



Development and Evaluation of a Laboratory-scale Pyrolysis Reactor for Bio-oil Production

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Abstract: Biomass pyrolysis is gaining interest as a renewable energy conversion pathway that valorizes agricultural residues while mitigating environmental hazards from open burning. This study aimed to design and fabricate a batch-fed laboratory-scale biomass pyrolysis reactor and evaluate its technical performance for bio-oil production using rice straw as feedstock. A split-plot experiment in a completely randomized design was employed, varying reactor insulation thickness (25, 50, and 75 mm), pyrolysis temperature (400°C, 450°C, and 500°C), and biomass loading density (60, 90, and 120 kg/m³). Analysis of variance and Scheffe's test were used to determine significant differences among treatments. Biomass loading density, pyrolysis temperature, and insulation thickness each had a significant effect on bio-oil production, whereas all two-way and three-way interactions were not significant. The combination of 25 mm insulation, 450°C pyrolysis temperature, and 90 kg/m³ loading density yielded the highest mean bio-oil (78.07 g, 76.74 g, and 73.26 g, respectively). The developed reactor demonstrated temperature stability and operational integrity at 400°C–500°C. The reactor is a viable tool for biomass pyrolysis, and the established standard operating procedure provides a useful guide for optimizing bio-oil and bio-char production from various biomass types.

Keywords: Biomass; pyrolysis; batch-fed reactor; bio-oil; bio-char

1. Introduction

Interest in renewable energy sources is growing significantly due to concerns about global climate change, environmental pollution, and the depletion of fossil energy resources [1,2]. Among renewable resources, biomass is the only resource capable of producing liquid fuel. Biomass has favorable attributes: it is renewable and carbon-based, and it is low in sulfur and nitrogen contents [2,3]. Abundantly available worldwide [4], biomass utilization in mainstream energy applications has received significant attention due to environmental considerations and increasing energy demands [3]. Combustion of biofuel produces fewer harmful gas emissions, such as nitrogen oxides (NO_x), sulfur dioxide (SO₂), and soot, than conventional fossil fuels. Zero or negative carbon dioxide (CO₂) emissions are possible from biomass fuel combustion because the released CO₂ can be recycled by plants through photosynthesis [5].

Biomass is a promising, eco-friendly alternative source of renewable energy. The current global energy supply is largely based on fossil fuels with

finite reserves. Given the growing world population, rising per capita energy consumption, and evidence of global warming, the need for long-term alternative energy sources is clear [1]. Biofuel, as an alternative fuel, has received considerable attention in the Philippines. Republic Act 9367 (Biofuels Act of 2006) mandates the use of biofuels as fuel blends and establishes a national biofuel program to reduce the Philippines' dependence on imported crude oil, increase rural employment, and reduce greenhouse gas emissions.

Among biomass-to-energy conversion processes, pyrolysis has attracted increased interest for producing liquid fuel due to advantages in storage, transport, and versatility in applications such as combustion engines, boilers, turbines, and power generation [6]. Pyrolysis is the thermal decomposition of biomass in the absence of oxygen, derived from Greek words “pyro” (fire) and “lysis” (decomposition) [7]. More than 5,500 years ago in Southern Europe and the Middle East, pyrolysis technology was used for charcoal production [8]. Pyrolysis technology can produce biofuel with high fuel-to-feed ratios, and its development continues worldwide [9,10]. Pyrolysis research in the Philippines has been focused primarily on industrial wastes such as rubber tires and plastics, with limited work on biomass resources. Rapsing [11] designed and fabricated a waste plastic oil converter, demonstrating conversion of waste plastics into fuel through pyrolysis. Pyrolysis of various agricultural and industrial biomass residues in the ASEAN region has also been investigated, including latex sediment from concentrated latex factories, demonstrating the potential of pyrolysis for regional waste valorization [12].

Maintaining critical design characteristics during scale-up enables prediction of process parameters from pilot-scale data [13]. A laboratory-scale pyrolysis system must be designed, constructed, and evaluated as the basis for commercial-scale development. This study, therefore, aimed to: (1) design and fabricate a batch-fed laboratory-scale biomass pyrolysis reactor; (2) evaluate its technical performance in terms of bio-oil and bio-char production using rice straw as feedstock under predetermined conditions; and (3) standardize the operating procedure for optimum bio-oil production.

