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Rice Straw Carbonizer: Potential Technology for Carbonized Rice Straw Production

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Abstract

Rice straw, the vegetative remnants of the rice plant, often discarded after harvest, faces issues when subjected to open burning, including loss of soil nutrients, moisture, pollution, and threats to nearby structures. The method of charcoal making involves biomass pyrolysis to produce biochar, effectively removing CO2 from the atmosphere. This study aimed to optimize biochar production using a locally designed rice straw carbonizer, accommodating 10 kg of material. Two moisture content samples, 8.90% and 11.70%, were examined for the carbonizer's performance, evaluating operation time, biochar yield, output capacity, air velocity, gas emissions, temperature, and cost. Findings revealed a biochar yield of 21.89% and an output capacity of 13.87 kg/hr for 8.90% moisture content, and 19.11% yield with 9.41 kg/hr output for 11.70% moisture content. The average operation time was 73.33 and 109.44 minutes for 8.90% and 11.70% moisture content, respectively, with a maximum temperature of 733.80°C. Air velocity averaged 0.70 m/s and 0.52 m/s for the two moisture levels. Flue gas analysis indicated the influence of moisture content on gas composition, with smaller valve openings leading to higher values. Cost analysis suggested a potential reduction in biochar production costs from PhP 12.60 to PhP 6.34 per kg by increasing processed rice straw from 5 to 12 tons annually. At a custom rate of PhP 8.00 per kg, processing 12 tons per year could yield approximately 2,672 kg of biochar. This research offers insights into enhancing biochar production efficiency and cost-effectiveness through moisture content adjustments and increased processing scale.

Keywords: Air velocity, Open Burning, Moisture Content, Fuel gas analysis, Biomass, Pyrolysis

Introduction

Rice straw is the vegetative part of the rice plant (Oryza sativa L.), cut during or after grain harvest and is left in the field as a residue. These are plowed down and allowed to decompose in the field as soil enhancers. It is also used as a feed for livestock in areas where rice straw is considered as a major forage (Kadam et al., 2000). Most farmers, however, still burn the rice straw especially those that piled up after the threshing operations. Stubble burning is one of the major contributors to atmospheric pollution in the world releasing particulate and gaseous pollutants that have severe effects on human health and the environment (Sharma et al., 2010). Carbonized rice straw is charcoal created through pyrolysis (burning with minimal oxygen) of biomass (e.g. agriculture and forest wastes) and is the most effective way to remove CO2 from the atmosphere. Carbonized rice straw is an almost pure carbon, where at least 50% of the CO2 emitted by a plant or tree absorbed from the atmosphere during its lifetime is trapped through the charring process. For every 1 kg of pure carbon produced, 3.67 kg of CO2 is taken out from the atmosphere (Bridle et al., 1990).

Carbonized rice straw, when incorporated into the soil, could remain for thousands of years. Carbonized rice straw or terra preta was developed thousands of years ago by the Native Americans in the Amazon region by smoldering agricultural waste. It was reported that Carbonized rice straw was used to enhance soil productivity, which earned their reputation in cultivating vast and fertile farmlands that are considered as the richest soil on Earth today. When used as soil amendment, Carbonized rice straw has the following benefits: (a) It boosts soil fertility; (b) prevents soil erosion; (c) improves soil quality by raising the soil pH; (d) traps moisture and renders growth of more beneficial fungi and microbes; (e) improves cation (positive ion) exchange capacity; (f) aids in soil nutrient retention; and (g) improves water quality by retaining agrochemicals and metals. Moreover, Carbonized rice straw is known to be a more stable nutrient source than compost and manure. Carbonized rice straw, therefore, as a soil amendment can be used to increase crop yields, reduce the need for chemical fertilizers, and minimize the adverse environmental effects of agrochemicals in the environment (PBiA, 2011).

Aside from smoldering agricultural waste, another option for making Carbonized rice straw is to turn the rice straw into charcoal by burning it while restricting the amount of oxygen to prevent the conversion of carbon into CO2. This can be done by returning the charcoal into the rice field. Therefore, instead of rice farming being a source of carbon emissions, it could actually store carbon, better known as carbon sequestration.

The general objective of the study was to develop a process to maximize the production of Carbonized rice straw using a rice straw carbonizer. The specific objectives were to design a rice straw carbonizer prototype for Carbonized rice straw production; fabricate the rice straw carbonizer using locally available materials; evaluate the performance of the device; and analyze the cost of producing Carbonized rice straw using the rice straw carbonizer.

Materials and Methods

<u>Design Concept and Consideration.</u> The concept of the design of the rice straw carbonizer was based on the principle that rice straw shall be burned inside a combustion chamber with controlled or limited supply of oxygen to produce a carbonized rice straw herein referred as Carbonized rice straw. In designing the carbonizer, the operating principle of the conventional batch-type rice hull carbonizer designed by the Philippine Rice Research Institute (PhilRice) was used for benchmarking purposes. The major concern of designing the carbonizer was finding ways to control the airflow since, aside from the material to be carbonized, it is the main factor that influences the carbonization process.

The concept can be viewed in the perspective design shown in Figure 1. The component parts of the device are: a) air inlet section with an air inlet valve to regulate the entry of air, b) combustion chamber, c) chimney, and d) frame assembly.

The device was designed considering the following:

a. It could accommodate about 10 kg of rice straw;
b. It could withstand high combustion temperature;
c. It should be easy to operate and maintain;
d. It should be low cost, simple in design, and can be fabricated using locally available materials and technology; and
e. It should be designed adhering to locally applicable standards (Philippine Agricultural and Biosystems Standards)

Design of the Major Components

Combustion chamber**.** The combustion chamber played a crucial role in the rice straw carbonization process. It was designed with a horizontal orientation to accommodate the majority of the loaded rice straw in a horizontal position. The dimension of the combustion chamber was set at a 0.80 m radius and 1.80 mm length, providing a total volume of 1.80 m^3, suitable for handling at least 10 kilograms of rice straw at 5 kg/bag increment. Considering a potential thickness of 2 mm for the mild steel plate, characterized by a density of 7.85 g/cm^3, the weight of the combustion chamber amounted to 88.45 kg.

Air Inlet Section**.** The air inlet section functioned as an entry point for the supplementary air, facilitating optimal and partial combustion within the combustion chamber. Regulating the airflow within the combustion chamber was managed by the 63.50 mm diameter globe valve integrated into this section, serving as the primary cover for the front section of the entire carbonizer. This design aimed to reduce air leakage during operation.

a. Air inlet valve. The 63.50 mm diameter of the globe valve, along with various openings, was considered to enhance the air delivery or suction within the combustion chamber. Positioned within this section, an anemometer was utilized to gauge the velocity of air flowing through the inlet section.
b. Air pipe extension. The 63.50 mm diameter air pipe extension was positioned in the lower part of the combustion chamber to facilitate the distribution of ambient air inside the chamber.

