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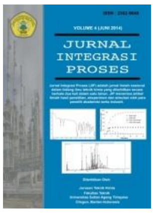

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ENHANCING THE QUALITY OF BIO OIL FROM RICE STRAW WITH A COMBINATION OF CO-PYROLYSIS WITH PLASTIC AND CO-CATALYST Fe/Al_2O_3

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Abstract

This study investigates the enhancement of bio-oil quality derived from rice straw through co-pyrolysis with plastic waste (polypropylene and low-density polyethylene) and utilizing a Fe/Al_2O_3 co-catalyst. The pyrolysis process was conducted at 500°C for 20 minutes, with variations in plastic ratios and catalyst concentrations (0–20%). The results indicated that both the yield and calorific value of the bio-oil significantly increased with higher LDPE content and catalyst addition, achieving an optimum yield of 30.56% and a calorific value of 41.308 MJ/kg at a 0:50 PP:LDPE ratio with 20% catalyst. Viscosity and density values were also optimized, falling within ASTM standards with 2.511 cSt and 0.856 g/cm^3. Gas chromatography-mass spectrometry (GC-MS) analysis confirmed the dominant presence of gasoline-range hydrocarbons and the absence of corrosive acetic acid. In contrast, ultimate analysis showed high carbon and hydrogen content, suggesting improved fuel quality. These findings indicate that combining co-pyrolysis with the Fe/Al_2O_3 catalyst and integrating plastic waste offers a promising method for producing high-quality, renewable bio-oil from rice straw.

Keywords: Co-catalyst; Co-pyrolysis; Plastic; Pyrolysis; Rice straw

Abstrak

Penelitian ini menyelidiki peningkatan kualitas bio-oil yang berasal dari jerami padi melalui ko-pirolisis dengan sampah plastik (polipropilena dan polietilena densitas rendah) serta pemanfaatan ko-katalis Fe/Al_2O_3. Proses pirolisis dilakukan pada suhu 500°C selama 20 menit, dengan variasi rasio plastik dan konsentrasi katalis (0–20%). Hasil penelitian menunjukkan bahwa baik hasil yield dan nilai kalor bio-oil meningkat signifikan dengan peningkatan kandungan LDPE dan penambahan katalis, mencapai hasil optimum sebesar 30,56% dan nilai kalor 41,308 MJ/kg pada rasio 0:50 PP:LDPE dengan 20% katalis. Nilai viskositas dan densitas juga dioptimalkan hingga 2,511 cSt dan 0,856 g/cm^3, berada dalam standar ASTM. Analisis kromatografi gas-spektrometri massa (GC-MS) mengonfirmasi dominasi hidrokarbon dalam kisaran bensin dan tidak ditemukannya asam asetat korosif, sementara analisis ultimate menunjukkan kandungan karbon dan hidrogen yang tinggi, yang mengindikasikan kualitas bahan bakar yang lebih baik. Temuan ini menunjukkan bahwa kombinasi ko-pirolisis dengan katalis Fe/Al_2O_3 dan integrasi sampah plastik menawarkan metode yang menjanjikan untuk menghasilkan bio-oil berkualitas tinggi dan terbarukan dari jerami padi.

***Kata Kunci**: Jerami padi; Ko-katalis; Ko-pirolisis; Pirolisis; Plastik*

1. INTRODUCTION

Indonesia is one of the countries with the highest energy consumption in the world. The use of crude oil continues to increase across all sectors, both at small and large scales (Afif & Martin, 2022). In 2022, energy consumption in Indonesia was distributed among the industrial sector (53%), households (23%), transportation (18%), and others (6%) (BPS, 2022).

This has resulted in an energy crisis due to the country's heavy reliance on fossil fuels to meet its energy needs. The non-renewable nature of fossil fuels further complicates the situation. To address this issue, many researchers are striving to find alternative energy sources that can replace fossil fuels (Afif & Martin, 2022). One potential alternative source is biomass found in agricultural residues and industrial waste. As an agricultural country, Indonesia is one of the largest producers of agricultural residues. However, agricultural waste has not been efficiently utilized; only a small portion is used for animal feed, less than 30%. Meanwhile, around 70% of agricultural waste is burned directly in the fields, contributing to air pollution by releasing greenhouse gases. Therefore, there is a need for better utilization of rice straw, such as converting it into valuable materials, one of which is renewable energy (Wulandari et al., 2023).

