to overcome these issues is to replace these inefficient traditional methods with developed biomass stoves and micro-gasifiers. By employing gasification principles, micro-gasifiers exhibit higher efficiency and lower pollution compared to traditional methods (Roth, 2011; Yunusa *et al.*, 2023). As a result, a higher heat flame was produced compared to traditional methods, improving fuel consumption (Raman, Murali, Sakthivadivel, & Vigneswaran, 2013). Even in countries rich in fossil fuels, rural and remote areas have always faced challenges in accessing fuel and ensuring its continuous supply. Therefore, using micro-gasifier biomass stoves, due to their good efficiency, and low cost and low pollution compared to traditional methods, could be a suitable option for replacing or utilising as a complementary approach alongside traditional methods (Rasoulkhani, Ebrahimi-Nik, Abbaspour-Fard, & Rohani, 2019).

In recent studies, which address micro-gasifier stoves, Ebrahimi-Nik and Rohani (2019) examined almond shell and corn cob as fuel sources. They stated that the flame produced by all mentioned fuels was smokeless and particulate-free, except in the final stage (complete combustion). Almond shell (350 g) was reported to exhibit the longest flaming duration, equal to 51 min. In a closed, non-ventilated environment, the average carbon monoxide concentration measured in an individual's breathing zone was 7.5 ppm, compared with 430 ppm produced by conventional combustion (Ebrahimi-Nik & Rohani, 2019). Rasoulkhani *et al.* (2019) evaluated the combustion of cotton stalk, corn cob, and walnut shell using a micro-gasifier stove. They reported that increasing the heat efficiency and boiling time occurred with an increase in fuel density, accompanied by a decrease in fuel consumption. They reported the highest efficiency for walnut shell fuel and the shortest boiling time for corn cobs (Rasoulkhani *et al.*, 2019). Parmigiani, Vitali, Lezzi, and Vaccari (2014) examined the gasification stove using rice husk as fuel. They admitted that the stove showed an acceptable pollution level. These researchers reported a calculated heat efficiency of 18% for the constructed biomass stove and an average stove operating time of 57 min. Makwana, Pandey, and Mishra (2019) also investigated the fluidised bed gasifier stove using rice husk as fuel. In this study, high calorific values of 6.3 MJ N.m^{-3} were reported, respectively. They stated a good heating value and low suspended particle and tar content for the stove.

Osei, Kemausuor, Commeh, Akowuah, and Owusu-Takyi (2020) focused on the design, construction, and evaluation of a downdraft gasifier (reverse gasification) using rice husk as the raw material. The performance evaluation of the gasifier showed a thermal efficiency between 30.5% and 38.1%. The analysis showed that the downdraft gasifier significantly reduces pollutant emissions compared to domestic stoves, demonstrating its high efficiency. Susastriawan and Saptoadi (2019) conducted a study in which they compared the performance of gasification in a fixed-bed gasifier fed with different raw materials: rice husk, sawdust, and their mixture. The gasification was carried out at different ratios of rice husk and sawdust (0.15, 0.20, and 0.25). The results showed the compatibility of the gasifier for rice husks, sawdust, and their mixture. At optimum ratios, the lower heating value of the gas produced for rice husks, sawdust and the mixture were given as 3.13, 2.69, and 0.35 MJ m^{-3}, respectively. The efficiency of the cold gas was given as 72.73%, 69.27%, and 82.08% for the respective materials. Park *et al.* (2021) investigated the operating characteristics gasification of 20 tons of rice husks per day in a fluidised bed reactor. The study found an optimum equilibrium ratio of 0.20 and a tar removal efficiency of 98% by the purification units. Gasification conditions were studied with equilibrium ratios of 0.35 to 0.20 and gasification temperatures of 850 to 700 degrees Celsius in a 20 tons per day fluidised bed gasification system. An equilibrium ratio of 0.2 and a gasification temperature of 800 degrees Celsius were determined as the optimum operating conditions, with the lower calorific value of the gas product and the efficiency of the cold gas being specified as 1.37 MJ m^{-3} and 70.75%, respectively.

The present study aims to optimise an existing and previously studied micro-gasifier stove (Ebrahimi-Nik & Rohani, 2019) by integrating an artificial aeration system for the utilisation of rice husk as fuel. The secondary objective is to investigate the effects of airflow velocity and fuel loading level (expressed as the fuel bed thickness within the combustion chamber) on selected performance parameters of the micro-gasifier stove.

Materials and Methods

Stove setup

The Stove has an updraft configuration and comprises two nested metal cylinders, each with a thickness of 0.6 mm, featuring dual sets of primary and secondary air inlet apertures, as illustrated in Figures 1 and 2. It has a 75 mm gap between the lower rims of the inner and outer cylinders, which significantly enhances operational efficiency based on empirical findings (Table 1).