Chimney. The dimension of the chimney, in terms of diameter and length, were determined through calculation using the Ergun equation. This design aimed to facilitate the smooth passage of ambient air into the combustion chamber, ensuring a smokeless flow towards the chimney.

$$Rice\ Straw(RS) + Ambient\ air$$
$$+ CarbonizedRiceStraw(CRS)$$
$$+ volatiles\ +\ heat$$

Hence, the focus of the design was directed towards determining the optimal height of the chimney, as it plays a crucial role in establishing the natural draft. The draft arises from the pressure differential between the ambient air and the flue gas, calculated through equation 1.

$$\Delta p = (\rho a - \rho g)h \qquad (1)$$

where: Δp = pressure head, mm water column
ρa = density of the ambient air, kg/m3
ρg = density of the flue gas, kg/m3
h = height of the chimney, m

To compute for the desired height of the chimney, value for the pressure head in eq. (1) was made high enough to overcome the pressure loss as air passing through the bed of RS (based on the assumption that the air needed in the carbonization process had to pass the whole span of the RS bed depth). By assuming that the bed of RS in the carbonizer was a bed of uniformly-sized particles, the Ergun equation 2 (Ergun, 1952) described below was used to compute for this pressure loss:

$$\frac{\Delta p}{L} = \frac{150\mu V_s(1-\varepsilon)^2}{(d_p)^2\varepsilon^3} + \frac{1.75V_s^2\rho(1-\varepsilon)}{d_p\varepsilon^3} \qquad (2)$$

where: Δp = pressure drop
L = length (depth) of bed
ρ = density of the fluid
μ = dynamic viscosity of the fluid
V_s= superficial velocity
d_p= particle diameter
ε = void fraction of the bed (the ratio of the void volume to the total volume of the bed)

Combining equations (1) and (2), the equivalent length of chimney that compensated for the pressure loss were computed as follow:

$$h = \left[\frac{L}{\rho_a - \rho_g}\right]\left[\frac{150\mu V_s(1-\varepsilon)^2}{(d_p)^2\varepsilon^3} + \frac{1.75V_s^2\rho(1-\varepsilon)}{d_p\varepsilon^3}\right] (3)$$

Belonio (2005) recommended a 10% allowance to overcome this resistance (pressure loss). Appendix Table 1 shows the data/assumptions used in computing for the chimney height.

Diameter of the chimney was computed using the mass of gases flowing through any cross section by the formula:

$$mg = \rho_g (A)(C) \text{ since } A = \pi \frac{D^2}{4} \quad (4)$$

$$D = 1.128 \sqrt{\frac{mg}{\rho_{g.C}}}$$

where: mg = mass of gases flowing through any cross section of the chimney
g = density of gases
C = velocity of gases passing through the chimney

Frame Assembly. The frame assembly functions as the structural support for all the parts of the carbonizer. With this prototype, the frame design considered the total weight of the other components, the load of the rice straw in the chamber, and the potential weight of an individual who might need to mount the frame for data collection at the chimney outlet or make necessary adjustments. Calculating the size of the steel angle bar that bears the majority of the load, it was determined to be 25.4 mm x 3 mm x 6 m. This standard size of the angle bar was used across all frames for consistency and visual appeal.

Principles of Operation. All components including the combustion chamber, air inlet section, air inlet valve, air pipe extension and the chimney were prepared and installed properly at the start of operation. Dry rice straw was collected from the field. To start Carbonization, the air inlet section that serves as the cover for loading and unloading, was pulled out. Combustion chamber was filled with 10 kilograms of rice straw. Reinstall the air inlet section, and a source of fire was introduced to the combustion chamber. The air inlet valve regulated airflow, initiating carbonization. The burned rice straw was unloaded once the chimney emitted less smoke, placed in a cooling pan, and weighted for recovery.

Fabrication and Assembly of the Device. The approved design plan of the device served as the guide of the fabrication in a local machine shop. Fabrications of each component were done following the basic techniques and processes shown in Table 1. After the component was fabricated, the combustion chamber was welded. The frame assembly served as base support of the whole carbonizer assembly. Air inlet section was then hooked down on the base front and fitted to the opening of the carbonizer. Air inlet valve was coupled on the air inlet section and fitted using the toggle latch assembly. Chimney assembly was coupled at the rear section of the rice straw carbonizer.

Table 1. Basic Fabrication method of different components of rice straw carbonizer.

COMPONENTS	FABRICATION METHODS
Combustion Chamber	Measuring, shearing, bending, cutting, and welding
Air Inlet valve	Measuring, cutting, machining, and welding
Toggle Latch Assembly	Measuring, cutting, machining, and welding
Air Inlet Section Assembly	Measuring, cutting, bending, machining, and welding
Chimney Assembly	Measuring, cutting, bending, and welding
Frame Assembly	Measuring, cutting, and welding

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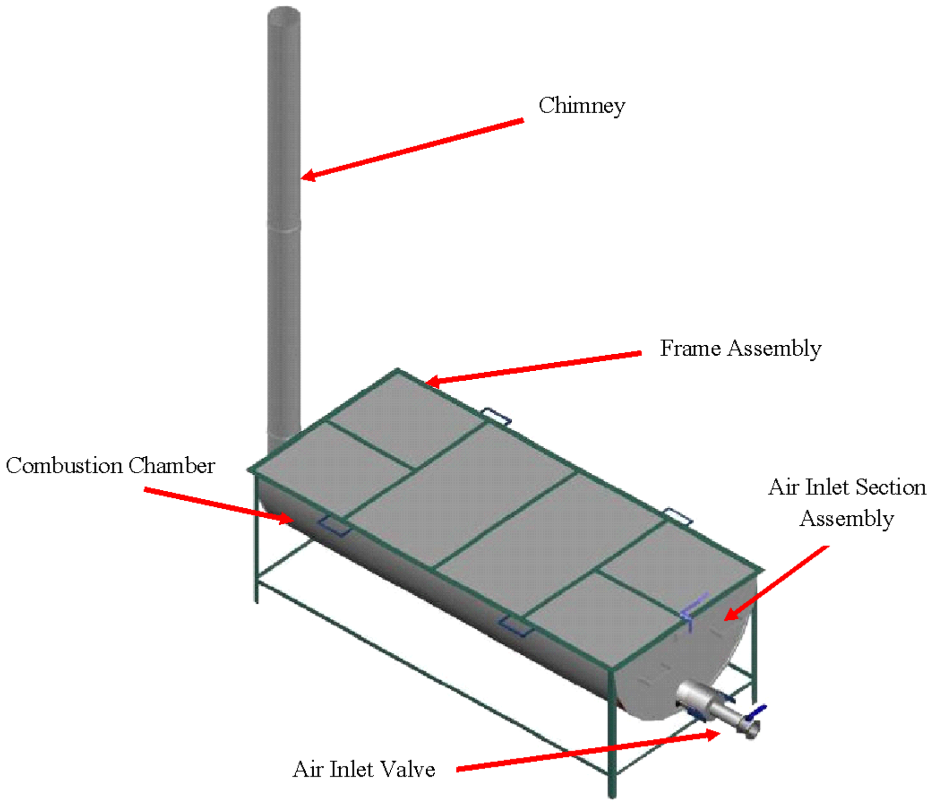

Figure 1. The rice straw carbonizer

Performance Evaluation of the Rice Straw Carbonizer

Preliminary Testing. The rice straw carbonizer prototype was initially tested using rice straw with a moisture content that was less than 12% to determine if the different components were functioning properly and to familiarize the operators with the different components that needed adjustments during operation.

Final Testing of the Rice Straw Carbonizer. The final testing of the carbonizer was done after initial operation, making necessary adjustments, preparing rice straw, and calibrating all the testing equipment.

Data Gathered

Start time. Starting time when the rice straw was ignited.

Start-up ignition time. Minutes taken from the moment fire was introduced into the combustion section up to the moment a vigorous flame is established.

Amount of ignition fuel use in firing the carbonizer. Crumpled paper or Diesel was used to start the firing of the carbonizer to its combustion section. The fuel was distributed on the exposed surfaces of the material to be carbonized at the combustion section.

Total time of operation (T). This covered the time from the start of firing the carbonizer up to the time it was emptied from carbonized material.

Air Velocity. To measure the air velocity that passed through the combustion zone, an anemometer was installed in the air inlet pipe. The probe was connected to an air velocity recorder to measure air velocity every after 1 minute while the carbonizer was in operation.