2. Materials and Methods

2.1 Design and Fabrication of the Laboratory-Scale Pyrolysis Reactor

2.1.1 Design considerations

The laboratory-scale reactor system was designed based on the principle of heating biomass in the absence of oxygen. A batch-fed configuration was adopted to maintain an oxygen-free environment during pyrolysis. The design targeted the pyrolysis of cellulosic biomass wastes, such as rice straw and other locally abundant agricultural residues. Flexibility in reactor insulation, biomass loading density, and heating temperature was incorporated to enable optimization of bio-oil production. Electric power was selected as the heat source, and a condenser was included to recover condensable pyrolytic gases as bio-oil. Fabrication was carried out using local materials and facilities [13].

2.1.2 Designing the reactor and its components

The essential components of the pyrolysis system were identified based on the design reference from Henkel [14], with modifications to simplify construction: vertical reactor orientation for easy loading, a larger reactor volume to accommodate varied biomass types, and an Arduino-based temperature controller, while retaining induction heating. Pyrolysis reactor. The reactor was a cylindrical, fixed-bed type made from a 5-mm-thick block of iron pipe with a 12 cm diameter and 44 cm length. The top was provided with a cover for loading biomass feedstock and maintaining an oxygen-free environment. A solid residue (bio-char) collector was hinged at the bottom. An exit pipe at the upper side channeled evolved gases through a condenser to extract bio-oil. The reactor volume and mass capacity were calculated using a bulk density of 60 kg/m³ for dried, chopped rice straw [15]:

$$V_r = \pi r^2 h = \pi (6 \text{ cm})^2 (44 \text{ cm}) = 4,976.28 \text{ cm}^3 \quad (1)$$

$$m_r = V_r \times D_{rs} = 4,976.28 \text{ cm}^3 \times 60 \text{ kg/m}^3 \approx 300 \text{ g} \quad (2)$$

The heater consisted of a 10-mm-diameter Canthel wire wound helically on the outer surface of the reactor. Heating was primarily through conduction, with a cylindrical metal casing and fiberglass wool insulation to minimize heat loss. The heater was rated based on total heat energy requirements, calculated as follows:

$$Q_T = Q_M + Q_L + SF \text{ (20\% safety factor)} \quad (3)$$

Where Q_T = total energy required (W·hr); Q_M = energy absorbed by reactor material and biomass; Q_L = energy lost by conduction from reactor surfaces. Calculations yielded a total power requirement of 3.08 kW for the reactor system. Reactor-heater insulation. Sheet pads of fiberglass wool were wrapped around the cylindrical metal casing to minimize heat loss during pyrolysis. Variable insulation thicknesses (25, 50, and 75 mm) were incorporated as experimental parameters for the volatile gas condenser. A vertical tube-type condenser was designed using a 12-mm pipe centrally inserted along a 150 × 300 mm cylindrical condenser body. Cold water at 10–20°C was circulated continuously to liquefy condensable pyrolytic gases into bio-oil. Pyrolysis system frame. An angular steel frame (45 cm × 60 cm × 70 cm) provided structural stability and safety for the assembled system. Temperature controller. The temperature control device consisted of an Arduino Uno circuit board, a 20-Amp electromechanical relay, K-type thermocouple wires, and a Max6675 digital integrated circuit. The relay automatically switched the power supply ON and OFF to maintain the set pyrolysis temperature.

2.1.3 Fabrication of the pyrolysis reactor system

Fabrication of the pyrolysis reactor and volatile gas condenser was job-ordered to a specialized machine shop in Cebu City. The reactor heater was fabricated at a specialized electrical shop in Lapu-Lapu City with a rated power of 3.0 kW. The Arduino temperature control device was constructed by the researcher with the assistance of an electronics professional. The system frame was fabricated locally by a skilled artisan. Total fabrication cost was PHP 60,370.00.

