

Characterization of Rice Husk Pyrolysis Products for Potential Renewable Energy Applications

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Abstract. Converting agricultural waste into value-added products offers a promising strategy for sustainable waste management and reducing dependence on fossil resources. This study investigates the slow pyrolysis of rice husk at 550 °C, with emphasis on product distribution and the physicochemical characteristics of the resulting biochar, bio-oil, and gaseous fraction. The process produced 50.88 ± 0.51 wt.% biochar, 38.18 ± 1.05 wt.% bio-oil, and an estimated gas yield of 10.94 ± 1.50 wt.%, calculated by mass difference. Gas chromatography (GC) identified carbon dioxide (17.251% of the reported GC composition) as the dominant detected gaseous component, followed by carbon monoxide, methane, and hydrogen. Gas chromatography–mass spectrometry (GC-MS) showed that the bio-oil contained esters (31.33%), fatty acids (24.48%), phenolic compounds (22.88%), hydrocarbons (9.97%), ketone/aromatic carbonyl compounds (7.84%), and other oxygenated compounds (2.28%) based on relative GC peak areas. Brunauer–Emmett–Teller (BET) analysis showed that the biochar had a specific surface area of $77.05 \text{ m}^2 \text{ g}^{-1}$, a total pore volume of $0.052 \text{ cm}^3 \text{ g}^{-1}$, and an average BJH pore diameter of 69.527 Å (6.95 nm), indicating a predominantly mesoporous textural structure. These results demonstrate the potential of rice husk as a feedstock for integrated production of a carbonaceous solid, condensable liquid products, and combustible gas components. Further application-specific testing is required to establish the performance of the individual fractions in energy and environmental applications.

Keywords: Biochar, Bio-oil, Gaseous Products, Pyrolysis, Rice Husk

INTRODUCTION

The global climate crisis and the continued dependence on fossil-based energy systems are among the major challenges of the twenty-first century. According to the International Energy Agency (IEA, 2024), total energy-related CO₂ emissions reached 37.4 Gt in 2023, increasing by 1.1% from the previous year. This continuing increase highlights the persistent dependence on fossil fuels and the need to accelerate the development of renewable and low-carbon energy technologies. In Indonesia, the transition toward renewable energy has also progressed relatively slowly. The Institute for Essential Services Reform (IESR, 2024) reported that renewable energy accounted for 13.1% of the national energy mix in 2023, still below the national target of 23% by 2025. These conditions emphasize the importance of developing renewable energy technologies based on abundant local resources while simultaneously addressing environmental challenges associated with waste generation.

Agricultural residues represent an important renewable resource for this transition, particularly in countries with substantial agricultural production. Rice husk is one of the most abundant agricultural residues in Indonesia because of the country's large rice production. However, a significant proportion of rice husk remains underutilized and may be disposed of through uncontrolled burning or other low-value practices. Such practices not only create environmental concerns but also result in the loss of a potentially valuable carbonaceous feedstock for energy and material production. Thermochemical conversion, particularly pyrolysis, offers an alternative pathway to convert rice husk into three

product fractions: biochar, bio-oil, and non-condensable gas (NCG). Depending on feedstock characteristics and operating conditions, these products can support energy recovery and value-added material applications (Guedes *et al.*, 2017; Rosli *et al.*, 2022).

The suitability of rice husk for pyrolysis is closely related to its physicochemical composition. Proximate analysis provides information on moisture, fixed carbon, volatile matter, and ash contents, whereas ultimate analysis determines the elemental composition of the biomass, including carbon, hydrogen, oxygen, nitrogen, and sulfur. These parameters are important because they influence biomass devolatilization, char formation, gas evolution, and the distribution and properties of pyrolysis products.

Although rice husk pyrolysis has been extensively investigated, reported product yields and product characteristics vary because of differences in feedstock composition, reactor configuration, heating rate, residence time, temperature, and pyrolysis mode. Previous studies have examined fast, slow, and catalytic routes, often emphasizing maximizing either bio-oil or biochar production. An integrated assessment linking feedstock characteristics with the distribution and measured characteristics of the solid, liquid, and gaseous fractions under a defined non-catalytic slow-pyrolysis condition therefore remains useful, particularly for evaluating the potential utilization of each fraction.

In the present study, slow pyrolysis was conducted at 550 °C in a fixed-bed reactor. This temperature was selected as a literature-supported operating condition because several previous studies reported favorable liquid-product yields from rice husk pyrolysis

near 550 °C under their respective experimental conditions. Importantly, 550 °C was not optimized in the present study and is not proposed as a universal optimum. Instead, this condition was used to investigate product distribution and product characteristics under a defined non-catalytic slow-pyrolysis condition.