Gas Emission Test. Gas analyzer was placed at the chimney outlet to the gas emission such as Carbon Monoxide (CO), Carbon Dioxide (CO_2), Methane (CH_4), Hydrogen (H_2) and Oxygen (O_2).

Temperature. Temperature probes were positioned along the carbonizer's body, connected at the three section sides of the carbonizer to monitor temperatures from the front, middle and rear portion of the combustion chamber. These probes were linked to a temperature recorder via K type thermocouple, with readings taken every minute during the operation.

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Weight of rice straw input. The weight of the rice straw sample was measured before the operation.

Weight of Carbonized rice straw output. The weight of the Carbonized rice straw after the process of carbonization was measured.

Proximate and Ultimate Analysis. To validate the collected carbonized rice straw after the operation. Samples of at least 200g for each treatment that served as composite samples were collected for the proximate and ultimate analysis. Samples were submitted to the Department of Science and Technology (DOST-ITDI) laboratory for sampling analysis.

Parameters Analyzed

Carbonized rice straw Yield (Y). This was the weight of Carbonized rice straw produced (output) over the initial weight of the raw material (10 kg input capacity). The following formula was used which was patterned from Sugumaran and Seshadri (2009):

$$Y = 100 \times (Wc \div Wt) \quad (5)$$

where: Y = Carbonized rice straw yield
W_c=total weight of biochar produced
W_t = Initial weight of the raw material

Output capacity (C). The amount of material that was carbonized per unit time, it was computed as follow:

$$C = Wt \div T \quad (6)$$

where: C = Output capacity of carbonized material
W_t = total weight of carbonized rice straw
T = total time of operation

Statistical Design. To establish the optimum performance of the proposed rice straw carbonizer for Carbonized rice straw production, statistical analysis using a two-factorial in completely randomized design (CRD) was used. Analysis of variance (ANOVA) and Least Significant Difference (LSD) were employed in the analysis.

Results and Discussion

Applying the process discussed in the previous section to Figure 5, the researchers obtain the shortest paths from every NATO station to the different colleges in CLSU. The results are summarized in Tables 2 – 4. For the complete details of the calculations, we refer the reader to Antalan et al. (201 Carbonized rice straw yield

Table 2 illustrates the outcomes of Carbonized rice straw yield recovery after the carbonization process for various treatment combinations in kilograms and corresponding percentage value. Results indicate that under dry conditions, rice straw achieved higher charcoal yield recovery across all valve openings compared to freshly harvested rice straw. The carbonizer valve openings demonstrated that at ½ opening (22.67%) and full opening (23.33%), charcoal yield recovery surpassed the ¼ valve opening (19.67%) dry condition of rice straw. Similarly, for freshly harvested rice straw, at ½ opening and full opening (20.00%), charcoal yield recovery exceeded the ¼ valve opening (17.33%). These results highlight the impact of different valve openings on the carbonization process for rice straw condition. Moreover, the data indicates that the carbonizer performs significantly in converting rice straw into carbonized form under dry conditions compared to freshly harvested conditions. The results suggest that the carbonizer optimally converts rice straw into carbonized form, particularly when the rice straw was dry, as opposed to when it was freshly harvested.

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Table 2. Carbonized rice straw yield (%) as affected by the different valve openings at different rice straw conditions.

MOISTURE CONTENT (%)	VALVE OPENING			MEAN
	1/4 opening	1/2 opening	Full opening	
8.90	19.67[y]	22.67[y]	23.33[x]	21.89[a]
11.70	17.33[x]	20.00[y]	20.00[y]	19.11[b]
Mean	18.50[l]	21.34[m]	21.67[m]	20.50

Means with the same letter are not significantly different

Output Capacity

Using the dry rice straw sample, the carbonizer achieved an average capacity of 13.87 kg/hr with 8.90% moisture content, while using the freshly harvested rice straw sample with 10.6% moisture content resulted in an average capacity of 9.41 kg/hr. Results also demonstrated that at full opening, the machine capacity obtained an average of 14.78 kg/hr, and at one-half (½) valve opening, it averaged 14.64 kg/hr, surpassing the one-fourth (¼) opening with an average of 12.21 kg/hr for dry rice straw. For freshly harvested rice, there was no significant difference between the full opening (average 8.38 kg/hr) and the one-half (½) valve opening (average of 8.36 kg/hr). However, a fully opened and one-half (½) opened valves exhibited higher machine capacity, as shown in Table 3.

Moreover, it showed that for rice straw at dry conditions, all valve openings achieved higher output capacity compared to freshly harvested rice straw across all valve openings. This suggests that the carbonizer efficiently converted rice straw into carbonized form, particularly when the rice straw was dry, as opposed to when it was freshly harvested.

Table 3. Output capacity (kg/hr) as affected by the different valve openings at different rice straw condition

MOISTURE CONTENT (%)	VALVE OPENING			MEAN
	1/4 opening	1/2 opening	Full opening	
8.90	12.21[x]	14.78[x]	14.64[x]	13.87[a]
11.70	11.50[x]	8.36[y]	8.38[y]	9.41[b]
Mean	11.85[l]	11.57[l]	11.51[l]	11.65

Means with same letter are not significantly different.

Air Velocity

In Table 4, the average air velocity at various valve openings and rice straw condition was presented. Using an air velocity recorder, measurements were taken at ¼ opening, ½ opening and full opening of the 63.50 mm diameter globe valve, starting after establishment of a vigorous flame ignition.

The data indicates that, during the carbonization process, different valve openings yielded higher air velocity values in the air inlet pipe section for dry rice straw conditions compared to freshly harvested rice straw conditions across different valve openings. Through multiple replications, it was determined that the average velocity reached 0.70 meters per second (m/s) during the carbonizer operation for dry rice straw conditions, contrasting with the average velocity of 0.52 meters per second (m/s) during the carbonizer operation for freshly harvested rice straw conditions. Moreover, the results showed a significant difference in the air velocity passing through the combustion chamber for dry rice straw conditions at various valve openings during the carbonization process compared to the air velocity measurements for freshly harvested rice straw conditions at different valve openings

Table 4. Average air velocity (m/s) as affected by the different valve openings at different rice straw conditions.

MOISTURE CONTENT (%)	VALVE OPENING			MEAN
	1/4 opening	1/2 opening	Full opening	
8.90	0.40^{x}	0.63^{x}	1.03^{x}	0.70^{a}
11.70	0.43^{x}	0.45^{y}	0.54^{y}	0.52^{b}
Mean	0.41^{l}	0.55^{m}	0.79^{n}	0.61

Means with the same letter are not significantly different.

It showed a significant difference in the air velocity for dry and freshly harvested rice straw conditions at different valve openings.

The dry rice straw sample required 3 minutes for supplementary air during the carbonization process, while the freshly harvested rice straw sample, at full valve opening, took 32 minutes. Similarly, at ½ opening, a significant air velocity difference was observed, with the dry rice straw sample requiring 6 minutes for a supplementary air to take place, whereas the freshly harvested sample took 68 minutes.

No air velocity values were measured at the ¼ valve opening for both dry and freshly harvested rice straw conditions, indicating no significant effect on the air velocity for either rice straw condition.

Gas Emission

The gas emission was determined using Portable Flue Gas Analyzer, recording all gases produced during the rice straw carbonizer operation.

The gas or smoke coming from the chimney was collected in a 20 liter-capacity plastic bag and analyzed using intake tubes. Data were recorded after stable instrument readings. Composition of gases such as Carbon Monoxide (CO), Carbon Dioxide (CO_2), Methane (CH_4), Hydrogen (H_2) and Oxygen (O_2), along with their corresponding heating values (HV), were obtained. The flue gas quality from the chimney was measured as a percentage.