2.2 Operating Principles

The system operated on the principle of pyrolysis—heating biomass in the absence of oxygen. Each batch of biomass was loaded, then thermally degraded at a set controlled temperature. Pyrolytic gases were channeled through the condenser to collect bio-oil. The operation was stopped when no further significant bio-oil production was observed, after which end-products (bio-oil and bio-char) were collected and weighed separately. The sealed batch configuration maintained the oxygen-free condition during pyrolysis; the reactor was fully closed before heating and remained sealed throughout each run.

2.3 Technical Performance Evaluation

2.3.1 Experimental set-up

The experimental setup consisted of a cylindrical batch reactor externally heated by a 3-kW electrical coil, with temperature controlled using an external Arduino circuit controller. The reactor had two openings at the upper section: one covered opening for loading feedstock and one for vapor exit connected to the condenser. A third opening at the bottom, with a push-pull metal valve, discharged biochar. Ice-cooled water circulated in the condenser as the cooling medium. Condensed liquid and solid products were collected and weighed immediately after each pyrolysis run. Gaseous product yield was calculated by material balance.

2.3.2 Experimental procedure

Pyrolysis experiments were conducted by varying pyrolysis temperature, feedstock loading density, and insulation thickness. The operating conditions — batch loading, temperatures of 400–500°C, and residence times of 20–30 min — are consistent with slow pyrolysis mode, which is characterized by low heating rates and extended solid and vapor residence times that favor char and gas production over liquid bio-oil [16]. The measured heating rate of the 3-kW external coil should be recorded and reported for each temperature set point to ensure reproducibility and allow comparison with other systems. Based on preliminary tests, each set temperature was maintained for 20–30 min to ensure complete conversion of biomass. Three experimental

groups were conducted at insulation thicknesses of 25, 50, and 75 mm. Within each group, three pyrolysis temperatures (400°C, 450°C, and 500°C) and three loading densities (60, 90, and 120 kg/m³) were tested, with three replications per condition.

2.3.3 Experimental design and analyses

The experiment was carried out in a split-plot completely randomized design (CRD) with insulation thickness (H) as the main plot and biomass loading density (D) and pyrolysis temperature (T) as sub-plot factors. Insulation thickness was treated as a hard-to-change (HTC) factor. Insulation thickness was designated as the HTC factor because physically modifying the fiberglass wool wrapping (removing, adjusting thickness, and reinstalling around the reactor assembly) between experimental runs required significantly more time and effort than adjusting temperature set-points or biomass loading, consistent with the split-plot design rationale. The three insulation thickness levels were randomized at the whole-plot level; a single reactor unit was used, and insulation was changed between experimental groups (one group per insulation level) rather than between individual runs. Factor levels were:

$H_1 = 25$ mm, $H_2 = 50$ mm, $H_3 = 75$ mm thick fiberglass wool insulation

$D_1 = 60$ kg/m³, $D_2 = 90$ kg/m³, $D_3 = 120$ kg/m³ biomass loading density

$T_1 = 400^\circ\text{C}$, $T_2 = 450^\circ\text{C}$, $T_3 = 500^\circ\text{C}$ pyrolysis temperature

Analysis of variance (ANOVA) was used to determine significant effects of variables and their interactions on bio-oil and bio-char production. Scheffe's test was employed to determine significant differences between factor levels. All statistical analyses were performed using SPSS software.

2.3.4 Preparation of feedstock

Rice straw samples were collected, cleaned, and sun-dried to a moisture content of approximately 10%. The straws were manually chopped to a maximum particle length of 10 mm. Samples were compacted to achieve target experimental densities using a compactor with the same inside diameter as the reactor. Proximate analysis (moisture, ash, volatile matter, fixed carbon) and ultimate analysis (C, H, N, O, S) of the rice straw feedstock should be determined and reported to allow yield contextualization and inter-study comparison; these data are standard inputs for pyrolysis studies and are needed to interpret the mass balance fully.

2.3.5 Data gathered

Temperature was measured inside the reactor using K-type thermocouples connected to the Arduino via the Arduino program. Bio-oil (condensable liquid yield) was collected in a container placed below the gas condenser throughout the pyrolysis process and weighed after each run using an analytical balance. Bio-char (solid residue) was removed from the reactor after each run, transferred to a metal container, covered to extinguish embers, cooled for approximately 5 min, and weighed.