Fig. 1. Schematic view (left) and interior view (right) of the Bioheat brand biomass stove used in this study

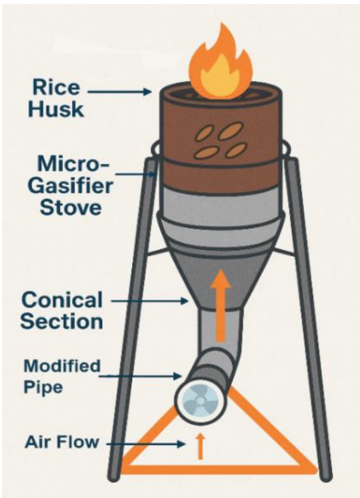

Fig. 2. Modified micro-gasifier stove (Bioheat) with an electric fan and piping as an artificial aeration system

Table 1- Geometrical dimensions of the Bioheat stove chamber

Original part (Stove cylinder)	Height (mm)	Diameter (mm)	Diameter of air holes (mm)	Space between air holes (mm)
External cylinder	305	200	15	10
			8	10
Inner cylinder	225	150	5	3

Stove optimisation

Burning rice husk in the micro-gasifier stove is challenging due to the peculiar shape and physical characteristics of rice husk, which tend to accumulate. Therefore, it requires an enhanced air supply. To address this issue and improve air supply, a manifold with a conical shape was designed for the lower part of the stove. A 20-watt DC fan was installed at the beginning of the manifold. Since most of these stoves are used in off-grid locations, powering the fan is feasible using rechargeable batteries. A support stand was installed to securely hold the stove in place. Screws, nuts, and aluminium adhesive were used to seal the surrounding space. Further fan specifications are provided in Table 2.

Table 2- Specifications of the fan used

Fan type	Nominal voltage	Fan diameter (mm)	Fan length (mm)	Power (W)	Maximum air speed (m s^{-1})
Jet fan	12 v DC	46	60	20	**19**

After igniting the stove, thermal imaging was utilised to examine the heat flow in the stove body. At lower temperatures, the thermal image exhibits a halo with blue, purple, or green hues, which transitions to a halo with red, orange, and yellow colours as the temperature increases. Figure 3 displays the thermal image of the rice husk gas stove, while Figure 4 illustrates the rice husk gas stove during experiments.

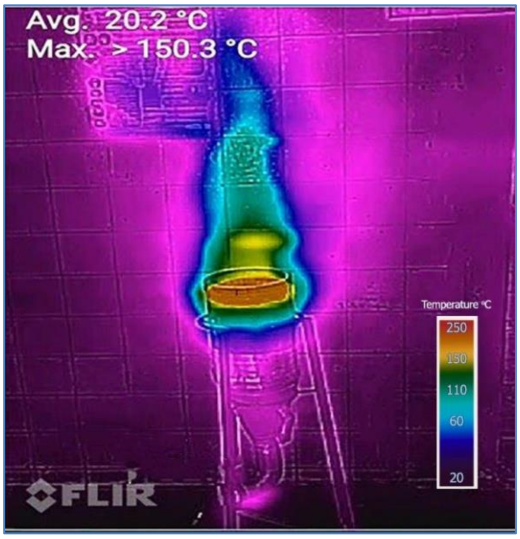

Fig. 3. Infrared thermal image of the rice husk–fuelled gas stove during operation, showing the temperature distribution and variations above the flame zone

Fig. 4. Rice husk gas stove and flame adjustment using air velocities of 0.6, 0.7, and 0.8 m s^{-1}

Descriptive Characteristics of Rice Husk

The present research utilises rice husk as fuel in micro-gasifier stoves. Rice husk was obtained from rice production workshops located in various regions of Guilan Province (north of Iran). Following the procurement of the fuel and its conditioning to ambient air and sunlight to achieve the specified moisture level, the bulk density of the prepared rice husk sample was measured to be 0.11 g cm^{-3} at a moisture content of 10.64% (dry basis). Three distinct charge quantities weighing 200, 300, and 400 g were prepared for experimental purposes. These fuel loads corresponded to approximate thicknesses of 10 cm, 15 cm, and 20 cm, respectively. Figure 5 illustrates the rice husk as fuel.

Table 3 summarises the physical, chemical, and thermal properties of rice husk, which significantly influence its behaviour during combustion and gasification in biomass stoves. The relatively low density (0.30–0.45 g cm^{-3}) and high porosity (~70%) (Jha, & Singh, 2007) indicate that the rice husk forms a loose and highly porous bed, which can hinder uniform oxygen distribution and gas flow through the fuel matrix. This structural characteristic often leads to incomplete combustion or unstable flame formation in conventional stoves. Chemically, the high silica content (15–20 wt%) contributes to ash formation and sintering, further obstructing gas permeability and affecting thermal efficiency. The moderate levels of carbon (35–40 wt%) and volatile components enable satisfactory heat release with a combustion heat value of about 13–16 MJ kg^{-1} (Della, Kuhn & Hotza, 2002), although the elevated ash percentage (~18%) and its high thermal stability (~1000 °C) pose challenges for continuous operation and residue removal. These combined properties explain the need for improved air supply mechanisms and optimised reactor design when using rice husk as a biomass fuel.