Table 5 presents a summary of gas emission for dry and freshly harvested conditions of rice straw sample at different opening of the rice straw carbonizer.

Table 5. Gas Emission percentage result of rice straw at dry and freshly harvested condition at different openings.

MOISTURE CONTENT (%)	VALVE OPENING	GAS EMISSION, %						ENERGY CONVERSION
		Carbon Monoxide (CO)	Carbon Dioxide (CO_2)	Methane (CH_4)	Hydrogen (H_2)	CnHm	Oxygen (O_2)	Kcal/m³
8.90	1/4 opening	1.30	2.48	0.28	0.04	0.04	17.63	71.67
	1/2 opening	1.12	2.38	0.19	0.00	0.06	17.57	55.33
	Full opening	0.43	1.06	0.09	0.00	0.01	19.53	20.33
	Mean	0.95	1.97	0.19	0.01	0.04	0.03	18.24
11.70	1/4 opening	1.11	2.49	0.29	0.05	0.02	17.79	65.67
	1/2 opening	0.71	1.80	0.14	0.00	0.05	18.83	36.67
	Full opening	0.64	1.45	0.11	0.00	0.03	19.11	29.33
	Mean	0.82	1.91	0.18	0.02	0.03	0.03	18.58

As shown in Table 5, the gas composition varied significantly based on the rice straw condition and valve opening, influencing the percentage values and heating values (HV) recorded by the flue gas analyzer.

For the dry condition of rice straw, a smaller the valve opening (¼ opening) resulted in higher the percentage values for gas emissions, such as Carbon Monoxide (CO) 1.30%, Carbon Dioxide (CO_2) 2.48%, Methane (CH_4) 0.28%, Hydrogen (H_2) 0.04% and Oxygen (O_2) 17.63%, with a heating value of 71.67 Kcal/m^3. With a ½ opening valve, the percentage values for gas emission were Carbon Monoxide (CO) at 1.30%, Carbon Dioxide (CO_2) at 2.38%, Methane (CH_4) at 0.19%, Hydrogen (H_2) at 0.00% and Oxygen (O_2) at 17.67%, with a heating value of 55.33 Kcal/m^3.

A fully opened valve yielded the lowest values on the analyzer for gas emissions, including Carbon Monoxide (CO) 0.43%, Carbon Dioxide (CO_2) 1.06%, Methane (CH_4) 0.09%, Hydrogen (H_2) 0.00% and Oxygen (O_2) 19.53% and heating value of 20.33 Kcal/m^3.

Temperature

Temperature profile for dry rice straw at ¼ opening of the valve. In terms of the heat generated at the combustion chamber, Figure 2 illustrates that under dry rice straw conditions using the ¼ opening of the valve, the initial trial recorded the highest temperature at 733.80°C within a 38-minute monitoring period at the front section of the combustion chamber. At the mid-section, the highest temperature reached 552.30°C within a 58-minute monitoring period, while at the rear section, the highest temperature recorded was 336.00°C within the 59-minute monitoring period.

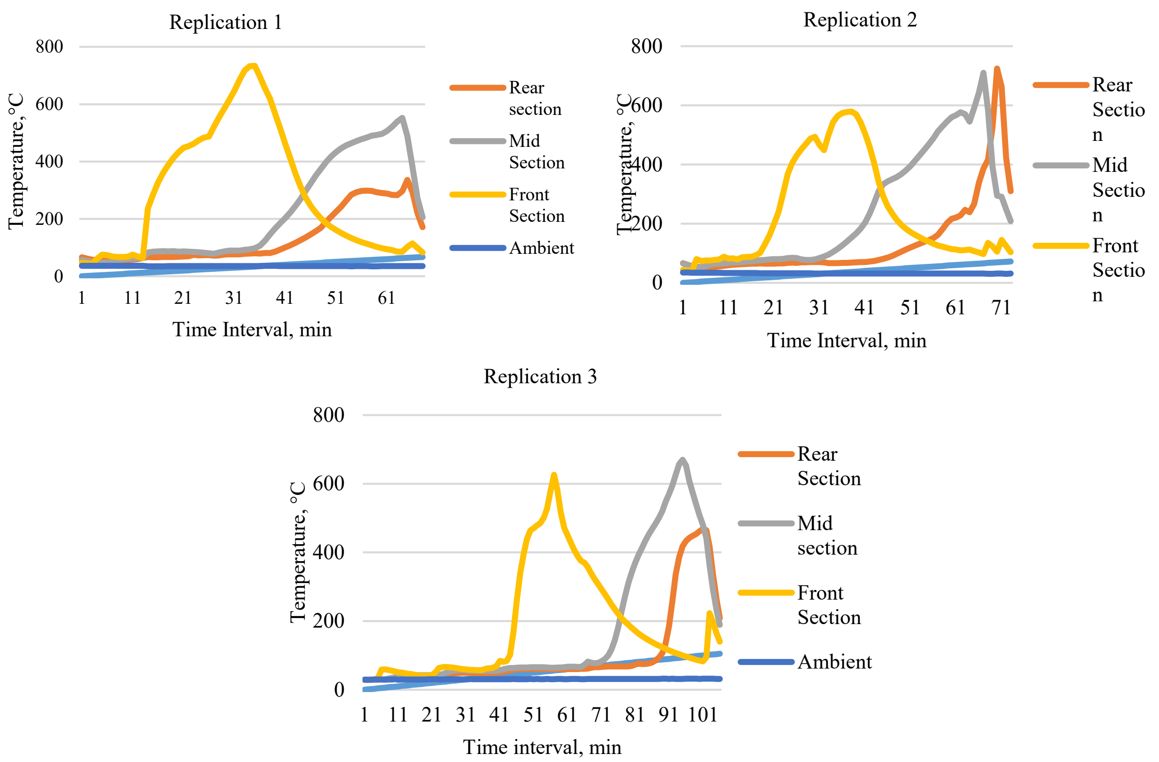

Figure 2. Temperature profile as affected by moisture content of rice straw at ¼ valve openings and time intervals in three replications.

The temperature trend generated in the combustion chamber under dry rice straw conditions with a ¼ opening of the valve displayed variation in successive replications. In the second trial, the front section recorded a temperature of 579.00°C within a 37-minutes monitoring period, the mid-section reached 710.00°C in 66 minutes, and the rear section attained the highest temperature of 724.40°C in 69 minutes. In the third trial, the front section registered a temperature of 626.00°C within a 46-minutes monitoring period, the mid-section reached 669.00°C in 84 minutes, and the rear section recorded 468.60°C in 90 minutes.

Temperature profile dry rice straw at ½ opening of the valve. Based on temperature measurements at the combustion chamber, Figure 3 shows that for dry conditions of rice straw with a ½ opening of the valve, the first trial recorded a temperature of 679.70°C within a 38-minute monitoring period at the front section of the combustion chamber. In the middle section, the temperature reached 569.50°C in 53 minutes, and in the rear section, the highest temperature recorded was 468.50°C within a 57-minute monitoring period. The second trial obtained a temperature of 625.30°C within a 13-minute monitoring period at the front section, with the mid-section reaching the highest temperature of 541.80°C in 62 minutes. The rear section recorded the lowest temperature of 390.20°C within a 62-minute monitoring period. The third trial obtained a temperature of 563.80°C within a 27-minute monitoring period at the front section, with the mid-section reaching the highest temperature of 563.40°C in 56 minutes. The rear section recorded the lowest temperature of 648.60°C within a 66-minutes monitoring period.

