

Potential of Bio-Oil from Rice Husk and Sawdust Pyrolysis as a Liquid Organic Hydrogen Carrier (LOHC)

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Abstract. Biomass represents a renewable and abundantly available energy resource; however, several residues, including rice husks and teak sawdust, remain underutilized. Their distinct physicochemical characteristics influence thermal decomposition behavior, making fast pyrolysis a promising pathway for producing higher-quality bio-oil. This study investigated the effect of varying mixtures of rice husks and teak wood on bio-oil yield and properties using a fixed-bed reactor operated at 500 °C with LPG as the heat source. The resulting bio-oil was characterized in terms of moisture content, pH, viscosity, higher heating value, elemental composition (C–H–O), atomic O/C and H/C ratios, and chemical compound distribution via GC–MS analysis. The results demonstrate that increasing the teak wood fraction consistently enhanced bio-oil performance. Product yield increased from 39.6% to 54%, moisture content decreased from 30% to 20%, and the calorific value improved from 17.5 to 19 MJ/kg. A reduction in the O/C ratio from 0.50 to 0.32 indicates significant deoxygenation, accompanied by a compositional shift from acid- and furan-rich compounds (typical of rice husks) toward more stable phenolic structures derived from teak lignin. The mixture containing 25% rice husks and 75% teak wood exhibited the most balanced performance. These findings confirm that fast pyrolysis effectively converts local biomass into cleaner, energy-dense liquid fuel and highlight its promising potential as a liquid organic hydrogen carrier (LOHC) for safer and more flexible hydrogen-based energy systems.

1 Introduction

The use of biomass as an alternative energy source has become a major focus in efforts to reduce dependence on fossil fuels and the impacts of climate change. Biomass, as an abundant renewable resource, particularly from agricultural and forestry waste such as rice husks and sawdust, offers great potential for conversion into various forms of energy, including bio-oil. Bio-oil, produced through a fast pyrolysis process, is not only environmentally friendly due to its low sulfur content but also has a high calorific value, making it a promising alternative fuel [1]. The high organic content of bio-oil, including

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lignin, alcohols, organic acids, and carbonyl compounds, suggests that it has the potential to be a significant source of renewable hydrogen [2]. Thermal conversion processes of biomass, such as pyrolysis, decompose lignocellulosic macromolecules into bio-oil, gas, and char, with bio-oil being the liquid fraction that has significant potential as a fuel [3]. The development of fast pyrolysis technology for waste biomass, such as rice husks and sawdust, is a promising approach to producing bio-oil as a primary product, aligning with the need for sustainable energy [4]. The utilization of this biomass is crucial, considering the tendency of Indonesian society to remain highly dependent on fossil energy, especially petroleum and coal, whose availability continues to decline [5]. In addition, biomass from the agricultural and plantation sectors, such as rice husks, is abundant and has not been utilized optimally; therefore, its utilization in bio-oil production can reduce waste and provide economic added value. The availability of raw materials derived from various sources, such as wood processing residues, sawdust, rice husks, and coconut shells, all of which can be converted into bio-oil [6][7].

The global dependence on fossil fuels has triggered an energy crisis and urgent environmental issues, prompting the search for sustainable alternative energy sources. Furthermore, biomass can also be specifically converted into bio-oil through pyrolysis techniques [8]. This pyrolysis process is a thermochemical decomposition of biomass that occurs in the absence of oxygen at a temperature range of 300°C to 600°C, producing products in the form of bio-charcoal, gas, and bio-oil [9]. The relative composition of these products is strongly influenced by the operational conditions of pyrolysis, including the type of biomass, temperature, and heating rate. The production of biofuels, including bio-oil, often requires energy-intensive reaction conditions such as high temperatures and pressures, as well as the involvement of catalysts in a non-oxygenic environment, which can limit the yield of liquids and gases. However, fast pyrolysis, a thermochemical method that involves rapidly heating biomass in the absence of oxygen, has been shown to produce bio-oil with higher liquid yields compared to slow pyrolysis. This process operates at intermediate temperatures (400°C-600 °C) with very short vapor residence times (<2 seconds), maximizing the production of bio-oil as the primary liquid phase. One of the advantages of fast pyrolysis is its ability to convert biomass into bio-oil with high efficiency, minimizing the production of char and unwanted gases [10]. Bio-oil produced from lignocellulosic biomass such as rice husk and sawdust exhibits complex characteristics, with chemical compositions varying greatly depending on the type of biomass and the pyrolysis parameters used [11]. Fast pyrolysis of rice husks at 400 °C- 600 °C, with the highest bio-oil yield reaching 70% at 450 °C, demonstrates significant potential for bio-oil production. However, the components of this bio-oil can be affected by the pyrolysis temperature.