2.3.6 Material mass balance calculation

The yield of each pyrolysis fraction was calculated using material balance equations [17]:

$$Y_{bo} = [(W_2 - W_1) / W_f] \times 100\% \quad (4)$$

$$Y_{bc} = [(W_4 - W_3) / W_f] \times 100\% \quad (5)$$

$$Y_g = 100\% - (Y_{bo} + Y_{bc}) \quad (6)$$

Where Y_{bo} = bio-oil yield (%); Y_{bc} = bio-char yield (%); Y_g = gas yield (%); W_1 = weight of empty bio-oil container (g); W_2 = weight of container with bio-oil after reaction (g); W_3 = weight of empty bio-char container (g); W_4 = weight of container with bio-char after reaction (g); W_f = weight of chopped rice straw fed to the reactor (g).

2.4 Standardization of the Operating Procedure

Results of preliminary tests and evaluations were analyzed to develop a standardized operating procedure (SOP) for optimum bio-oil production. The SOP covers: preparation of equipment and materials;

component connections; activation of the temperature controller; pre-heating; temperature monitoring; biomass loading; bio-oil collection; condenser cooling water maintenance; end-of-operation protocol; bio-char collection; and system maintenance for subsequent runs.

3. Results and Discussion

3.1 The Laboratory-Scale Pyrolysis Reactor System

The designed pyrolysis reactor system consists of five main components: (1) pyrolysis reactor chamber, (2) electrical heater, (3) pyrolytic gas condenser, (4) Arduino temperature control device, and (5) system metal frame (Figure 1). The reactor vessel was fabricated from a 5-mm-thick block of iron pipe (12 cm diameter, 44 cm length) and mounted on an angle-bar frame for stability and safety. A helical 3-kW electric heating coil was mounted on the outer surface of the reactor chamber, enclosed by a 1-mm sheet-metal casing and insulated with fiberglass wool of variable thickness (25–75 mm). The Arduino-based temperature controller maintained stable pyrolysis temperatures by automatically switching an ON/OFF relay in response to signals from K-type thermocouple sensors.