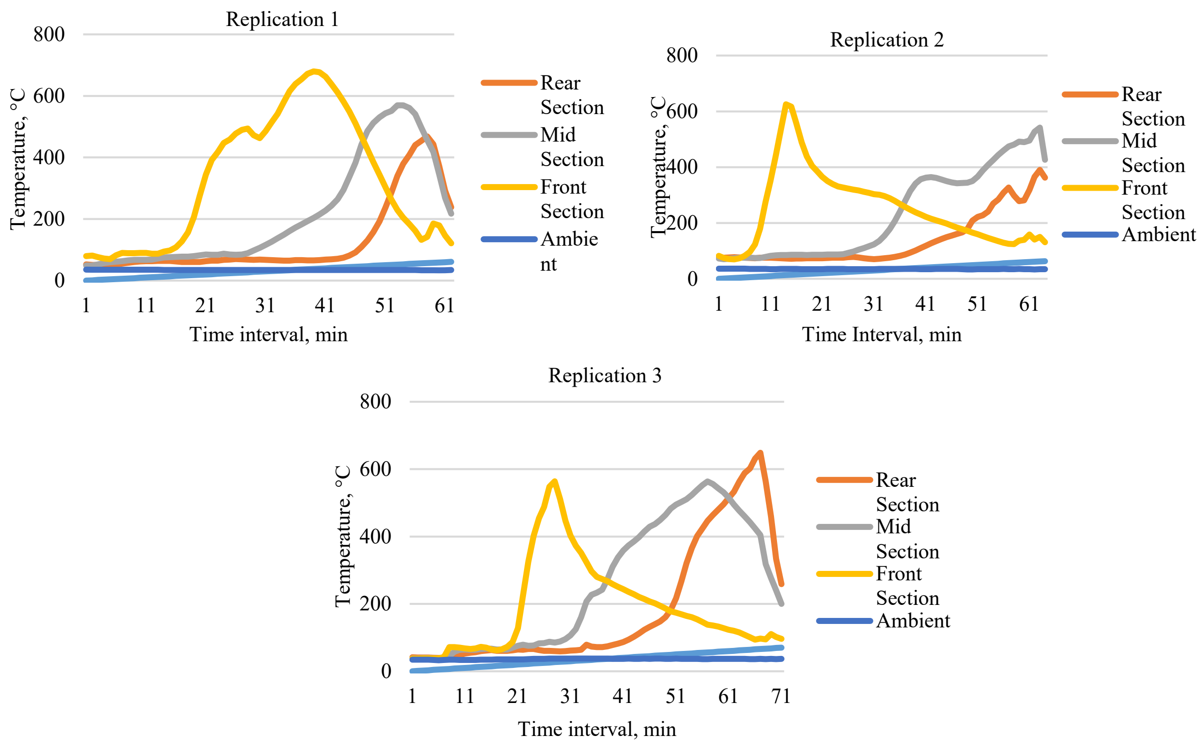

Figure 3. Temperature profile as affected by moisture content of rice straw at ½ valve openings and time intervals in three replications.

Temperature profile for dry ice straw at full opening of the valve. Based on the temperature measurements at the combustion chamber, Figure 4 demonstrates that under dry rice straw with a fully opened valve, the first trial recorded a temperature of 640.10°C within a 45-minutes monitoring period at the front section combustion chamber. In the middle section, the temperature reached 575.80°C in 71 minutes, and in the rear section, the highest temperature recorded was 454.30°C within a 63-minute monitoring period.

In the second trial, a temperature of 625.20°C was recorded within a 31-minute monitoring period at the front section, with the mid-section reaching the highest temperature of 535.70°C in 55 minutes. The bottom section recorded the lowest temperature of 596.90°C within a 60-minute monitoring period. The third trial recorded a temperature of 667.30°C within a 17-minute monitoring period at the front section, with the mid-section reaching the highest temperature of 716.20°C in 47 minutes. The rear section recorded the lowest temperature of 520.50°C within a 60-minute monitoring period.

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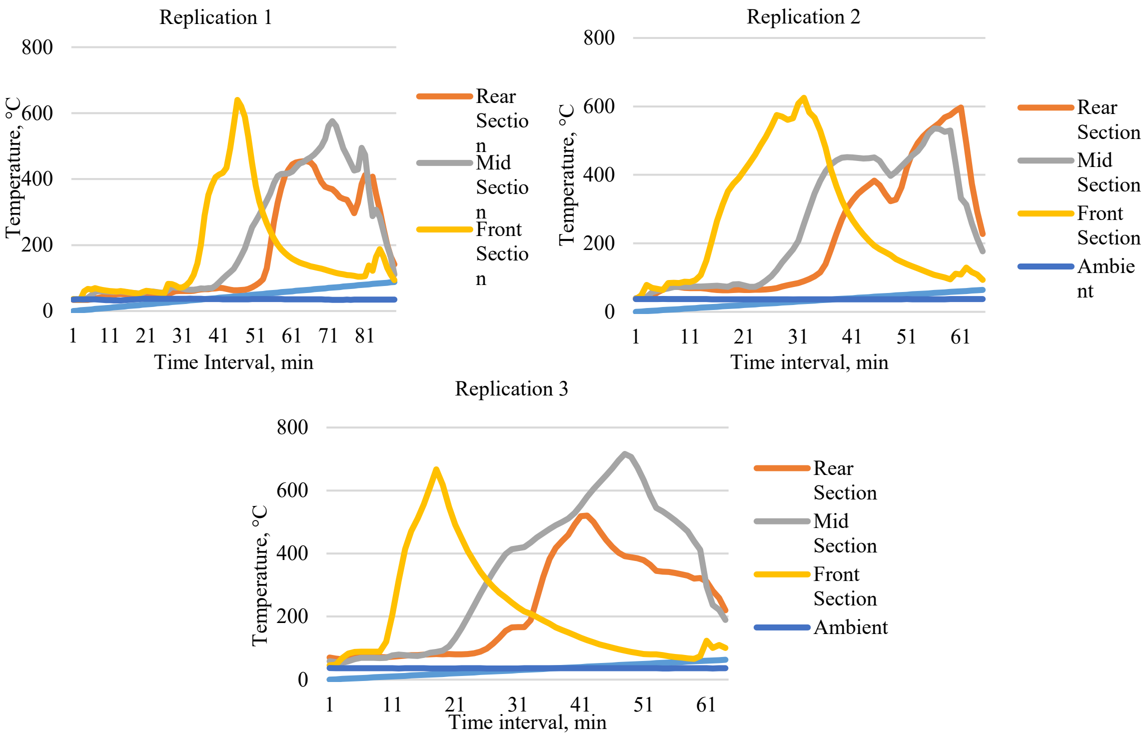

Figure 4. Temperature profile as affected by moisture content of rice straw at full valve openings and time intervals in three replications.

<u>Temperature profile for fresh rice straw condition at ¼ Opening of the Valve</u>. In Figure 5, under freshly harvested condition of rice straw using a ¼ opening of the valve, the first trial recorded the highest temperature of 485.80°C within a 23-minute monitoring period at the front section of the combustion chamber. In the mid-section, the highest temperature reached 592.50°C in 75 minutes, and in the rear section, the highest temperature recorded was 456.60°C within an 81-minute monitoring period.

The second trial registered a temperature of 507.30°C within a 20-minute monitoring period at the front section, with the mid-section reaching the highest temperature of 552.60°C in 58 minutes. The rear section recorded the highest temperature of 566.50°C within an 80-minute monitoring period. The third trial obtained a temperature of 594.40°C within a 30-minute monitoring period at the front section, with the mid-section reaching the highest temperature of 500.80°C in 71 minutes. The rear section recorded the lowest temperature of 599.30°C within an 86 minute monitoring period.