Furthermore, the potential of co-pyrolysis-derived bio-oil from agricultural and forestry residues as a hydrogen-rich liquid precursor relevant to Liquid Organic Hydrogen Carrier (LOHC) applications remains insufficiently explored through integrated elemental, thermochemical, and molecular-level analyses.

The novelty of this study lies in the systematic evaluation of co-pyrolysis between rice husk and teak sawdust as locally abundant but contrasting biomass wastes, with a specific focus on their transformation into hydrogen-rich bio-oil under a fixed-bed fast pyrolysis configuration. This study introduces an integrated assessment combining proximate–ultimate analysis, O/C–HHV correlation, and GC–MS compound profiling to elucidate the physicochemical pathway from raw biomass to bio-oil. Furthermore, this work provides one of the first experimental indications that bio-oil derived from co-pyrolysis of agricultural and forestry residues can serve as a hydrogen-rich liquid precursor with potential applicability toward Liquid Organic Hydrogen Carrier (LOHC) systems, thereby bridging biomass pyrolysis and hydrogen energy storage within a single conversion framework.

2 Methods

2.1 Raw Material Preparation and Characterization

Rice husks and teak sawdust were selected as representative biomass waste from the agricultural and forestry sectors, possessing contrasting physical and chemical characteristics. Prior to use, both raw materials were naturally dried to a moisture content below 11% (wet weight) and sieved to obtain a relatively uniform particle size. Initial characterization was performed through proximate and ultimate analysis following ASTM standards, including determining moisture content, volatile matter, fixed carbon, ash, and the elemental composition of carbon (C), hydrogen (H), and oxygen (O). This baseline data was used as a reference to evaluate the effect of feedstock composition on pyrolysis behavior and the quality of the resulting bio-oil.

2.2 Fast Pyrolysis Procedure

Fig. 1 fast pyrolysis experiment was conducted using a laboratory-scale fixed-bed reactor constructed of heat-resistant steel. The reactor was heated externally using LPG fuel and operated at a constant temperature of 500°C, selected based on its ability to produce optimal bio-oil yield from lignocellulosic biomass. To maintain oxygen-free conditions throughout the process, inert nitrogen (N_2) gas is continuously circulated into the reactor at a flow rate of 1 liter/minute, helping to accelerate the transfer of pyrolysis vapor to the condensation system. Heating rate 17°C/minute, vapor residence time \approx 1 minute. The pyrolysis vapor is then passed through a water-cooled, multistage condenser to collect the liquid fraction (bio-oil), while the non-condensable gaseous products are released, leaving the solid residue as biochar in the reactor.

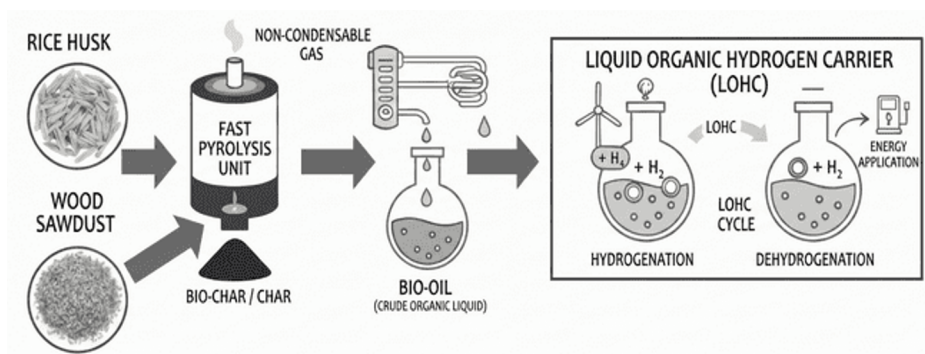


Fig. 1. Schematic Fast pyrolysis process to produce bio oil.