Table 3- Physical, chemical, and thermal properties of rice husk

	Feature	Approximate value	Reference
Physical properties	Density	About 0.96-1.04 g cm^{-3}	(Jha, & Singh, 2007)
	Bulk density	0.11 g cm^{-3}	This study
	Porosity	70%	
	Moisture	10.64	
	Colour	Greyish brown	
	Carbon	35-40% (wt)	
	Oxygen (O)	30-35% (wt)	
	Hydrogen (H)	4-6% (wt)	
	Potassium (K_2O)	1-3% (wt)	
	Calcium MgO, Fe_2O_3 (CaO)	1%> (wt)	
Thermal Properties	Heat value of combustion	13-16MJ kg^{-1}	(Della *et al.*, 2002)
	Thermal decomposition temperature	220-315°C	
	Complete combustion temperature	500-600°C	
	Thermal conductivity	0.05-0.09 $W·m^{-1}·K^{-1}$	
	Ash percentage	18% (wt)	
	Ash thermal stability	1000°C	
	Lower heating value of biomass (LHV_b)	14.5 (MJ kg^{-1})	
	Lower heating value of charcoal (LHV_c)	27 (MJ kg^{-1})	

Fig. 5. The rice husk used in this study as the stove fuel

Statistical Analysis

In order to investigate the performance of micro-gasifier stoves using rice husk as fuel, experiments were designed based on a completely randomised factorial with two independent factors: injection air velocity at three levels of 0.6, 0.7, and 0.8 m s^{-1}, and stove fuel at three levels of 200, 300, and 400 g, using three repetitions. Dependent factors included efficiency and heat power in the water boiling test. After analysis of variance and evaluation of the results of each assessment index, the Tukey test was performed on the results using Minitab 17 statistical software.

The Water Boiling Test (WBT)

The water boiling test (WBT) is one of the commonly used methods to assess the performance of biomass stoves and has been extensively used by researchers to evaluate stove thermal performance (Wang *et al.*, 2016). To evaluate biomass stoves under controlled laboratory conditions, the water boiling test is utilised, which simulates a simple cooking process. WBT consists of three phases: cold start, warm-up, and half-boil, which are sequentially followed. All tests conducted in the present study were based on the cold start phase of the water boiling test. In each repetition, 1 kg of water was heated in a 3-litre aluminium container from ambient temperature (27°C ± 2°C) to boiling temperature (Rasoulkhani *et al.*, 2019) using 200, 300, and 400 grams of fuel. At the end of each cold start phase, the amount of evaporated water reaching boiling temperature was measured using weighing scales. Additionally, to examine the effects of artificial aeration by the fan, stove performance evaluations were conducted at three air velocity levels of 0.6, 0.7, and 0.8 m s^{-1} by adjusting the voltage of the power supply. The experiments were conducted at the Biogas Laboratory of the Biosystems Engineering Department, Faculty of Agriculture, Ferdowsi University of Mashhad, located at an average altitude of 1,050 m above sea level, with a local boiling temperature of 96°C.

Calculation of Efficiency

The generated heat is partially transferred to the surrounding environment as well as to the stove itself. A higher thermal efficiency means that a greater amount of energy is transferred to the water container, or in other words, that the majority of the heat generated is directed towards the primary goal (boiling water). Another part of efficiency refers to the efficiency of fuel conversion. This refers to how much of the heat energy contained in the rice husks is effectively converted with oxygen to generate heat (Rasoulkhani *et al.*, 2019).

Stove efficiency based on the amount of heat transferred to water is calculated according to Equation (1) (Global Alliance for Clean Cookstoves, 2014).

$$\eta = \frac{c_w m_w (T_{eb} - T_{env})}{m_b LHV_b - m_c LHV_C} \times 100 \tag{1}$$

where: c_w is the specific heat of water (4.18 kJ $kg^{-1}K^{-1}$), m_w is mass of water, $T_{eb} - T_{env}$ is the temperature difference between boiling and initial temperatures (K), m_b is the mass of biomass fed into the stove (kg), LHV_b is the lower heating value of biomass (MJ kg^{-1}), m_c is the mass of remaining charcoal (kg) and LHV_c is the lower heating value of charcoal.

Calculation of Heat Power

The heat power of the stove is calculated according to Equation (2) (Global Alliance for Clean Cookstoves, 2014).

$$P = \frac{m_b LHV_b - m_c LHV_c}{TD_s} \quad (2)$$

where TD_s is test duration in seconds, and P is the thermal power of the stove in watts.