Figure 6 illustrates the graph for the trial 1 concerning the heat generated from freshly harvested rice straw condition at a ½ opening of the valve. In this trial, the first recorded temperature was 421.20°C within a 90-minute monitoring period at the front section of the combustion chamber. In the mid-section, the highest temperature reached 636.00°C in 89 minutes, and in the rear section, the lowest temperature recorded was 563.10°C within a 53-minute monitoring period

At ½ opening of the valve, the second trial also recorded 421.20°C within a 90-minutes monitoring period at the front section of the combustion chamber. In the mid-section, the highest temperature reached 636.00°C within a monitoring period of 89 minutes, while in the rear section, the lowest temperature recorded was 563.10°C within a 53- minute monitoring period. The third trial, concerning the heat generated from freshly harvested rice straw condition at a ½ opening of the valve, obtained a temperature reading of 416.90°C within a 70-minute monitoring period at the front section. The mid-section reached the highest temperature of 627.50°C in 117 minutes, and the rear section recorded a highest temperature of 411.30°C within a 140 minutes monitoring period.

Figure 7 illustrates the graph for the first trial regarding the heat generated from freshly harvested rice straw conditions at full opening of the valve. The first trial recorded a temperature of 416.90°C within a 70-minute monitoring period at the front section. In the mid-section, the highest temperature reached 627.50°C in 117 minutes, while in the rear section, the highest temperature recorded was 411.30°C within a 140 minutes monitoring period. The temperature reading on the second trial obtained was 416.90°C within a 70-minute monitoring period at the front section. The mid-section reached the highest temperature of 627.50°C in 117 minutes, and the rear section recorded the highest temperature of 411.30°C within a 140 minutes monitoring period. The third trial recorded 421.20°C within an 86-minute monitoring period at the front section. In the mid-section, the highest temperature recorded was 668.10°C in 119 minutes, while in the rear section recorded the highest temperature of 606.20°C within 119 minutes of the monitoring period. The temperature readings in the combustion chamber were influenced by the time of the front section temperature during the carbonization process, followed by the temperature attained at middle section, which reached the highest temperature over a period of time.

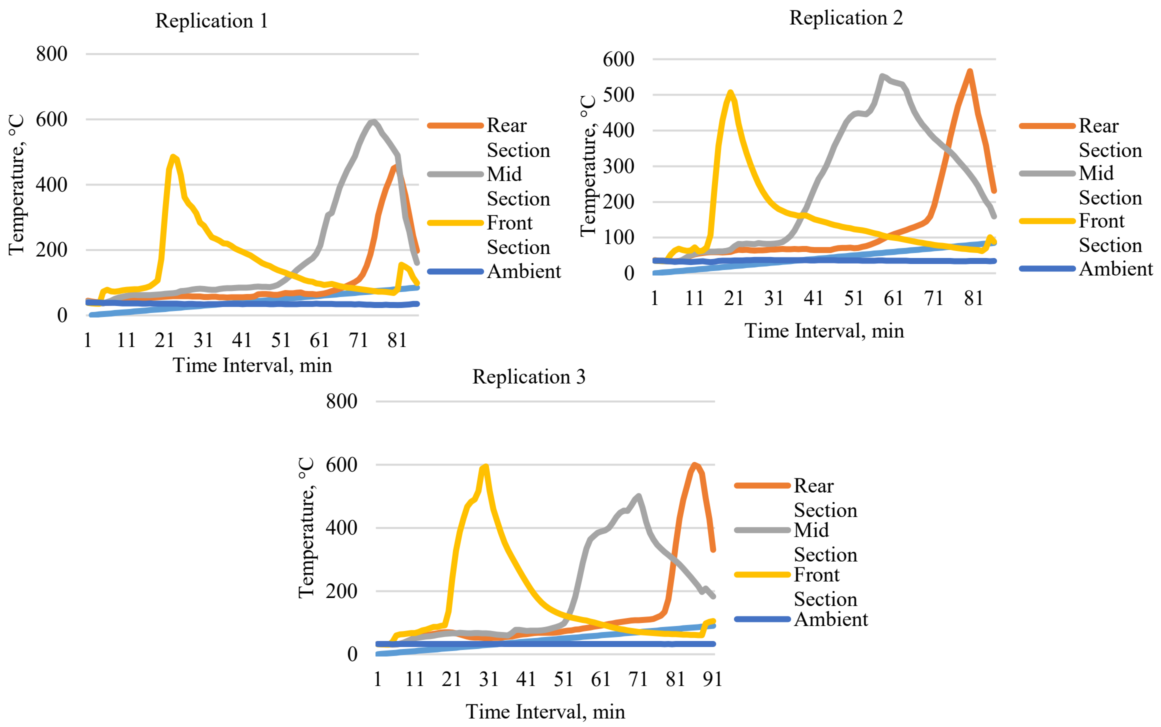

Figure 5. Temperature profile as affected by moisture content of rice straw at ¼ valve openings and time intervals in three replications.

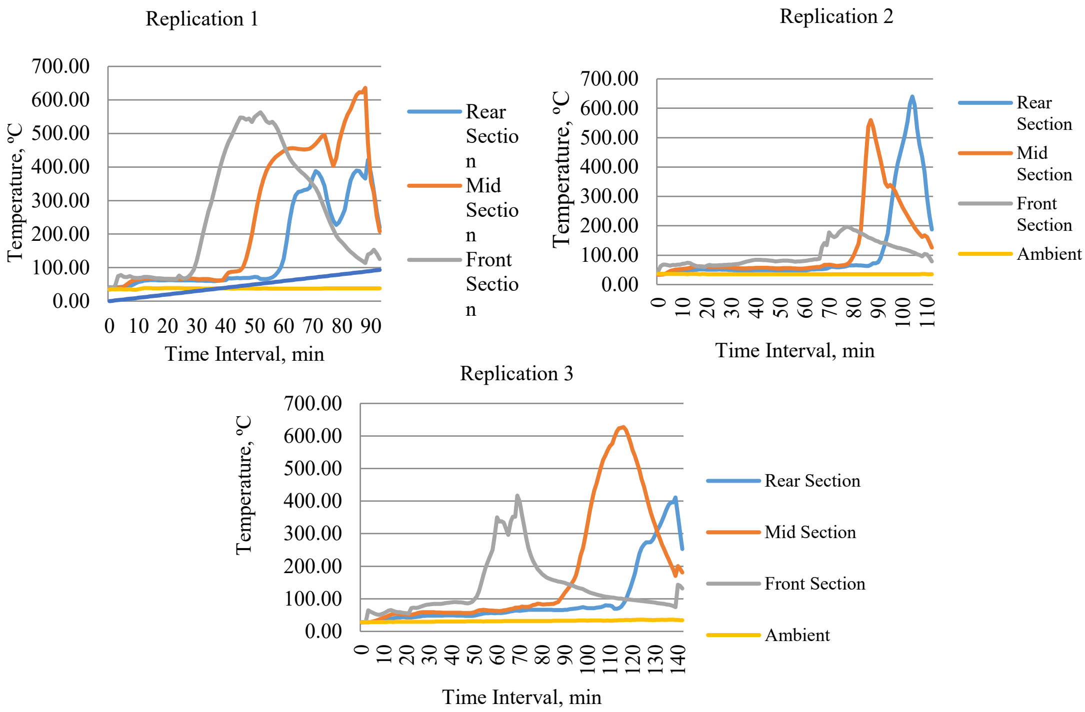

Figure 6. Temperature profile as affected by moisture content of rice straw at ½ valve openings and time intervals in three replications.