Fig. 1 illustrates the schematic of the biomass fast pyrolysis process. The feedstocks, consisting of rice husk and wood sawdust, are fed into a fast pyrolysis unit that operates at high temperature under oxygen-free conditions. This process produces three main products: bio-oil, non-condensable gases, and biochar. The produced bio-oil has the potential to be further utilized as a Liquid Organic Hydrogen Carrier (LOHC).

2.3 Feedstock and Blending Strategy

To assess the effect of raw material mixing on product distribution and bio-oil quality, rice husks and teak sawdust were mixed in various mass ratios: 100:0, 75:25, 50:50, 25:75, and

0:100. This co-pyrolysis approach was designed to reveal the synergistic interactions between high-ash biomass (rice husks) and high-volatile biomass (teak sawdust) during the fast pyrolysis process.

2.4 Product Yield Determination

The yield of pyrolysis products, including bio-oil, bio-charcoal, and gas, was determined based on a mass balance against the initial mass of dry feedstock. Bio-oil yield was calculated from the mass of condensed liquid, bio-charcoal yield from the solids remaining in the reactor, while gas yield was obtained indirectly through the mass difference. This approach allows for quantitative evaluation of product distribution as a function of variations in feedstock composition.

2.5 Bio-Oil Characterization

The obtained bio-oil was analyzed to determine its physicochemical and energy properties. Moisture content was measured using the Karl Fischer method, while pH, density, and viscosity were analyzed following standard procedures. The higher heating value (HHV) was determined to evaluate the energy content of the bio-oil. Elemental composition data were then used to calculate the H/C and O/C atomic ratios as indicators of the degree of deoxygenation and hydrogen enrichment in the bio-oil.

2.6 Chemical Composition and Structural Analysis

The identification and classification of key compounds in bio-oil were performed using gas chromatography–mass spectrometry (GC–MS). Furthermore, the H/C and O/C atomic ratios were visualized using Van Krevelen diagrams to illustrate changes in the chemical structure of biomass during thermochemical conversion. This integrated analytical approach was used to elucidate the relationship between feedstock composition, deoxygenation behavior, and the improved properties of bio-oil fuel.

3 Results and discussion

3.1 Results

Based on the characteristics of the raw materials for the fast pyrolysis study, proximate and ultimate testing of rice husk and sawdust were conducted. The results of the proximate and ultimate tests are presented in **Table 1**.

Table 1. Raw Material Characteristics

Parameter	Rice Husk	Sawdust
Moisture (ar,wt%)	9.2	13.5
Volatile Matter (db,wt%)	65.3	92
Fixed Carbon (db,wt%)	17.4	6.45
Ash (db,wt%)	17.5	1.55
C (db,wt%)	37.6	48.7
H (db, wt%)	5	6.4
O (by diff,wt%)	36.6	44.1

Fast pyrolysis results from a mixture of various raw materials, rice husks and teak sawdust, show clear variations in product distribution between bio-oil, char, and gas. Changes in feedstock composition affect devolatilization behavior and secondary reactions during pyrolysis, thus impacting the yield of each product fraction. Pyrolysis product yields can be seen in **Fig. 2**.