Several studies support selecting this operating condition. Islam *et al.* (2011) investigated rice husk pyrolysis over 400–650 °C and reported a maximum bio-oil yield of approximately 47 wt.% at 550 °C with a residence time of 30 min. Zhou *et al.* (2013) reported a maximum bio-oil yield of 49.91% at 550 °C using a fixed-bed reactor. Fermanelli *et al.* (2020) reported a maximum bio-oil yield of approximately 45 wt.% at 550 °C within a temperature range of 350–650 °C, while Zhao *et al.* (2016) reported a maximum bio-oil yield of 53.81 wt.% at 550 °C under non-catalytic conditions. These studies indicate that approximately 550 °C can provide a useful operating condition for rice husk pyrolysis; however, the optimum temperature is system-specific and depends on feedstock properties, reactor configuration, heating rate, residence time, and product-recovery conditions.

The contribution of the present study is therefore not the use of 550 °C itself, but the integrated quantitative characterization of the feedstock and the three major pyrolysis product fractions under a defined non-catalytic slow-pyrolysis condition. Product distribution was quantified as biochar, bio-oil, and estimated gas yields; the gaseous fraction was characterized by gas chromatography (GC), the bio-oil by gas chromatography–mass spectrometry (GC-MS), and the biochar by Brunauer–Emmett–Teller (BET) and BJH analyses. This combination enables discussion of feedstock

characteristics in relation to product distribution and the physicochemical or chemical characteristics of each fraction. Accordingly, this study aims to quantify the products obtained from rice husk slow pyrolysis at 550 °C and characterize the resulting gaseous, liquid, and solid fractions using GC, GC-MS, and BET/BJH analyses. The results provide quantitative evidence for assessing the potential utilization of rice husk in renewable-energy and value-added carbon-material pathways, while also identifying analytical limitations that should be addressed in future scale-up studies.

MATERIALS AND METHOD

The main material used in this research was rice husk, obtained from a local rice milling waste source. Before use, the rice husk was cleaned to remove impurities such as dust and small stones, then dried at room temperature until its moisture content stabilized. The main apparatus used in this research included a pyrolysis reactor and analytical instruments such as Gas Chromatography–Mass Spectrometry (GC-MS), Gas Chromatography (GC), and a Brunauer–Emmett–Teller (BET) surface area analyzer.

Experimental Procedures

The experimental procedure for rice husk pyrolysis was as follows. A total of 15 grams of rice husk was prepared as the main sample. The rice husk was cleaned and dried to minimize moisture content, which can significantly influence pyrolysis efficiency and the composition of the liquid products. The dried rice husk sample was then placed into a pyrolysis reactor. The pyrolysis process was carried out under anaerobic conditions (absence of oxygen) to prevent combustion.

The total gas yield was not measured directly. Instead, it was estimated by mass difference from the initial rice husk mass and the recovered masses of biochar and bio-oil. The estimated gas yield was calculated as: gas yield (wt.%) = 100 – biochar yield (wt.%) – bio-oil yield (wt.%). This approach assumes that the unrecovered mass is attributable to the gaseous fraction; therefore, the estimate may also include uncollected condensable compounds, deposits inside the reactor or connecting lines, minor material losses, and measurement error. The gas composition reported later in this paper was determined separately from GC analysis of the collected gas sample and should not be interpreted as a direct measurement of the total gas yield.

Rice husk pyrolysis was conducted at 550 °C in a fixed-bed reactor using a biomass loading of 15 g and a retention time of 45 min. The volatile products generated during pyrolysis were directed through a condenser to recover the liquid fraction. The resulting bio-oil was characterized using a Shimadzu GCMS-QP2010 SE equipped with an Rtx-5MS column. For GC-MS analysis, the injector temperature was 280 °C, the injection was performed in split mode at a split ratio of 50:1, and the column flow rate was 0.65 mL min⁻¹. The GC oven temperature was initially maintained at 120 °C for 1 min, increased to 200 °C at 10 °C min⁻¹ and held for 9 min, and subsequently increased to 300 °C at 20 °C min⁻¹ and held for 17 min. Mass spectra were acquired over m/z 20–600.

During pyrolysis, volatile vapors were directed through a condenser to separate the liquid phase (bio-oil), while the solid residue (biochar) remained in the reactor. The gas exiting the system was collected as a sample for GC analysis. After completion of pyrolysis and cooling to room temperature, the products were separated into three fractions:

(1) biochar, defined as the solid carbonaceous residue retained in the reactor; (2) bio-oil, defined as the condensed liquid fraction collected from the condenser; and (3) gas, defined operationally as the estimated gaseous fraction obtained from the mass balance and the gas sample analysed by GC.