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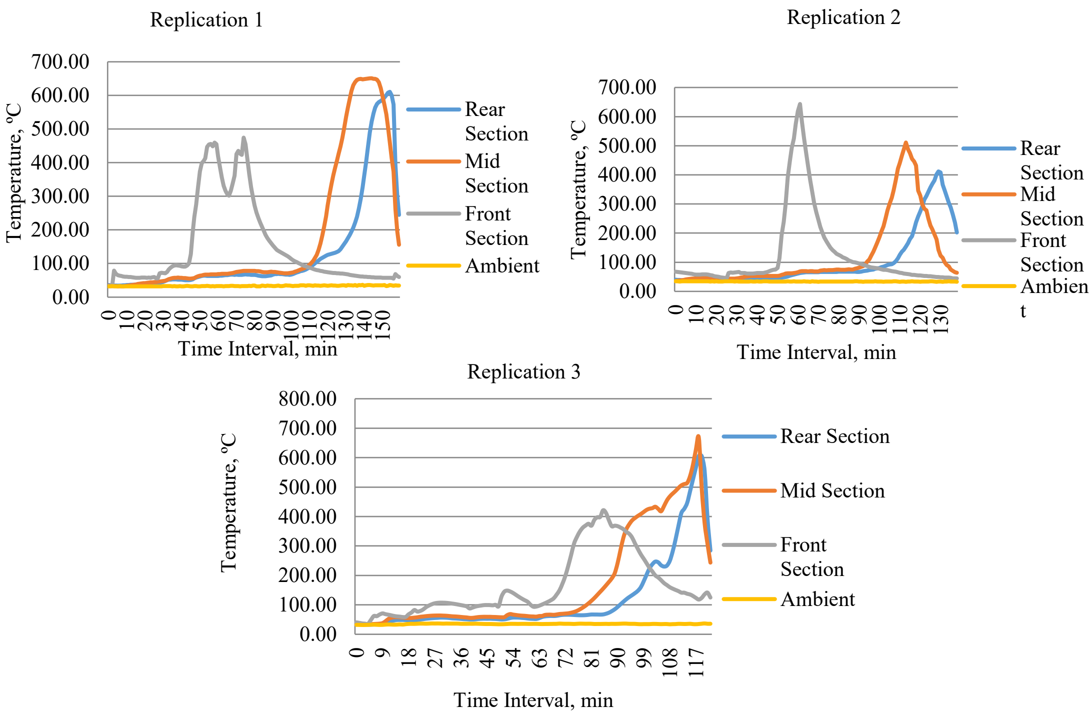

Figure 7. Temperature profile as affected by moisture content of rice straw at full valve openings and time intervals in three replications.

Similarly, the rear section of the combustion chamber reached its peak temperature over a period of 119 minutes. The freshly harvested rice straw took some time to ignite during the carbonization process. Consequently, it was necessary to open the front section of the carbonizer for re-ignition, facilitating vigorous flame for a continuous burning process. This procedure led to an increase of the temperature within the ignition chamber, influencing the middle and rear section of the carbonizer, ensuring the ongoing process of carbonization.

Proximate and Ultimate Analysis

The laboratory analysis conducted by the Department of Science and Technology – Industrial Technology Development Institute (DOST-ITDI) provided results for rice straws with moisture contents of 8.9% and 11.7%, as well as the carbonized rice straw post-experiment. Composite samples were collected for each treatment combination. Table 6 presents the parameters for proximate and ultimate analysis for dry rice straw and carbonized rice straw at various valve openings.

In proximate analysis, the rice straw with 8.90% moisture content exhibited a higher volatile matter content of 64.10% compared to carbonized rice straw samples at different valve openings. Carbonized rice straw at different valve openings showed no significant difference in moisture content.

For volatile combustible matter, larger valve openings during carbonization led to higher percentages, with 6.39% at ¼ valve opening, 7.58% obtained for ½ valve opening, and the highest obtained was 7.89% at full valve opening. Rice straw, relative to other biomass and agricultural residues, displayed a higher volatile matter up to 85% at a dry basis. This indicated that the rice straw was easier to ignite and to burn, although the combustion was expected to be rapid and difficult to control. Experience showed that the high volatile matter content significantly affected the combustion process (Oanh et al, 2010). Fixed carbon percentages were affected by the valve opening, with lower percentages at larger openings during combustion. Dry rice straw obtained the result of 16.20%, for the carbonized rice straw, the highest percentage recorded was 44.00% (¼ valve opening), 40.00% (½ valve opening) and the lowest was 31.30% (full valve opening). Ash content varied, dry rice straw obtained the result of 19.70%, for the carbonized rice straw, the lowest obtained was 49.60% (¼ valve opening), 52.40% (½ valve opening), and the highest was 60.80% at full valve opening. Computed heating values for dry rice straw and carbonized rice straw were 14.19 MJ/kg and 14.42MJ/kg (¼ valve opening), 13.26 MJ/kg (½ valve opening) and 10.70 MJ/kg (full valve opening), suggesting that valve opening significantly influenced heating value during carbonization.

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In ultimate analysis, carbon content for dry rice straw was 36.38%, while carbonized rice straw showed variations at different valve openings. The highest carbon content obtained was 40.39% (¼ valve opening), 36.98% (½ valve opening), while the lowest carbon obtained was 29.20% (full valve opening). Carbonized rice straw showed variations at different valve openings. Hydrogen content obtained on dry rice straw condition was 6.35%. For carbonized rice straw, 3.10% (¼ valve opening), 3.05% (½ valve opening), and 2.51% (full valve opening). The nitrogen content for dry rice straw was 0.12%, and carbonized rice straw at different valve openings showed results of 0.21% (¼ valve opening), 0.15% (½ valve opening), and 0.13% (full valve opening). No content of sulfur was found on the dry rice straw and carbonized straw at different valve openings.

Similarly, the proximate analysis for the rice straw with 11.70% moisture content appeared to have higher volatile matter content of 62.70% compared to carbonized rice straw samples at various valve openings. Results indicated the lowest moisture content for carbonized rice straw at 3.89% (¼ valve opening), 4.19% (½ valve opening), and 3.69% at full valve opening, with no significant difference observed across different valve openings.

In terms of volatile combustible matter, the lowest result was 5.11% at ¼ valve openings, the highest obtained was 6.79% for ½ valve openings, and 5.26% at full opening of the valve. Larger valve openings during carbonization higher volatile combustible matter production. Freshly harvested rice straw showed 16.00% fixed carbon, while carbonized rice straw had the highest result of 33.00% at ¼ valve opening, 28.90% for ½ valve opening and the lowest of 23.60% at full valve opening. Larger valve openings resulted in lower fixed carbon percentage during the combustion.

Ash content for rice straw was 21.30%, while carbonized rice straw showed the lowest at 61.90% (¼ valve opening), 54.30% (½ valve opening), and the highest result was 71.10% (full valve opening). For the computed heating value, dry rice straw obtained the result of 13.26 MJ/kg. Computed heating values for dry rice straw and carbonized rice straw were 10.93 MJ/kg (¼ valve opening), 13.26 MJ/kg (½ valve opening), and the lowest heating value of 9.91 MJ/kg (full valve opening). These results indicated a significant effect on different valve openings during carbonization of freshly harvested rice straw

Table 6. Proximate and ultimate analysis of rice straw (RS) and carbonized rice straw (CRS) as affected by the moisture content of rice straw at different valve openings.