Evaluation Equipment

For real-time monitoring of flame temperature and water temperature at two-second intervals during the tests, a four-channel thermometer TM-947SD (Lutron, Taiwan) with a data logger equipped with a type K thermocouple was used, and it was capable of displaying and recording four temperatures simultaneously with a minimum data recording time of one second. A precise digital scale GF-6100 (A&D, Japan) with a maximum capacity of 6100 g and measurement accuracy of 0.01 g was utilised for the monitoring of weight changes. The injection air flow rate was kept constant at three levels of 0.6, 0.7, and 0.8 m s^{-1} by adjusting the voltage of the fan power supply using an adjustable power supply. The air velocity was measured at the top of the fuel level in the stove using a hot-wire anemometer Testo 425 (Testo, Germany). For each air velocity level and for the three different fuel loading levels, the air velocity measurement test was performed before igniting the stove, and the corresponding fan supply voltage was recorded using an adjustable power supply.

Results and Discussion

The overall performance of each cookstove is evaluated using four factors: ease of fuel feeding, flame quality, thermal efficiency, and power output (Ebrahimi-Nik & Rohani, 2019). In this study, the ease of fuel feeding was simply assessed by observing how easily the top cover could be removed for fuel addition. The flame quality was evaluated based on a visual observation of a clean, relatively smokeless flame with a bright orange colour observed in some cases. During the experiments, no significant odour or eye irritation was noticed, indicating clean combustion. Thermal efficiency was determined using the Water Boiling Test (WBT) based on standard procedures, and the results are presented in the following sections.

Technical evaluation of the stove

To investigate the performance of the stove during the cold start phase, indices such as heat output, thermal efficiency, fuel consumption rate, and time to boiling were calculated (see Tables 4 to 6). These indices were analysed during the cold start phase using a completely randomised factorial design with two independent factors: Air velocity and fuel level (each at three levels). The heat output in Table 4 shows that the air speed and fuel level factors contribute significantly to the variation in heat output at a significance level of one percent (p-value = 0.00). After determining the significant effects of air velocity, fuel level, and their interactions on all indices, mean comparisons of the factors were conducted using Tukey's method at a confidence level of 99%, as shown in Figures 6 to 9. As observed, there are significant differences in the heat power produced among different levels of air velocity and fuel levels.

Heat power

Table 4 presents the analysis of variance (ANOVA) for the effects of air speed, fuel level, and their interaction on the thermal power index. The results indicate that both main factors significantly influenced the thermal power index, whereas their interaction effect was not statistically significant.

Air speed had the greatest contribution to the variation in the thermal power index, accounting for 57.75% of the total changes. The factor showed a highly significant effect ($F = 58.28$, $P < 0.01$), indicating that variations in air speed substantially altered the thermal power index. Fuel level was the second most influential factor, contributing 29.67% to the total variation. Like air speed, fuel level also had a statistically significant effect on the thermal power index ($F = 30.95$, $P < 0.01$), demonstrating that changes in fuel level significantly affected the response variable. In contrast, the interaction between air speed and fuel level explained only 3.50% of the total variation and was not statistically significant ($F = 1.74$, $P > 0.05$). This result suggests that the combined effect of these two factors did not produce a significant interaction on the thermal power index. The remaining variation (9.08%) was attributed to the experimental error. Overall, the ANOVA results demonstrate that air speed and fuel level independently play significant roles in determining the thermal power index, with air speed being the dominant factor.

Table 4- Analysis of variance of the effect of factors on the thermal power index

Sources of change	Degrees of freedom	Sum of squares	Share of changes (%)	F-value	P-value
Air speed	2	27,505,277	57.75	58.28	0.000**
Fuel level	2	14,131,422	29.67	30.95	0.000**
Air speed × Fuel level	4	1,667,136	3.50	1.74	
Error	18	4,322,255	9.08		
Total	26	47,626,090	100		

The trends in Figure 6 can be explained by the interaction between air supply and fuel level characteristics during combustion and gasification. During the experiments, it was evident that the flame intensity increased with the increase in fan air velocity. The highest heat power value was obtained at an air velocity of 0.8 m s^{-1}, indicating that increasing the air velocity leads to higher heat power. Increasing the air velocity enhances oxygen availability and mixing within the combustion zone, leading to complete oxidation of gaseous products and a higher flame temperature. This intensified reaction raises the thermal power at the maximum air velocity (0.8 m s^{-1}). The maximum power was above 5000 W at 0.8 m s^{-1} air speed. This is while Parmigiani *et al.* (2014) reported an average power of 4000 W.