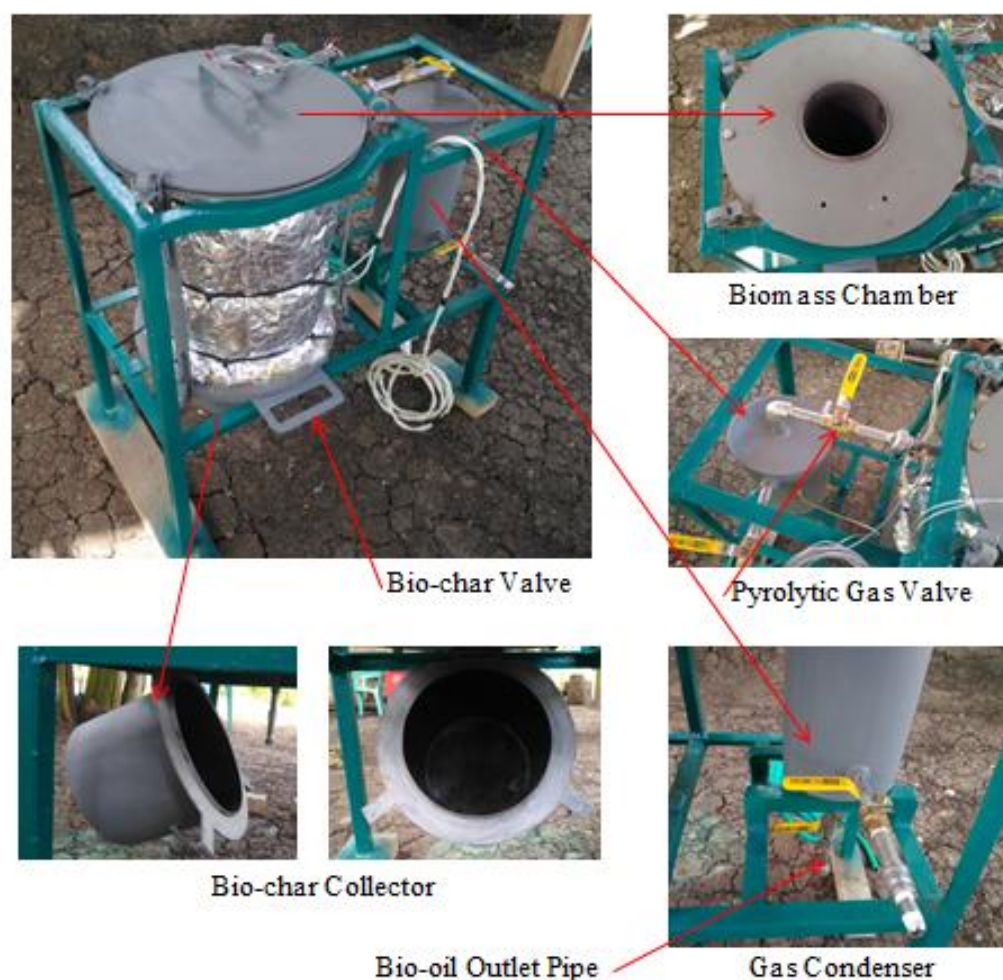


Figure 1. Perspective drawing of the pyrolysis reactor system components.

3.2 Reactor Integrity and Operational Stability

Temperature stability was demonstrated by steady temperature profiles at all set points (Figure 2). Pyrolysis temperature steady-state conditions were reached on average in 20, 25, and 30 min after setting the temperature to 400°C, 450°C, and 500°C, respectively, upon activating the Arduino controller. The steady-state condition was maintained for at least 30 min, sufficient for complete rice straw pyrolysis. Loading the reactor with biomass did not disrupt the steady-state temperature, demonstrating the effective operation of the

temperature control device. The maintained functional condition through more than 5 hours of continuous operation confirmed the integrity of the pyrolysis system.

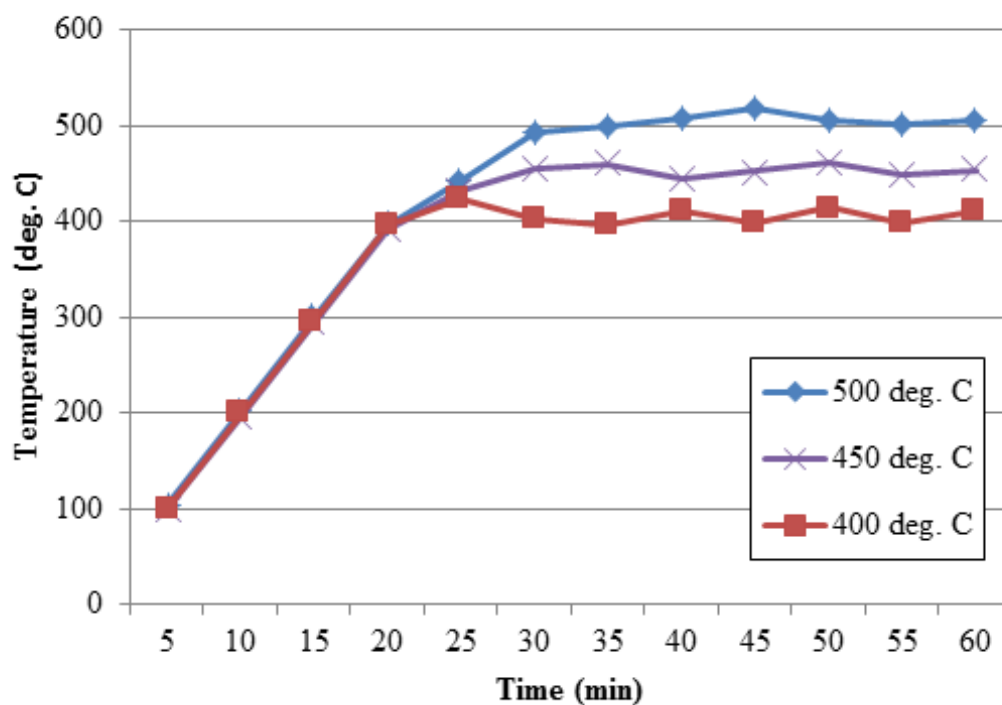


Figure 2. Temperature profiles of the pyrolysis reactor at 400°C, 450°C, and 500°C set points.