- 1) Biochar is the solid carbonaceous residue retained inside the reactor.
- 2) Bio-oil is the condensed liquid fraction collected from the condenser.
- 3) Gas is the non-condensable gaseous fraction exiting the system.

The pyrolysis experiments were conducted in triplicate under the same operating conditions. Product yields are reported as mean ± standard deviation (SD) of the three independent runs. Because the gas yield was estimated by mass difference rather than measured directly, its SD reflects the variability propagated from the measured biochar and bio-oil recoveries.

Rice Husk Characterization

Table 1 presents the quantitative characteristics of the rice husk investigated in this study, along with comparative data reported by Gaur and Reed (1998).

The results in Table 1 demonstrate several characteristics relevant to the thermal conversion behavior of the investigated rice husk. The volatile matter content was 66.50 wt.%, slightly higher than the 63.60 wt.% reported by Gaur and Reed (1998). The difference of 2.90 percentage points indicates a relatively high proportion of thermally decomposable organic matter in the present feedstock.

In contrast, the ash content was substantially lower, at 8.50 wt.% compared with 20.60 wt.% reported by Gaur and Reed (1998), corresponding to a difference of 12.10

percentage points. The lower ash content is potentially favorable for thermochemical conversion because a smaller inorganic fraction leaves a larger proportion of the feedstock available for thermal decomposition and carbonaceous product formation.

Table 1. Proximate, ultimate, and structural composition of rice husk

Analysis	Parameter	This study (wt.%)	Gaur & Reed (1998) (wt.%)
Proximate	Moisture content	5.43	–
	Fixed carbon	19.57	15.80
	Volatile matter	66.50	63.60
	Ash	8.50	20.60
Ultimate	C	33.89	38.30
	H	5.87	4.30
	O	59.06	35.40
	N	0.38	0.80
	S	0.79	0.00
Structural composition	Cellulose	33.80	–
	Hemicellulose	28.34	–
	Lignin	19.40	–

The ultimate analysis also revealed notable differences between the present feedstock and the literature data. The carbon content was 33.89 wt.%, compared with 38.30 wt.% reported by Gaur and Reed (1998), whereas the hydrogen content increased from 4.30 to 5.87 wt.%. The most pronounced difference was observed for oxygen, which accounted for 59.06 wt.% in the present study compared with 35.40 wt.% in the literature data. This difference of 23.66 percentage points indicates a considerably more oxygen-rich feedstock in the present study. Such a characteristic is relevant to pyrolysis because oxygen-containing biomass constituents can contribute to the formation of oxygenated

compounds in the liquid fraction and influence the quality and stability of the resulting bio-oil.

The sulfur content of the investigated rice husk was relatively low at 0.79 wt.%, while nitrogen accounted for only 0.38 wt.%. The low nitrogen and sulfur contents are favorable from a fuel-conversion perspective because they indicate a relatively small contribution of nitrogen- and sulfur-containing elements to the feedstock. However, the ultimate composition alone does not determine the environmental performance of the pyrolysis products; their actual chemical composition and subsequent utilization or combustion pathways must also be considered.

The structural composition further confirms the lignocellulosic nature of the feedstock, consisting of 33.80 wt.% cellulose, 28.34 wt.% hemicellulose, and 19.40 wt.% lignin. These components decompose over different temperature ranges and contribute differently to the formation of gases, condensable vapors, and solid carbonaceous residues. Consequently, the relatively high volatile matter content and lignocellulosic composition of the investigated rice husk provide a suitable basis for evaluating its conversion into multiple pyrolysis products.

Differences between the present results and those reported by Gaur and Reed (1998) also demonstrate that rice husk should not be treated as a chemically uniform feedstock. Biomass composition can vary with rice variety, geographical origin, cultivation conditions, soil characteristics, harvesting practices, moisture content, and analytical procedures. Therefore, direct characterization of the feedstock used in each pyrolysis experiment is essential for interpreting product yields and product properties.

Product Characterization

Biochar Analysis

The biochar was characterized using the Brunauer–Emmett–Teller (BET) method to determine specific surface area and total pore volume. In contrast, the BJH method was used to estimate pore-size characteristics. These measurements describe the biochar's textural properties and provide a basis for further application-specific adsorption studies.