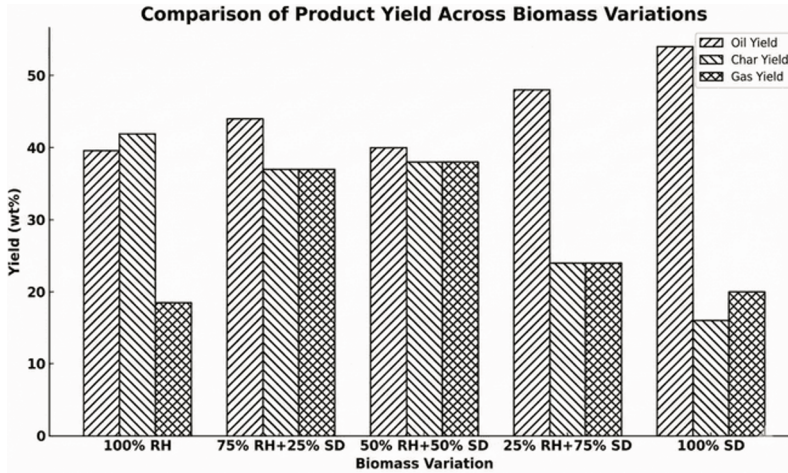


Fig 2. Pyrolysis products from various biomasses.

Fast pyrolysis results from various biomass feedstocks demonstrate a strong correlation between the feedstock composition and the energy quality of the bio-oil produced. **Fig. 3** shows the relationship between the O/C atomic ratio of bio-oil and its high calorific value (HHV), which reflects the changes in chemical properties due to thermal decomposition during pyrolysis. Variations in the proportions of sawdust and rice husk affect the degree of deoxygenation of organic compounds, thus directly impacting the energy content of bio-oil. Therefore, analyzing the O/C–HHV relationship is an important approach to evaluate the effectiveness of fast pyrolysis in improving the quality of bio-oil as a renewable liquid fuel.

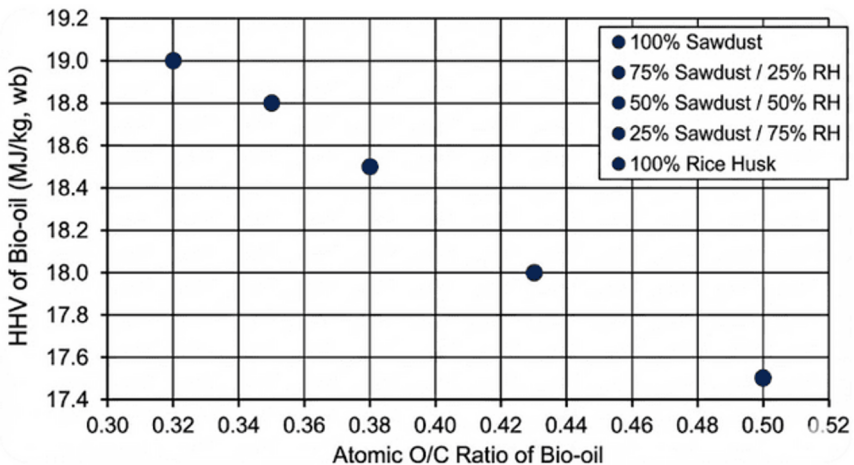


Fig 3. Relationship between O/C and HHV

The graph in **Fig. 4** presents the relationship between the H/C and O/C atomic ratios of the biomass feedstock and the bio-oil produced from fast pyrolysis. This diagram is widely used to evaluate changes in elemental composition and the degree of deoxygenation that occur during the thermochemical conversion process. Comparing the positions of the feed and bio-oil points on the Van Krevelen diagram provides a clear picture of the structural transformation of the biomass due to pyrolysis, particularly in terms of oxygen reduction and changes in the hydrocarbon character of the resulting liquid product.