3.3 Bio-oil Production

Analysis of variance on bio-oil production showed that biomass loading density (D) had a highly significant effect ($p < 0.010$), pyrolysis temperature (T) had a significant effect ($p = 0.026$), and insulation thickness (H) had a highly significant effect ($p < 0.010$) on bio-oil production (Table 1). In contrast, none of the two-way or three-way interaction terms was significant, indicating that each factor acted independently in influencing bio-oil production.

Table 1. Split-plot ANOVA in a completely randomized design on bio-oil production from pyrolysis experiments.

Source of Variation	Factor	df	Sum of Squares	Mean Square	F comp.	p-value
Main Plot	Insulation (H)	2	4152.765	2076.383	15.652	0.000
	Main plot error	6	1294.444	215.741	1.626	0.160
Sub-plot	Density (D)	2	18723.877	9361.938	70.572	0.000
	Temperature (T)	2	1050.395	525.198	3.959	0.026
	H × D	4	1049.901	262.475	1.979	0.113
	H × T	4	198.272	49.568	0.374	0.826
	D × T	4	1155.605	288.901	2.178	0.086
	H × D × T	8	1498.617	187.327	1.412	0.216
	Sub-plot error	48	6367.556	132.657	—	—

Further analysis using Scheffe's test (Table 2) showed that 25 mm insulation produced significantly higher bio-oil (78.07 g) than 50 mm (65.26 g) or 75 mm (61.30 g) insulation, though no significant difference existed between the latter two. This counterintuitive result — where thinner insulation yields more bio-oil despite higher expected heat loss — may be explained by the interaction between insulation thickness and the

Arduino-based ON/OFF relay controller. With thinner insulation, the heating element cycles more frequently to maintain the set temperature, resulting in a faster effective heating rate and shorter residence time in the intermediate temperature zone (250–350°C) where secondary char-forming reactions predominate. Conversely, thicker insulation may cause transient temperature overshoots during heater-ON cycles that briefly exceed the set point, promoting secondary cracking of condensable vapors into non-condensable gases and thereby reducing liquid yield. Additionally, moisture retained within thicker fiberglass wool at elevated temperatures may affect local vapor condensation dynamics. The significant interaction between insulation thickness and pyrolysis temperature observed in bio-char production (Table 3) further supports the conclusion that insulation effects are thermally mediated and not reducible to simple heat-loss reduction. For loading density, 90 kg/m³ (76.74 g) produced significantly more bio-oil than 60 kg/m³ (46.85 g), but was not significantly different from 120 kg/m³ (81.04 g). This finding supports the observation of Weerachanchai et al. [18] that denser packing of smaller biomass particles impedes sweeping gas flow, ultimately reducing liquid fuel production. For the pyrolysis temperature, a significant difference was found only between 400°C (65.11 g) and 450°C (73.26 g). Production at 500°C (66.26 g) was intermediate and not significantly different from either extreme, likely because higher temperatures favor greater gas formation at the expense of bio-oil. The non-condensable gas produced was highly flammable, with characteristics similar to syngas [19].

Table 2. Scheffe's test of significance on mean bio-oil production (g) by factor level.

Factor	Level	N	Mean (g)
Biomass Loading Density (D)	D ₁ = 60 kg/m ³ (300 g rice straw)	27	46.85 a
	D ₂ = 90 kg/m ³ (450 g rice straw)	27	76.74 b
	D ₃ = 120 kg/m ³ (600 g rice straw)	27	81.04 b
Pyrolysis Temperature (T)	T ₁ = 400°C	27	65.11 a
	T ₂ = 450°C	27	73.26 b
	T ₃ = 500°C	27	66.26 ab
Insulation Thickness (H)	H ₁ = 25 mm	27	78.07 a
	H ₂ = 50 mm	27	65.26 b
	H ₃ = 75 mm	27	61.30 b

Means within a factor followed by the same letter are not significantly different at $\alpha = 0.05$.