Bio-oil Analysis

The chemical composition of the bio-oil was determined using Gas Chromatography–Mass Spectrometry (GC–MS). The technique identified volatile organic compounds, including esters, fatty acids, phenolic compounds, hydrocarbons, and other oxygenated compounds. The measured mass spectra were compared with the NIST library database to support compound identification. The reported group percentages are based on relative GC-MS peak areas and therefore represent composition within the detected chromatographic fraction rather than gravimetric mass percentages.

Gas Analysis

The gaseous sample was analyzed using Gas Chromatography (GC) to identify major components including CO, CO₂, H₂, CH₄, and light hydrocarbons. The GC results were used to describe the composition of the detected gas sample. Because the total gas yield was estimated independently by mass difference, the GC composition and gravimetric gas-yield estimate are reported and interpreted as separate measurements.

RESULTS AND DISCUSSION

Composition of Pyrolysis Products at 550 °C

The pyrolysis products consisted of biochar, bio-oil, and gas, which were calculated using Equations (1) – (3) and are presented in Figure 1 below.

$$\% \text{ char} = \frac{W_{\text{char}}}{W_{\text{total}}} \times 100\% \quad (1)$$

$$\% \text{ bio oil} = \frac{W_{\text{bio oil}}}{W_{\text{total}}} \times 100\% \quad (2)$$

$$\% \text{ gas} = \frac{W_{\text{gas}}}{W_{\text{total}}} \times 100\% \quad (3)$$

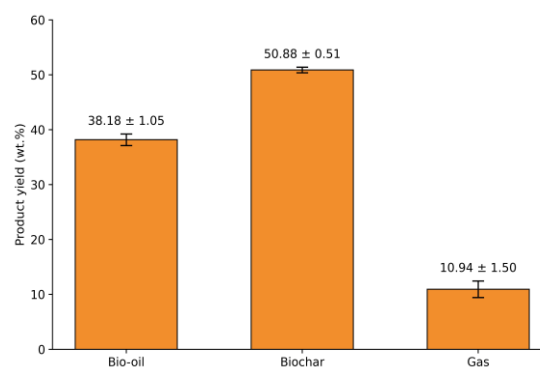


Fig. 1: Yield of pyrolysis rice husk at 550°C

Based on Figure 1, the product distribution obtained from the three replicate experiments was 50.88 ± 0.51 wt.% biochar, 38.18 ± 1.05 wt.% bio-oil, and 10.94 ± 1.50 wt.% estimated gas. The three yields sum to approximately 100 wt.% within rounding. The relatively high biochar fraction is consistent with the lignocellulosic nature of rice husk and its inorganic ash content, particularly silica, which remains largely in the solid residue. Hemicellulose and cellulose contribute substantially to volatile formation, whereas lignin decomposes over a broader temperature range and can promote char formation as well as phenolic vapors. Because the gas yield was obtained by mass

difference, the reported 10.94 wt.% should be regarded as an estimated fraction rather than a direct measurement of non-condensable gas production.

At 550 °C, primary pyrolysis vapors can undergo secondary cracking, dehydration, condensation, and repolymerization. Cracking reactions contribute to the formation of non-condensable gases such as CO, CO₂, H₂, and CH₄. In contrast, condensation and repolymerization of reactive oxygenated and lignin-derived vapors can contribute to secondary char formation. The measured bio-oil yield of 38.18 ± 1.05 wt.% represents the condensable fraction recovered by the experimental condensation system. Thus, the observed distribution reflects the combined effects of primary devolatilization, secondary vapor reactions, condensation efficiency, char formation, and the inorganic fraction of the rice husk. The result should be interpreted as the product distribution obtained under the selected operating condition rather than as an optimized yield.

Comparison with the literature (Table 2) shows that the product distribution obtained in this study falls within the broad range reported for rice husk pyrolysis. Differences among studies are expected because feedstock composition, reactor configuration, temperature range, heating rate, residence

time, and product-recovery conditions can substantially affect relative yields. Therefore, the values in Table 2 provide contextual comparison rather than a direct performance ranking. Under the present fixed-bed condition, the process produced a substantial condensable fraction together with a dominant solid fraction.

GC-MS Analysis of the Chemical Composition of Rice Husk Pyrolysis Bio-oil

Figure 2 presents the distribution of the major chemical groups identified in the rice husk pyrolysis bio-oil based on their relative GC-MS peak areas. Esters represented the largest detected group (31.33%), followed by fatty acids (24.48%) and phenolic compounds (22.88%). Hydrocarbons, ketone/aromatic carbonyl compounds, and other oxygenated compounds accounted for 9.97%, 7.84%, and 2.28%, respectively. The values sum to approximately 100% and represent relative peak-area contributions within the detected chromatographic fraction; they should not be interpreted as gravimetric mass percentages.