Similarly, a lower fuel load (e.g., 200 g) improves air permeability through the rice-husk bed, facilitating uniform oxidation and efficient gasification, which results in higher power output. Conversely, thicker fuel layers (300–400 g) restrict airflow, reduce oxygen penetration, and cause incomplete combustion, thereby decreasing thermal power. These results highlight the importance of optimal air supply and fuel bed thickness for achieving efficient heat generation in forced-draft biomass stoves.

Thermal efficiency

Table 5 presents the analysis of variance (ANOVA) for the effects of air speed, fuel level, and their interaction on the thermal efficiency index. Fuel level was identified as the dominant factor affecting the thermal efficiency index, accounting for 85.49% of the total variation. The very high F-value ($F = 1173.8$, $P < 0.01$) indicates that changes in fuel level strongly influenced the efficiency of the system. Air speed also had a statistically significant effect on the thermal efficiency index ($F = 122.07$, $P < 0.01$), contributing 12.27% to the total variation. Although its contribution was smaller than that of the fuel level, the significant influence of air speed demonstrates that adjusting the airflow substantially affects the combustion and heat transfer conditions. This result confirms that the implementation of the auxiliary air supply system was an appropriate design choice, as variations in air speed significantly improved the thermal efficiency performance of the system.

The interaction between air speed and fuel level was also statistically significant ($F = 11.29$, $P < 0.01$), but its contribution to the total variation was relatively small (1.60%), indicating that the combined effect of these two factors played a limited role compared with their individual effects. The experimental error accounted for only 0.64% of the total variation, indicating good experimental precision. Overall, the ANOVA results demonstrate that while fuel level is the primary determinant of thermal efficiency, air speed—representing the auxiliary air supply—also plays a significant and beneficial role in improving the system's thermal efficiency

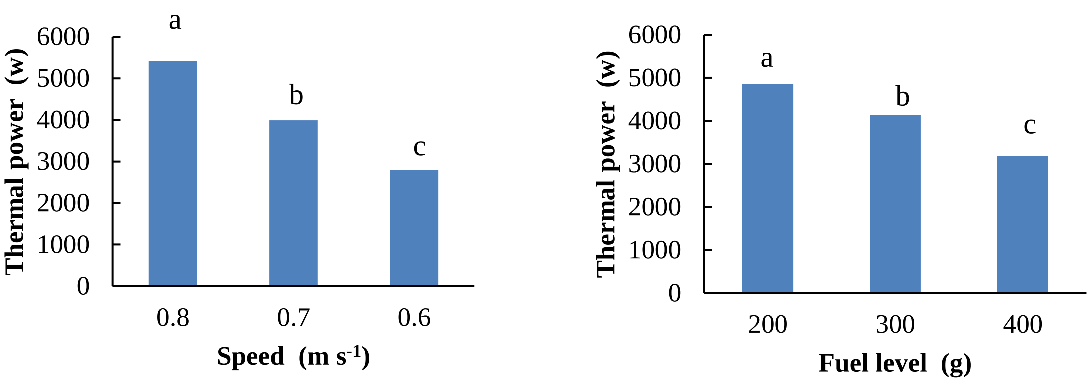

Fig. 6. Comparison of the average thermal power due to the main effect of fuel level and air flow

Table 5- Analysis of variance of the effect of factors on the thermal efficiency index

Sources of change	Degrees of freedom	Sum of squares	Share of changes (%)	F-value	P-value
Air speed	2	318.40	12.27	122.07	0.000**
Fuel level	2	2,219.42	85.49	1173.8	0.000**
Air speed × Fuel level	4	41.59	1.60	11.29	0.000**
Error	18	16.58	0.64		
Total	26	2596	100		

Comparisons of the averages between different levels of fuel for efficiency changes also showed statistically significant differences. The highest efficiency rate, with an average of 51.7%, according to Figure 7, was achieved with a combination of 0.6 m s^{-1} air velocity and 200 g of fuel level. This is in contrast to the report by Rasoulkhani *et al.* (2019) with an average efficiency rate of 27%. Parmigiani *et al.* (2014) also reported an average efficiency rate of 18%. It should be noted that, in calculating the stove's efficiency, the heat absorbed by the water for evaporation was not included. Therefore, the actual efficiency is slightly higher than the reported value.

The reason for the relatively high efficiency obtained in this study can be attributed to the stove's design and the pot used during the water boiling test, which effectively transferred heat from the flame to the pot. The flame produced was stable and moderately intense, resulting in minimal heat loss through radiation or convection.

Fuel consumption rate

Table 6 presents the analysis of variance (ANOVA) results for the effects of air speed, fuel level, and their interaction on the fuel consumption rate index. The results show that all studied factors had a statistically significant effect on the fuel consumption rate ($P < 0.01$).

Air speed was the most influential factor, accounting for 50.44% of the total variation, with a significant F-value of 35.34. Fuel level also significantly affected the fuel consumption rate, contributing 19.31% of the total variation (F = 17.76). In addition, the interaction between air speed and fuel level was statistically significant (F = 6.96), explaining 18.37% of the variation. The experimental error represented 11.88% of the total variation. Overall, the results indicate that air speed plays a dominant role in determining the fuel consumption rate index.