3.4 Biochar Production

ANOVA on bio-char production showed highly significant effects ($p < 0.010$) for all three factors: loading density, pyrolysis temperature, and insulation thickness (Table 3). Significant two-way interactions were found between insulation thickness and pyrolysis temperature ($p = 0.050$) and between loading density and pyrolysis temperature ($p = 0.019$). The three-way interaction was also significant ($p = 0.013$), indicating that the combined influence of factors affected biochar production.

Table 3. Split-plot ANOVA in a completely randomized design on bio-char production from pyrolysis experiments.

Source of Variation	Factor	df	Sum of Squares	Mean Square	F comp.	p-value
Main Plot	Insulation (H)	2	4729.580	2364.790	8.312	0.001
	Main plot error	6	1330.000	221.667	0.779	0.590
Sub-plot	Density (D)	2	203755.728	101877.864	358.077	0.000
	Temperature (T)	2	3391.580	1695.790	5.960	0.005
	H × D	4	2540.272	635.068	2.282	0.079
	H × T	4	2927.309	731.827	2.572	0.050
	D × T	4	3720.272	930.068	3.269	0.019
	H × D × T	8	6311.728	788.966	2.773	0.013
	Sub-plot error	48	13656.667	284.514	—	—

Scheffe's test results (Table 4) showed a continuous, significant increase in bio-char production across all loading density levels, unlike bio-oil, which plateaued at D₂. This is consistent with the finding of Weerachanchai et al. [18] that denser biomass packing impedes sweeping gas flow, yielding higher bio-char. For pyrolysis temperature, significantly more bio-char was produced at 400°C (180.19 g) than at 500°C (164.81 g), indicating that higher temperatures direct more biomass toward gas formation rather than solid char. For insulation thickness, H₂ (50 mm, 161.04 g) produced significantly less bio-char than H₁ (179.26 g) or H₃ (173.85 g); this unexpected result may be attributed to the significant interaction between insulation thickness and pyrolysis temperature. The biochar produced in this study represents a potentially valuable co-product: biochar derived from thermochemical conversion of biomass has demonstrated benefits as a soil amendment, improving soil nutrient availability and supporting plant growth when applied at optimized rates [20].

Table 4. Scheffe's test of significance on mean bio-char production (g) by factor level.

Factor	Level	N	Mean (g)
Biomass Loading Density (D)	D ₁ = 60 kg/m ³ (300 g rice straw)	27	110.15 a
	D ₂ = 90 kg/m ³ (450 g rice straw)	27	171.00 b
	D ₃ = 120 kg/m ³ (600 g rice straw)	27	233.00 c
Pyrolysis Temperature (T)	T ₁ = 400°C	27	180.19 a
	T ₂ = 450°C	27	169.15 ab
	T ₃ = 500°C	27	164.81 b
Insulation Thickness (H)	H ₁ = 25 mm	27	179.26 a
	H ₂ = 50 mm	27	161.04 b
	H ₃ = 75 mm	27	173.85 a

Means within a factor followed by the same letter are not significantly different at $\alpha = 0.05$.

3.5 Material Mass Balance

The material mass balance showed that bio-oil yield was consistently lower than that of bio-char and syngas across all factor combinations (Figure 3). As the reaction temperature increased from 400°C to 500°C, gas yield increased, consistent with progressive thermal cracking of both primary volatile products and bio-char. The optimum temperature of 450°C produced the highest bio-oil yield (16.6%), and the optimum loading density of 90 kg/m³ produced the highest bio-oil yield (17.1%). These values are substantially lower than the 28.4% reported by Kumar et al. [21] for similar agricultural biomass under comparable conditions. Two factors likely contribute to this difference. First, the present reactor operated under slow pyrolysis conditions (temperature range 400–500°C, batch-fed, 20–30 min residence time), which characteristically favors char and gas formation over liquid yield; fast pyrolysis systems optimized for bio-oil production typically achieve liquid yields of 40–60% through very high heating rates and short vapor residence times [16]. Second, condenser efficiency is a limiting factor: the tube-in-shell condenser used in this study (150 × 300 mm body, 12-mm central pipe, cooling water at 10–20°C) likely allowed a fraction of condensable vapors to escape uncollected, as no quantitative assessment of condensation efficiency was conducted. It should also be acknowledged that calculating gas yield by difference (Equation 6) accumulates measurement errors from bio-oil and bio-char weighing; direct gas measurement by gas chromatography in future studies would improve mass balance accuracy. The present reactor design is therefore more appropriate for slow pyrolysis applications and bio-char production studies than for optimizing bio-oil yield, and future design iterations should incorporate a higher-capacity condenser with quantified heat transfer area and cooling water flow rate.