The dominance of esters, fatty acids, and phenolic compounds is consistent with the decomposition of the lignocellulosic constituents of rice husk. Oxygenated compounds can originate from fragmentation and secondary reactions of cellulose and hemicellulose, whereas

Table 2. Comparison of rice husk pyrolysis product yields under reported operating conditions

Material	Temperature (°C)	Biochar (wt.%)	Liquid fraction (wt.%)	Gas (wt.%)	References
Rice husk	550	58.02	29.43	12.55	Wijayanti <i>et al.</i> (2020)
	500	33.0	51.0	14.0	Yu <i>et al.</i> (2016)
	550	50.88 ± 0.51	38.18 ± 1.05	10.94 ± 1.50	This study

Note: Product yields are presented for contextual comparison because feedstock properties, reactor configuration, heating rate, residence time, and product-recovery conditions differ among studies. For Wijayanti *et al.* (2020), the reported liquid fraction is the sum of oil (3.27 wt.%) and water (26.16 wt.%), giving 29.43 wt.%; it is therefore not directly equivalent to the bio-oil yield reported in the present study.

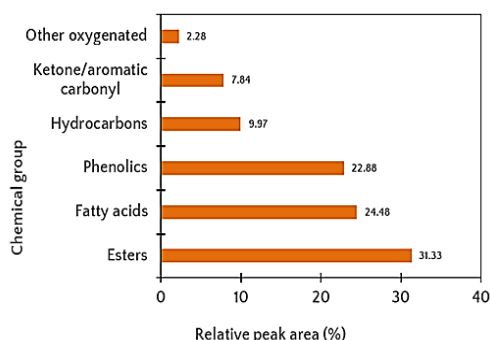


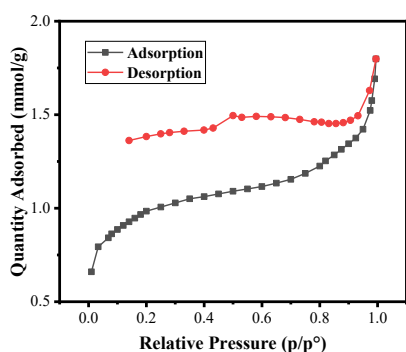
Fig. 2: Relative GC-MS peak-area distribution of chemical groups identified in rice husk pyrolysis bio-oil

phenolic compounds are commonly associated with lignin-derived vapors. The presence of hydrocarbons and carbonyl compounds indicates that secondary cracking, dehydration, and rearrangement reactions also occurred. The relatively high proportion of oxygenated groups suggests that the bio-oil would require further upgrading or application-specific evaluation

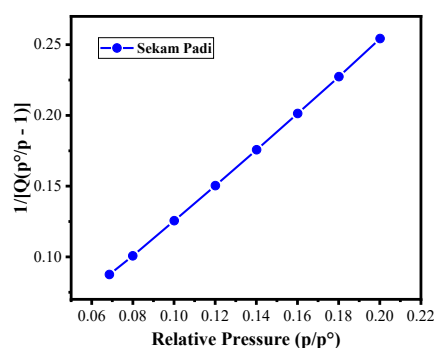
before it could be considered a direct replacement for conventional hydrocarbon fuels. Nevertheless, its chemical composition indicates potential as a source of value-added oxygenated chemicals, subject to further purification and characterization.

Surface Area and Pore Size Analysis of Biochar Using BET

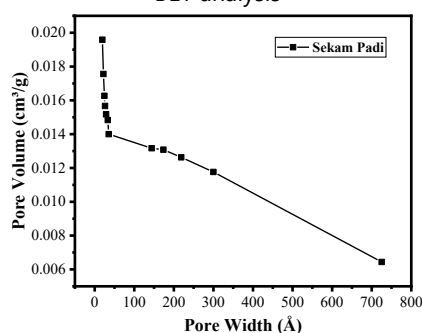
Based on the Brunauer–Emmett–Teller (BET) analysis of the rice husk pyrolysis product, the nitrogen adsorption–desorption isotherm revealed a characteristic pattern of porous materials. The obtained isotherm exhibited a Type IV profile with a hysteresis loop, indicating the presence of mesoporous structures within the material. The specific surface area reflects the extent of active sites available for adsorption processes, while the pore size distribution lies predominantly within the mesoporous range.