According to Kasar et al. (2020), rice straw biomass comes from the stems and stalks of rice plants after harvesting. Rice straw contains 39.04% cellulose, 20.91% hemicellulose, and 5.71% lignin. With this high cellulose, hemicellulose, and lignin content, rice straw can be converted into an alternative energy source, namely bio-oil. However, bio-oil is often produced under conditions that do not meet quality standards, especially in terms of its high heating value (HHV), making it unsuitable for everyday use. Literature shows that the HHV of rice straw is in the range of 14.08 MJ/kg to 15.09 MJ/kg, which is below the acceptable standard (Gummert et al., 2020). One of the drawbacks of pyrolysis using only lignocellulosic biomass is its relatively low hydrogen and carbon content. This leads to a low HHV of the resulting bio-oil, making it unsuitable as an alternative energy source.

Plastics are a type of macromolecule formed through polymerization into compounds with lower molecular weights. Carbon and hydrogen are the main elements in plastic polymer compounds. LDPE and PP plastic waste contain polyolefins with a higher C/H ratio compared to biomass sources. Therefore, plastics can be useful for increasing the C/H ratio. HHV is directly proportional to the amount of energy released during combustion. Since PP and LDPE contain no oxygen, no energy is "wasted" in forming water during combustion, unlike biomass, which is rich in oxygen (such as cellulose and hemicellulose). Thus, co-pyrolysis is needed to enhance the carbon and hydrogen quality by mixing plastics with biomass (Chattopadhyay et al., 2016).

In a study by Terry et al. (2021), a co-pyrolysis process using LDPE plastic with palm shell as the raw material produced a bio-oil yield of 47% and an HHV of 39.35 MJ/kg. Although these results are promising in terms of energy content, the bio-oil derived from LDPE has been reported to exhibit very low viscosity, too low to be classified as standard bio-oil based on conventional fuel specifications. Similarly, research by Suriapparao et al. (2020) on rice husks combined with polypropylene (PP) plastic achieved an HHV of 42 MJ/kg. However, in contrast to LDPE, the viscosity of the oil produced from PP is excessively high, which also falls outside the acceptable range for bio-oil classification. These findings emphasise the contrasting fluid properties of LDPE and PP in co-pyrolysis applications. According to Cai et al. (2021), the yield and HHV of bio-oil are two of the most important indicators for evaluating biomass as a raw material. To enhance both yield and HHV while addressing viscosity issues, the addition of catalysts like Fe/Al_2O_3 becomes crucial.

To optimize the reaction, a catalyst was added. Metal-based catalysts are known to reduce the acidity of bio-oil by decreasing the oxygen content in acidic compounds. Research by Cai et al. (2021) using Fe/Al_2O_3 achieved a high yield above 20%. This is due to the properties of iron (Fe), which can accelerate the decarboxylation reaction, and Al_2O_3, which provides high thermal stability and excellent adsorption capacity. Fe/Al_2O_3 catalyst demonstrates superior performance compared to zeolite and Ni/Al_2O_3 in the pyrolysis and upgrading of bio-oil, particularly due to its effective deoxygenation capabilities. Iron possesses redox properties that facilitate decarboxylation and decarbonylation reactions, enabling the removal of oxygen-containing functional groups such as hydroxyl, carbonyl, and carboxyl. Unlike zeolite, which promotes aromatisation and cracking due to its strong acidity and microporous structure, Fe/Al_2O_3 exhibits better selectivity toward non-aromatic, aliphatic hydrocarbons, resulting in improved fuel quality. Compared to Ni/Al_2O_3, iron is more cost-effective, environmentally friendly, and less prone to catalyst deactivation caused by coke formation. Furthermore, Fe/Al_2O_3 offers high thermal stability and is suitable for processing complex feedstocks like lignocellulosic biomass mixed with plastic waste (Zdainal Abidin et al., 2019). Therefore, Fe/Al_2O_3 is considered a promising catalyst for enhancing the quality of bio-oil through co-pyrolysis, especially when hydrogen-free processes are preferred.

Based on previous research findings, this study focuses on the innovative production of bio-oil from rice straw through co-pyrolysis with polypropylene (PP) and low-density polyethylene (LDPE) plastics, along with the addition of Fe/Al_2O_3 catalysts. The primary objective is to enhance both the calorific value (HHV) and the yield of rice straw-derived bio-oil, in order to meet established quality standards and promote its feasibility as an alternative energy source. The use of Fe/Al_2O_3 catalysts is expected to increase the bio-oil yield by facilitating deoxygenation reactions and improving the thermal cracking efficiency of the feedstock, thus converting a greater portion of the biomass into liquid products. Meanwhile, the combination of PP and LDPE is aimed at producing bio-oil with a high HHV, leveraging the high energy content of plastics while simultaneously adjusting the viscosity to fall within the acceptable range defined by ASTM standards. By carefully balancing the PP:LDPE ratio, this study seeks to address the typical issues found in plastic-derived oils, namely, the overly high viscosity of PP-derived oil and the excessively low viscosity of

LDPE-derived oil, so that the resulting product achieves optimal fuel characteristics.