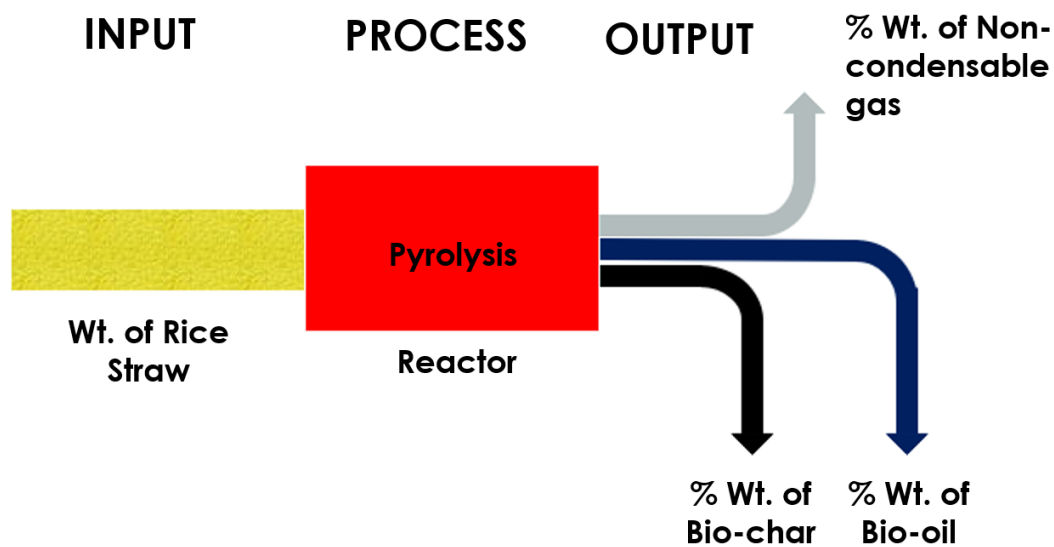


Figure 3. Material mass balance input-process-output diagram for the pyrolysis reactor system.

3.6 Standardization of the Pyrolysis Operation

Based on a series of pyrolysis tests, evaluations, and experimental trials, a step-by-step SOP was drafted for optimum use of the developed laboratory-scale pyrolysis system. The SOP covers all operational phases: preparation of equipment and materials; component connections; activation of the temperature controller; pre-heating; temperature monitoring; biomass loading; bio-oil collection; maintenance of condenser cooling water; end-of-operation protocol; bio-char unloading and collection; and system maintenance for subsequent runs. Adherence to the SOP ensures consistent and reproducible pyrolysis results.

4. Conclusions

The developed laboratory-scale batch-fed pyrolysis reactor system is a viable tool for pyrolysis of rice straw and biomass with similar physical characteristics. The reactor demonstrated temperature stability and operational integrity at pyrolysis temperatures of 400°C–500°C. Among the experimental conditions evaluated, 25 mm reactor insulation thickness, 450°C pyrolysis temperature, and 90 kg/m³ loading density produced the optimum bio-oil yield. All three factors independently influenced bio-oil and bio-char production, while their interactions were generally not significant for bio-oil. The established standard operating procedure provides an effective guide for using the system to pyrolyze various biomass types and optimize pyrolysis end products. The bio-oil extracted, together with the flammable non-condensable syngas co-product, represents a potential renewable energy resource. Further experiments using other biomass feedstocks and improved condenser designs are recommended to increase bio-oil recovery efficiency.

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