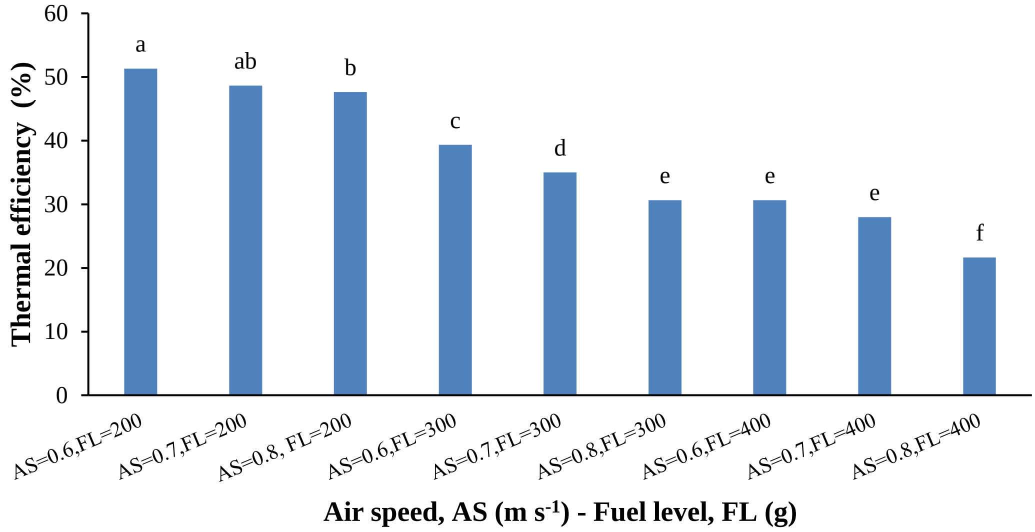

Fig. 7. Comparison of average thermal efficiency due to the shared effects of speed and fuel

Table 6- Analysis of variance of the effect of factors on the fuel consumption rate index

Sources of change	Degrees of freedom	Sum of squares	Share of changes (%)	F-value	P-value
Air speed	2	1021.3	50.44	35.34	0.000**
Fuel level	2	391.1	19.31	17.76	0.000**
Air speed × Fuel level	4	372	18.37	6.96	0.001**
Error	18	240.5	11.88		
Total	26	2024.9	100		

Figure 8 illustrates the combined effect of fuel loading and forced air velocity on the fuel consumption rate of the rice husk stove. The highest fuel consumption rate (49.84 g min^{-1}) was observed when 200 g of fuel was used at an air velocity of 0.8 m s^{-1}, while the lowest value (22.03 g min^{-1}) occurred at the same fuel load with a lower air velocity of 0.6 m s^{-1}. These results indicate that increasing the airflow significantly intensifies the combustion process and accelerates the rate at which the fuel is consumed.

From a physical perspective, higher air velocity increases the supply of oxygen to the combustion and gasification zones, which enhances the oxidation of volatile gases and char within the fuel bed, leading to stronger flames and faster reaction rates. Consequently, the biomass is converted and burned more rapidly, resulting in a higher fuel consumption rate. Fuel loading also affects this behaviour by altering the structure and permeability of the fuel bed. In contrast, increasing the fuel load forms a thicker fuel layer that restricts airflow through the inter-particle spaces, reducing oxygen availability and slowing both gasification and oxidation reactions. As a result, the fuel consumption rate decreases with increasing fuel bed thickness.

The minimum fuel consumption rate obtained in this study (22.03 g min^{-1}) was slightly higher than the value of 18 g min^{-1}

reported by Parmigiani *et al.* (2014) under natural aeration conditions.