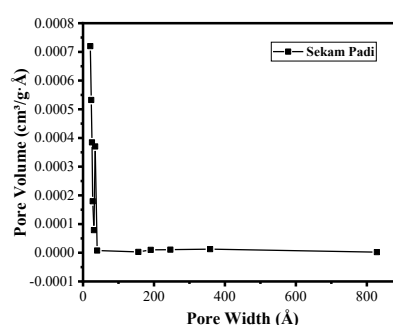
a. Nitrogen adsorption–desorption isotherm from BET analysis



b. BET surface area plot.



c. Pore size distribution from BJH desorption analysis.



d. Differential pore volume plot from BJH desorption analysis.

Fig. 3: BET and BJH analysis of rice husk biochar: (a) nitrogen adsorption–desorption isotherm, (b) BET linear plot, (c) BJH pore-size distribution, and (d) differential pore-volume distribution

The nitrogen adsorption–desorption isotherm obtained from the BET analysis is presented in Figure 3(a), while the BET linear plot is shown in Figure 3(b). The adsorption–desorption behavior corresponds to a Type IV isotherm, which is characteristic of materials containing mesopores (2–50 nm) according to the IUPAC classification (Thommes *et al.* 2015). The observed hysteresis at intermediate-to-high relative pressures is consistent with capillary condensation in mesopores. The exact hysteresis subtype should be assigned only from the measured curve; therefore, the present study uses the isotherm and pore-size data primarily to establish the presence of a mesoporous contribution rather than to infer a specific pore geometry. Adsorption at low relative pressure may also indicate micropores. Still, the measured average BJH pore diameter and pore-size distribution indicate that mesopores constitute an important part of the accessible pore structure.

The BET analysis showed that the rice husk biochar produced at 550 °C had a specific surface area (S_{BET}) of 77.05 m² g^{−1}, a total pore volume of 0.052 cm³ g^{−1}, and an average BJH pore diameter of 69.527 Å (6.95 nm). The Type IV isotherm and the pore-size results indicate a predominantly mesoporous textural structure. The average pore diameter falls within the mesopore range and may facilitate diffusion of relatively large molecules, while the measured surface area provides a quantitative basis for further adsorption studies. Compared with the K₂CO₃-activated rice husk carbon reported by Scapin *et al.* (2021), which reached a surface area of 1850 m² g^{−1} and a pore volume of 0.79 cm³ g^{−1} after activation, the non-activated biochar in this study had substantially lower textural development. This difference is consistent with the absence of a chemical

activation step in the present preparation route.

Overall, the BET results indicate that direct pyrolysis at 550 °C generated a biochar with a measurable surface area and a substantial mesoporous contribution. These properties suggest that the material is a suitable candidate for further application-specific adsorption testing. However, BET and BJH measurements alone do not establish adsorption capacity, adsorption kinetics, or catalytic performance. Such functional properties should therefore be verified through dedicated adsorption or catalytic experiments before specific applications are claimed.

The BET linear plot in Figure 3(b) was evaluated within the selected relative-pressure range of $P/P_0 = 0.05\text{--}0.30$. The slope and intercept of the linear region are used to calculate the specific surface area. A high R^2 value indicates good linear agreement between the selected BET data and the regression model within that pressure interval. However, R^2 alone does not establish pore homogeneity or adsorption performance; the BET result should be interpreted alongside the adsorption–desorption isotherm, hysteresis behavior, pore volume, and pore-size distribution.

The pore-size distribution of the rice husk biochar was further evaluated using the Barrett–Joyner–Halenda (BJH) method applied to the nitrogen desorption data. Figure 3(c) shows the resulting distribution. The measured average BJH pore diameter of 69.527 Å (6.95 nm) lies within the mesopore range defined by IUPAC (2–50 nm), supporting the interpretation that mesopores make an important contribution to the measured pore structure. Because the distribution itself is broader than a single ideal pore size, the data should not be

described as demonstrating a highly uniform pore network.

- Micropores: <2 nm
- Mesopores: 2–50 nm
- Macropores: >50 nm

The pore-size distribution should therefore be interpreted in terms of the dominant pore-size range rather than as evidence of structural homogeneity. A broad or multi-component distribution is common in biomass-derived chars because devolatilization, mineral content, lignin decomposition, and secondary char formation can generate pores of different dimensions.

Figure 3(d) presents the differential pore-volume plot derived from the BJH desorption data. The curve provides complementary information on how pore volume is distributed with pore diameter. The observed contribution within the mesopore range is consistent with the average pore diameter of 6.95 nm obtained from the BJH analysis. Together with the Type IV isotherm, these results support the conclusion that the biochar contains a substantial mesoporous fraction.