PARAMETER	RICE STRAW	CARBONIZED RICE STRAW			RICE STRAW	CARBONIZED RICE STRAW		
		¼ valve opening	½ valve opening	Full valve opening		¼ valve opening	½ valve opening	Full valve opening
Moisture content (%)	8.90	5.48	5.90	5.67	11.70	3.89	4.19	3.69
Volatile Combustible matter (%)	64.10	6.39	7.58	7.89	62.70	5.11	6.79	5.26
Fixed carbon (%)	16.20	44.00	40.00	31.30	16.00	33.00	38.90	23.60
Ash content (%)	19.70	49.60	52.40	60.80	21.30	61.9	54.30	71.10
Heating value (MJ/kg)	14.19	14.42	13.26	10.70	13.26	10.93	13.26	7.91
Carbon (%)	36.38	40.39	36.98	29.20	34.41	31.2	36.02	22.01
Hydrogen (%)	6.35	3.10	3.05	2.51	6.03	3.40	2.76	1.98
Nitrogen (%)	0.12	0.21	0.15	0.13	0.01	0.49	0.28	0.12
Sulfur (%)	none	none	none	none	none	none	none	none

In the ultimate analysis, carbon content for freshly harvested rice straw was 34.41%. Carbonized rice straw showed variations at different valve openings, with the highest at 31.20% (¼ valve opening), 36.02% (½ valve opening), and the lowest at 22.01% (full valve opening). These results indicated a significant effect on different valve openings during carbonization at freshly harvested rice straw.

For combustible gas such as hydrogen, freshly harvested condition rice straw had 6.03%, while carbonized rice straw showed differences at 3.40% (¼ valve opening), 2.76% (½ valve opening), and 1.98% (full valve opening). The valve opening had a significant effect on hydrogen content, with larger openings resulting in lower percentages during combustion

Nitrogen content for freshly harvested rice straw was 0.01%, while carbonized rice straw at different valve openings showed 0.49% (¼ valve opening), 0.28% (½ valve opening), and 0.12% (full valve opening). Nitrogen content was affected by different valve openings, with larger openings resulting in lower percentages during combustion. No sulfur content was found on rice straw and carbonized straw at different valve openings.

Cost Analysis

The cost analysis in Appendix 39 yielded an annual fixed cost of PhP 8,606.24 and a variable cost of PhP 66.38 per hour. Varying capacities of producing carbonized rice straw production from rice straws with different moisture contents influenced the cost curve in Figure 8, illustrating the lower cost of using the carbonizer with lower moisture content. The curves indicate a decrease in cost with an increasing annual carbonized rice straw production.

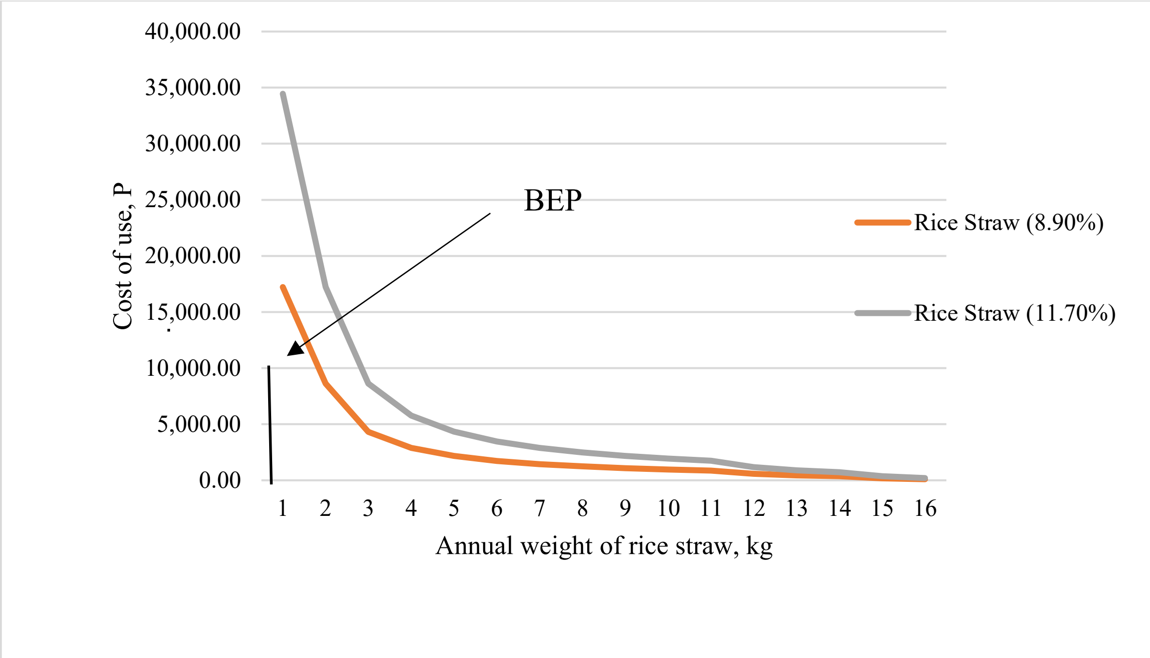

Figure 8. Cost Analysis of Rice Straw Carbonizer

When the rice straw carbonizer processed 5 tons of rice straw obtained from a one-hectare rice farm, it yielded approximately 1,100 kg of carbonized rice straw. Assuming this output represents the annual carbonized rice straw production, the cost of producing one-kg of carbonized rice straw was calculated at PhP12.60. With a tenfold increase in output (5,500 kg per year), the cost per kg of carbonized rice straw was decreased to PhP 6.34. This demonstrates a reduction in the cost of carbonized rice straw production as the annual output increases. Considering a custom rate of PhP 8.00 per kg of carbonized rice straw, the rice straw carbonizer would reach a break even with the annual output of 2,672 kg of carbonized rice straw. This is equivalent to about 12 tons of rice straw.

Conclusion

This study aimed to produce carbonized rice straw using a rice straw carbonizer and assessed its performance with rice straw samples of varying moisture content (8.90% and 11.70%). Parameters like carbonized rice straw yield, output capacity, operation time, gas composition (CO, CO_2, CH_4, H_2, and O_2), temperature, and proximate/ultimate analysis were evaluated. The experiment employed a two-factor design in a completely randomized design (CRD) with 3 replications and included a cost analysis covering investment, operating cost, and custom rates.

The carbonizer with 8.90% moisture content achieved a 21.89% carbonized rice straw yield, 13.87 kg/hr output, and a peak temperature of 733.80°C in 73.33 minutes. The 11.70% moisture content sample resulted in 19.11% carbonized rice straw yield, 9.41 kg/hr output, and an average velocity of 0.52 m/s at different valve openings. Gas composition during carbonization showed variations influenced by moisture content. The 8.90% moisture content had an average gas emission percentage of CO (0.95%), CO_2 (1.97%), CH_4 (0.19%), H_2 (0.01%), O_2 (18.27%), with a heating value of 49.11 Kcal/m^3. The 11.70% moisture content showed slightly different values with a heating value of 43.89 Kcal/m^3. DOST_ITDI laboratory analysis revealed variations in proximate and ultimate analysis between dry and freshly harvested rice straw, impacting factors like volatile matter, fixed carbon, ash content, and heating value. Operational costs were estimated at Php 84.41 per hour for dry rice straw and Php 46.81 per hour freshly harvested rice straw. Custom rates, covering use and labor, were Php 121.81 per hour for dry rice straw and Php 84.31

per hour for freshly harvested rice straw. Therefore, the designed carbonizer exhibited superior performance, achieving high carbonized rice straw yield and acceptable gas emission. Recommendations include using dry rice straw, modifying the ignition chamber for increased capacity, and optimizing the prototype design. The study suggests potential use of carbonized rice straw as a soil amendment and offers an alternative method for farmers to convert rice straw into carbonized rice straw. Further experimentation, including the entire rice straw plant for carbonization, is recommended for comparison and thorough exploration

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