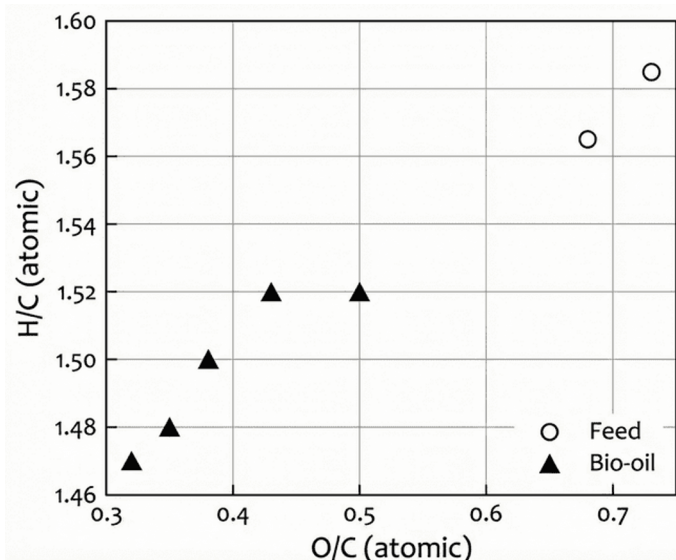


Fig 4. Graph of the Relationship between H/C and O/C Atoms

3.2 Discussion

Proximate (table 1) analysis showed that rice husk contained significantly higher ash (17.5 wt%) and fixed carbon (17.4 wt%) than sawdust (1.55 and 6.45 wt%), respectively. This led to a greater tendency for char formation. Meanwhile, sawdust exhibited very high volatile matter content (92 wt%), which significantly contributed to the formation of higher liquid products during fast pyrolysis. Ultimate analysis confirmed the superior energy quality of sawdust due to its higher carbon and hydrogen contents (48.7 and 6.4 wt%). As a result, sawdust had a higher calorific value compared to rice husk. These results matched the experimental product distribution. Increasing sawdust fraction increased the bio-oil yield from 39.6% (100% rice husk) to 54% (100% sawdust) and decreased the char yield.

At a pyrolysis temperature of 500°C, pure sawdust produced the highest liquid fraction (54%) with minimal char (20%), indicating efficient devolatilization of lignocellulosic components under oxygen-free heating. In contrast, pure rice husk produced a significantly higher solid residue (char \approx 41.9%) and a lower liquid yield (39.6%), reflecting the influence of the high ash/mineral content (especially silica) in rice husk in inhibiting complete evaporation and stabilising the carbon matrix during thermal decomposition. Blends of sawdust and rice husk showed intermediate results. A blend containing 75% sawdust and 25% rice husk achieved a bio-oil yield of 48%, significantly higher than pure rice husk, demonstrating the synergistic effect of co-pyrolysis. This observation aligns with a previous study reporting a bio-oil yield of 51.9% at a 50:50 sawdust:rice husk ratio in fluidised bed co-pyrolysis [12]. From an application perspective, the ability to direct product distribution—

either favouring bio-oil, bio-char, or syngas—by manipulating the feedstock composition underscores the flexibility and practical value of co-pyrolysis. This relationship is crucial because the O/C and HHV values directly influence the quality and energy potential of bio-oil, making them important parameters for commercial evaluation and fuel applications. Therefore, examining the O/C vs. HHV ratio is essential for optimising the pyrolysis process to produce bio-oil with characteristics similar to conventional fossil fuels.

Fig. 3 shows a negative relationship between O/C and HHV, with a decrease in O/C indicating deoxygenation, which is accompanied by an increase in heating value (HHV). This analysis will reveal how the decrease in oxygen content in bio-oil, reflected by a lower O/C ratio, is positively correlated with an increase in HHV, indicating potential improvements in fuel quality. Furthermore, biomass with an O/C ratio of around 0.6 to 0.7 has the potential to produce bio-oil with higher viscosity, which is an important consideration in liquid fuel applications [13][14].

Proximate and ultimate analyses reveal a fundamental relationship between biomass oxygenation degree and its intrinsic energy release capacity. Rice husk exhibits a relatively high O/C atomic ratio (± 0.73), corresponding to a lower higher heating value (HHV) of 14.52 MJ/kg. In contrast, sawdust presents a lower O/C ratio (± 0.68) and a significantly higher HHV of 18.24 MJ/kg. The inverse trend observed in the O/C–HHV relationship confirms that progressive deoxygenation enhances fuel energy density. Thermochemically, a lower oxygen fraction relative to carbon increases the proportion of combustible bonds (C–C and C–H), thereby elevating the net calorific output per unit mass. The energy disparity between the two biomasses is not governed solely by elemental ratios but also by their structural and compositional characteristics. Sawdust contains higher carbon and hydrogen contents and substantially lower ash (1.55 wt%) compared with rice husk (17.5 wt%). Elevated C and H fractions promote exothermic oxidation reactions, whereas ash behaves as inert ballast, diminishing flame stability and reducing effective heat transfer. This observation aligns with contemporary HHV predictive models, in which carbon and hydrogen contribute positively to energy yield, while oxygen and ash exert negative effects on fuel efficiency.