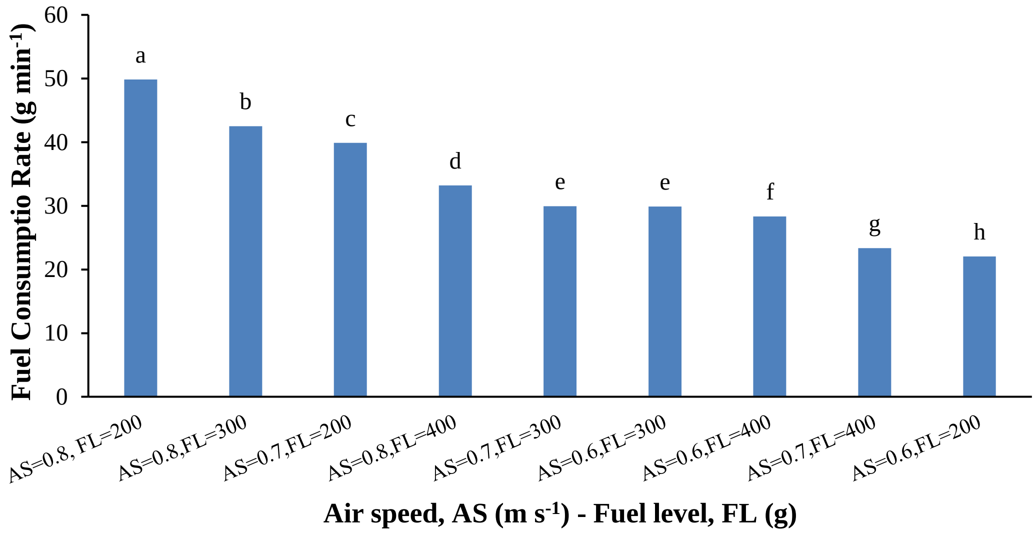

Fig. 8. Comparison of the average fuel consumption rate due to the shared effects of speed and fuel level

Time to boiling

Table 7 presents the ANOVA results for the effects of air speed, fuel level, and their interaction on the boiling time index. The results indicate that all factors significantly affected the boiling time ($P < 0.01$). Air speed had the greatest influence, accounting for 36.50% of the total variation ($F = 34.98$), followed by fuel level with a contribution of 33.82% ($F = 27.14$). The interaction between air speed and fuel level was also significant, explaining 18.48% of the variation. The experimental error accounted for 11.20% of the total variation. Overall, both air speed and fuel level played important roles in determining the boiling time index.

Table 7- Analysis of variance of the effect of factors on the boiling time index

Sources of change	Degrees of freedom	Sum of squares	Share of changes (%)	F-value	P-value
Air speed	2	25.792	36.50	34.98	0.000**
Fuel level	2	23.900	33.82	27.14	0.000**
Air speed × Fuel level	4	13.058	18.48	0.001	0.001**
Error	18	7.917	11.20		
Total	26	70.667	100		

Figure 9 presents the combined effects of fuel loading and forced air velocity on the time required to bring water to a boil. The longest boiling time was recorded for the combination of 400 g of fuel at an air velocity of 0.6 m s^{-1}, whereas the shortest boiling time was achieved using 200 g of fuel at an air velocity of 0.7 m s^{-1}. These results demonstrate that both insufficient air supply and excessive fuel loading adversely affect the heating performance of the stove. The comparison of the mean values was performed using Tukey's test, and the results are indicated by different letters above the bars in Figure 9. The observed separation of groups confirms that variations in air velocity and fuel loading lead to meaningful changes in boiling time. In particular, treatments with low air velocity and high fuel load form a distinct group with significantly longer boiling times, while combinations involving higher air velocity and lower fuel load are grouped separately with significantly shorter boiling times.

Moderate fuel loading coupled with higher air velocity improves air–fuel interaction and enhances the generation and combustion of volatile gases. The improved mixing and higher flame temperature increase the convective and radiative heat flux to the cooking pot, reducing the boiling time. The results are consistent with trends reported in previous studies, such as those by Rasoulkhani *et al.* (2019) and Parmigiani *et al.* (2014), and highlight the importance of balancing air supply and fuel bed thickness to achieve rapid and efficient heating in forced-draft biomass stoves.

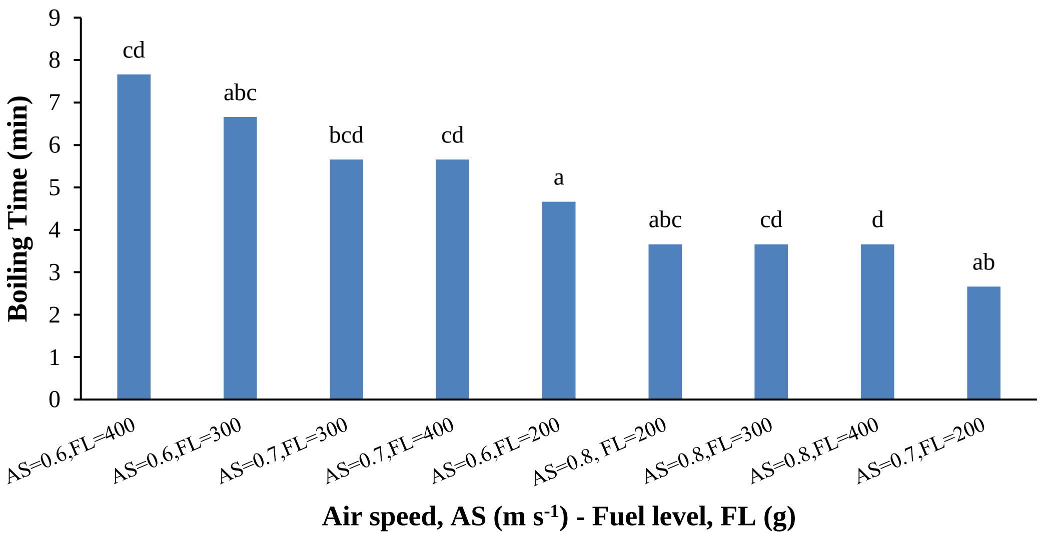

Fig. 9. Comparison of the average boiling time due to the shared effects of speed and fuel level