The mesoporous characteristics indicate that the biochar warrants further investigation as an adsorbent, particularly for applications in which pore accessibility is important. Nevertheless, the present study does not directly measure adsorption capacity or adsorption kinetics; therefore, these performance parameters are considered potential application areas rather

than demonstrated functions. Future work should evaluate textural properties alongside surface chemistry and application-specific adsorption experiments.

Compared with previous studies, the results indicate that both pyrolysis and activation conditions influence the textural properties of rice husk-derived carbon materials. Table 3 presents a contextual comparison of specific surface area, pore volume, and pore diameter.

Table 3 shows that the textural properties of rice husk-derived carbon materials depend strongly on the preparation route. The K_2CO_3 -activated material reported by Scapin *et al.* (2021) had a substantially higher surface area and pore volume than the non-activated biochar produced in the present study, illustrating the effect of chemical activation on pore development. The present pyrolysis biochar exhibited $S_{BET} = 77.05 \text{ m}^2 \text{ g}^{-1}$, $V_{TOT} = 0.052 \text{ cm}^3 \text{ g}^{-1}$, and an average BJH pore diameter of 69.527 Å (6.95 nm). The lower surface area relative to the activated material is consistent with the absence of a chemical activation step. This comparison is contextual because the activation route, pyrolysis conditions, and analytical procedures differ across studies.

The present biochar was produced by direct pyrolysis at 550 °C without chemical activation or post-treatment. Decomposition and devolatilization of cellulose, hemicellulose, and lignin can generate pores within the carbon matrix, while the mineral fraction of rice husk can also influence pore

Table 3. Specific surface area and pore-size characteristics of rice husk-derived carbon materials

Method	Surface area (S_{BET}) (m^2/g)	Pore volume (V_{Total}) (cm^3/g)	Pore diameter (BJH) (Å)	References
Pyrolysis + K_2CO_3 activation	1850	0.79	–	Scapin <i>et al.</i> (2021)
Pyrolysis, 550 °C	77.05	0.052	69.527	This study

development. The resulting S_{BET} of $77.05 \text{ m}^2 \text{ g}^{-1}$ and pore volume of $0.052 \text{ cm}^3 \text{ g}^{-1}$ indicate moderate textural development, with an average BJH pore diameter of 6.95 nm. These values provide a useful baseline for future activation or surface-modification studies aimed at increasing surface area or tailoring pore accessibility.

Gas Analysis Using Gas Chromatography (GC)

The gaseous products generated during rice husk pyrolysis were analyzed by Gas Chromatography (GC). The chromatographic profile of the gas sample obtained from slow pyrolysis at 550°C is presented in Figure 4. Because the total gas yield was estimated independently by mass difference, the GC results are used here to describe the relative composition of the analyzed gas sample rather than to calculate the total gas mass yield.

The GC chromatogram in Figure 4 shows several gaseous components at different retention times. Hydrogen (H_2) was detected at 4.606 min, methane (CH_4) at 6.456 min, carbon monoxide (CO) at 6.722 min, and light hydrocarbons including ethylene (C_2H_4) and ethane (C_2H_6) between 6.856 and 6.958 min. Propylene (C_3H_6) was detected at 10.700 min, while carbon dioxide (CO_2) produced the most prominent peak at a retention time of 21.716 min. These retention times identify the detected compounds under the analytical conditions used in this study and should not be interpreted as quantitative yields without calibration data.

The pronounced CO_2 peak indicates that CO_2 was the dominant gas component identified in the analyzed sample. The presence of CO , CH_4 , H_2 , and light hydrocarbons is consistent with the fragmentation and secondary reactions of

lignocellulosic vapors during pyrolysis. The combustible components, particularly H_2 , CO , CH_4 , and light hydrocarbons, indicate that the gas fraction may have energy-recovery potential; however, a complete gas composition and a measured volumetric flow rate or heating value would be required to quantify its fuel performance.

Figure 5 summarizes the relative concentrations of the four major quantified gases. The reported values were $\text{H}_2 = 1.637\%$, $\text{CO} = 14.524\%$, $\text{CH}_4 = 3.702\%$, and $\text{CO}_2 = 17.251\%$. Their sum is 37.114% of the GC-reported composition. These percentages describe the identified components in the analyzed gas sample and do not represent the $10.94 \pm 1.50 \text{ wt.}\%$ estimated total gas yield obtained from the product mass balance.