Volatile matter (VM) further differentiates their combustion behavior. Sawdust, with approximately 92 wt% VM, favors rapid devolatilization and higher combustion temperatures. Conversely, rice husk's lower VM and high mineral residue constrain its thermal performance. Consequently, sawdust is inherently suitable for direct combustion applications, whereas rice husk requires upgrading strategies—such as torrefaction, pyrolysis, or co-blending—to reduce oxygen and ash content. Collectively, these findings underscore the importance of physicochemical tailoring in optimizing biomass utilization pathways within a sustainable energy transition framework.

Fig. 4 illustrates the correlation between H/C and O/C atomic ratios for both the original feedstock and the resulting pyrolysis-derived bio-oil, providing insight into the degree of chemical transformation during thermal conversion. The feedstock data (circle symbols) are distributed within an O/C range of approximately 0.56–0.72 and an H/C range of 1.56–1.59, characteristic of lignocellulosic biomass rich in oxygenated functional groups such as hydroxyl, carbonyl, and carboxyl moieties. These elevated O/C ratios reflect the inherently oxidized nature of raw biomass, which thermodynamically limits its energy density and contributes to lower heating values compared to fossil-derived fuels [15].

Following pyrolysis, the bio-oil data points (triangle symbols) shift toward a region of lower O/C values (≈ 0.30 – 0.50) and slightly reduced H/C ratios (≈ 1.47 – 1.52). This systematic migration from the upper-right to the lower-left region of the diagram signifies substantial deoxygenation, primarily driven by dehydration, decarboxylation, and decarbonylation reactions that release H_2O , CO_2 , and CO . The reduction in oxygen relative to carbon indicates a progressive enrichment of energy-dense carbonaceous structures, while the moderate

adjustment in H/C suggests partial aromatization and structural rearrangement rather than excessive cracking.

The transition from feedstock compositions around O/C \approx 0.70 and H/C \approx 1.59 to bio-oil values as low as O/C \approx 0.32 demonstrates that the pyrolysis process effectively enhances fuel quality by increasing chemical stability and calorific potential. The resulting bio-oil occupies a compositional domain closer to conventional liquid fuels, indicating promising applicability as a renewable energy carrier and a potential intermediate for Liquid Organic Hydrogen Carrier (LOHC) systems after targeted upgrading.

4 Conclusion

This study confirms that fast pyrolysis is an effective and sustainable approach for converting biomass, specifically rice husks and teak sawdust, into bio-oil as a renewable energy source. The differences in chemical and physical properties between the two biomasses resulted in distinct responses during the pyrolysis process, with increasing the proportion of teak wood resulting in significant improvements in the quality and quantity of bio-oil. This is reflected in increased liquid yield, decreased moisture content, increased calorific value, and a decreased O/C ratio, indicating better deoxygenation. A mixture of 25% rice husks and 75% teak wood performed optimally, demonstrating positive synergies in the production of more stable and higher-energy-value bio-oil. Analysis using the Van Krevelen diagram and GC–MS confirmed that the resulting bio-oil exhibited improved fuel characteristics and a chemical composition closer to that of fossil fuels. Utilizing this currently undervalued biomass waste can provide a solution for environmental cleanliness while supporting regional energy independence. Furthermore, the increased hydrogen content and energy storage properties of bio-oil open up potential applications as a Liquid Organic Hydrogen Carrier (LOHC) in the future—a crucial step toward a clean, safe, and flexible energy transition. Therefore, the results of this research can serve as a strategic basis for the development of inclusive renewable energy, empowering biomass waste, and supporting a sustainable vision for future generations.

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