Conclusion

In this study, the performance of a semi-gasifier (micro-gasifier) biomass stove fuelled with rice husk was experimentally evaluated to determine the effects of air velocity and fuel loading on key performance indicators. The experiments were conducted under cold start conditions using the Water Boiling Test (WBT) protocol based on the EPTP standard, with three fuel levels (200, 300, and 400 g) and at three air velocities (0.6, 0.7, and 0.8 m s^{-1}).

The results demonstrated that both air supply rate and fuel bed thickness play a significant role in controlling the combustion and gasification processes inside the stove. Increasing the air velocity enhanced oxygen availability and improved the oxidation of combustible gases, which increased the thermal power of the system. Accordingly, the highest thermal power was obtained at an air velocity of 0.8 m s^{-1}. However, higher airflow also accelerated the combustion reactions and resulted in a higher fuel consumption rate, with the maximum value observed for 200 g of fuel and 0.8 m s^{-1} air velocity.

Fuel loading significantly influenced airflow distribution and permeability within the fuel bed. The highest thermal efficiency was achieved with 200 g of fuel at an air velocity of 0.6 m s^{-1}, while the shortest boiling time was obtained at 200 g of fuel and 0.7 m s^{-1} air velocity. In contrast, higher fuel loads increased bed resistance to airflow, which reduced oxygen penetration and slowed the gasification and combustion processes.

Overall, the findings indicate that the integration of a forced air supply system can significantly improve the combustion behaviour and thermal performance of rice husk–fuelled micro-gasifier stoves, particularly during the cold start phase.

Optimising the balance between air velocity and fuel loading is therefore essential for achieving higher efficiency, stable combustion, and faster heating performance in biomass cooking systems.

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Author Contributions

Z. Ebrahimi: Investigation (Data acquisition), Data curation (Pre and post-processing), Writing – original draft.

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ارزیابی عملکرد اجاق زیست‌توده‌سوز مجهز به سیستم هوادهی اجباری به‌منظور گازی‌سازی پوسته برنج

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چکیده

پوسته برنج یکی از پسماندهای کشاورزی رایج در بسیاری از کشورهای در حال توسعه است. گازی‌سازی آن در اجاق‌های میکروگازیفایر، روشی عملی برای تولید انرژی پاک به شمار می‌رود. با این حال، شکل منحصربه‌فرد و چگالی خاص پوسته برنج باعث پل‌زنی سوخت و جریان ضعیف هوا می‌شود؛ این امر، در صورت عدم تامین مصنوعی و کافی هوا، به گازی‌سازی ناقص می‌انجامد. در این تحقیق، اصلاحات طراحی بر روی یک اجاق میکروگازیفایر اعمال گردید و یک سیستم هوادهی اجباری به‌منظور اطمینان از تامین اکسیژن کافی در طول احتراق به آن افزوده شد. آزمایش به‌صورت فاکتوریل در قالب طرح کاملاً تصادفی با سه تکرار اجرا شد. محفظه احتراق اجاق دارای قطر ۱۵۰ میلی‌متر و ارتفاع ۲۲۵ میلی‌متر بود. ارزیابی‌ها طی آزمون جوشش آب در مرحله شروع سرد، در سه سطح جرم سوخت (۲۰۰، ۳۰۰ و ۴۰۰ گرم) که به‌ترتیب معادل ۴۵، ۶۸ و ۹۰ درصد حجم بارگیری محفظه بودند، و سه سرعت هوا (۰/۶، ۰/۷ و ۰/۸ متر بر ثانیه) تامین‌شده توسط یک فن الکتریکی انجام گرفت. نتایج نشان داد که سرعت هوای تزریقی و جرم سوخت به‌طور معنی‌داری بر شاخص‌های عملکرد اجاق، از جمله توان حرارتی، بازده حرارتی، نرخ مصرف سوخت و زمان جوشش تاثیر می‌گذارند. بیشترین بازده حرارتی (۵۱/۷ درصد) با ۲۰۰ گرم سوخت و در سرعت هوای ۰/۶ متر بر ثانیه به‌دست آمد، در حالی که بیشترین توان حرارتی (۵۴۲۰ وات) در سرعت هوای ۰/۸ متر بر ثانیه ثبت شد.

واژه‌های کلیدی: اجاق گازی‌ساز، بازده حرارتی، پوسته برنج، توان حرارتی، زیست‌توده

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