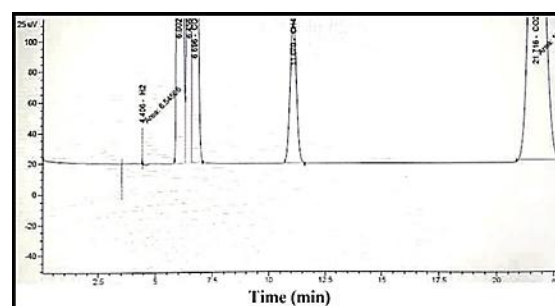


Fig. 4: GC chromatogram of gaseous products from rice husk slow pyrolysis at 550°C

The predominance of CO_2 is consistent with the decomposition of oxygen-containing functional groups during thermal degradation of lignocellulosic biomass. Decarboxylation and related deoxygenation reactions can contribute to CO_2 formation, whereas CO may arise from decarbonylation, cracking, and secondary vapor reactions. CH_4 can be formed through cleavage of methyl- and methoxy-containing structures, particularly from lignin-derived compounds, while H_2 can arise from secondary

dehydrogenation, cracking, and reforming reactions at elevated temperatures.

The four major quantified gases accounted for 37.114% of the GC-reported composition. The remaining 62.886% was not individually assigned in the present analysis. It may include other non-condensable components, light hydrocarbons, or unidentified compounds; however, no specific composition is assigned without supporting analytical data. This limitation matters because the GC analysis covered only the identified components and the total gas yield was estimated separately by mass difference.

Overall, the GC analysis indicates that CO₂ was the dominant identified gas component, followed by CO, CH₄, and H₂. The detected combustible gases support the possibility of energy recovery from the gaseous fraction, but the present data are insufficient to establish a complete fuel specification. Future work should include calibrated quantitative GC analysis of the complete gas stream, gas-flow measurement, and heating-value determination to evaluate its energy potential more rigorously.

The distinction between gas composition and gas yield is important. The value of 37.114% is the sum of the four identified GC components, whereas the estimated total gas yield was 10.94 ± 1.50 wt.% based on the product mass balance. These two quantities should not be combined or interpreted as measurements of the same variable. The present GC results therefore provide information on the composition of the analyzed gas sample, while the mass-difference calculation estimates the total gaseous fraction.

Using the product mass balance, the estimated gas yield was calculated as $100 - \text{biochar yield} - \text{bio-oil yield}$. With mean yields

of 50.88 wt.% biochar and 38.18 wt.% bio-oil, the corresponding mean estimated gas yield was 10.94 wt.%. This value is independent of the 37.114% relative GC composition of H₂, CO, CH₄, and CO₂ and should be reported as an estimated rather than directly measured gas yield.

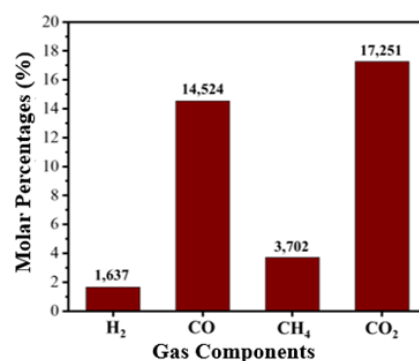


Fig. 5: Relative composition of the major gas components identified by GC

CONCLUSIONS

Based on the experimental results, slow pyrolysis of rice husk at 550 °C produced three measurable product fractions: 50.88 ± 0.51 wt.% biochar, 38.18 ± 1.05 wt.% bio-oil, and an estimated gas yield of 10.94 ± 1.50 wt.% based on mass difference. The relatively high solid yield is consistent with the lignocellulosic composition and inorganic fraction of rice husk. In contrast, the substantial condensable fraction demonstrates the formation of recoverable liquid products under the selected operating conditions. GC-MS analysis showed that the detected bio-oil was dominated by esters (31.33%), fatty acids (24.48%), and phenolic compounds (22.88%) on a relative peak-area basis, indicating a chemically diverse oxygenated liquid fraction. BET/BJH analysis showed that the biochar had a specific surface area of $77.05 \text{ m}^2 \text{ g}^{-1}$, a total pore volume of $0.052 \text{ cm}^3 \text{ g}^{-1}$, and an average pore

diameter of 6.95 nm, supporting a predominantly mesoporous textural structure. GC analysis identified CO₂ as the dominant detected gas component, followed by CO, CH₄, and H₂; these four components accounted for 37.114% of the GC-reported composition. Importantly, this value describes the composition of the analyzed gas sample and should not be confused with the estimated total gas yield of 10.94 ± 1.50 wt.%. Overall, the results demonstrate that rice husk can generate solid, liquid, and gaseous products with distinct characteristics under the selected slow-pyrolysis condition. The biochar and bio-oil show potential for further application-specific evaluation. At the same time, gaseous fraction requires complete quantitative gas analysis and heating-value measurement before its fuel performance can be established.

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