2. MATERIALS AND METHODS

2.1 Materials

Rice straw was obtained from an agricultural group in Nganjuk, Surabaya, Indonesia. Polypropylene and low-density polyethylene were sourced from plastic waste at UPN "Veteran" Jawa Timur. Distilled water (aquadest), $Fe(NO_3)$ and Al_2O_3 analytical reagent grade, ethanol, and alumina 220 mesh were obtained from PT Chemindo Surabaya.

2.2 Methods

The research was conducted at the Research Building of UPN "Veteran" Jawa Timur, Surabaya. The research consisted of two main stages: catalyst preparation and the pyrolysis process.

2.2.1 Preparation for Catalyst

The Fe/Al_2O_3 catalyst was prepared using the impregnation process, specifically by dissolving 0.72 grams of $Fe(NO_3)$ in 30 ml of absolute ethanol while continuously stirring until fully dissolved. Subsequently, 0.9 grams of Al_2O_3 were added to the iron salt solution to ensure a Fe loading content of 10%. The mixture was stirred with a magnetic stirrer at 50°C until it formed a paste. The paste was then dried in an oven for 12 hours at 105°C to remove the absolute ethanol. The solid was ground, followed by calcination at 800°C for 2 hours, then cooled to room temperature (Cai et al., 2021).

2.2.2 Pyrolysis

Fifty grams of rice straw were cleaned and chopped with a chopper, while the PP and LDPE plastic materials were reduced in size using a shredder. The chopped rice straw was fed into the reactor with a plastic addition ratio (PP:LDPE) of 1:1 with the rice straw (0:50g; 12.5:37.5g; 25:25g; 37.5:12.5g; 50:0g). Once both materials were in, Fe/Al_2O_3 was also added according to the catalyst concentration (0, 5, 10, 15, and 20%). Following the addition of the catalyst, the pyrolysis process was carried out at a temperature of 500°C for 20 minutes.

2.2.3 Purification

The bio-oil produced from pyrolysis forms two phases and contains solid tar. Filtration was performed using a regular filter paper to remove the tar, then separating the oil and water. The yield of the bio-oil product is calculated using the equation below. The value is calculated using formula 1:

$$\%yield = \frac{weight\ of\ oil}{total\ weight\ of\ bio\ oil} \qquad (1)$$

3. RESULTS AND DISCUSSION

3.1 Yield

Based on Table 1, the yield data ranges from 9.74 to 30.56%. This increase is correlated with the rising percentage of catalyst added during the pyrolysis process. According to previous research by Wijayanti et al. (2020), which involved the co-pyrolysis of rice husk with 50 wt% LDPE plastic, the yield of the upper phase was reported at 24 wt%, while the lower phase yielded 6 wt%. The yield improvement observed in the previous study was approximately 1% to 2%. As shown in Table 1, the bio-oil yield obtained from a mixture containing 50 grams of LDPE was higher than that of mixtures with a greater proportion of PP. This can be attributed to the simpler molecular structure of LDPE, which allows for more efficient thermal degradation into bio-oil compared to PP.

Table 1. Yield of bio-oil pyrolysis

Katalis (%)	PP (gram)	LDPE (gram)	Yield (%)
0	50	0	9.74
0	37.5	12.5	14.39
0	25	25	17.94
0	12.5	37.5	20.5
0	0	50	25.34
5	50	0	11.04
5	37.5	12.5	15.78
5	25	25	21.02
5	12.5	37.5	22.87
5	0	50	27.45
10	50	0	12.5
10	37.5	12.5	17.34
10	25	25	21.93
10	12.5	37.5	23.89
10	0	50	28.93
15	50	0	13.33
15	37.5	12.5	18.12
15	25	25	22.49
15	12.5	37.5	24.38
15	0	50	29.41
20	50	0	13.77
20	37.5	12.5	19.24
20	25	25	22.7
20	12.5	37.5	24.91
20	0	50	30.56

Based on Figure 1, it can be observed that the curve increases with the rising percentage of catalyst. A higher catalyst concentration leads to a greater quantity of bio-oil produced, as the catalyst lowers the activation energy required for the reaction, thereby positively influencing the yield within the 20-minute pyrolysis duration. The catalyst plays a vital role in the pyrolysis process by enhancing reaction efficiency through the reduction of activation energy. As illustrated in Figure 1, the highest yield was obtained from the 0PP:50LDPE variable at a catalyst concentration of 20%, reaching a value of 30.56%.

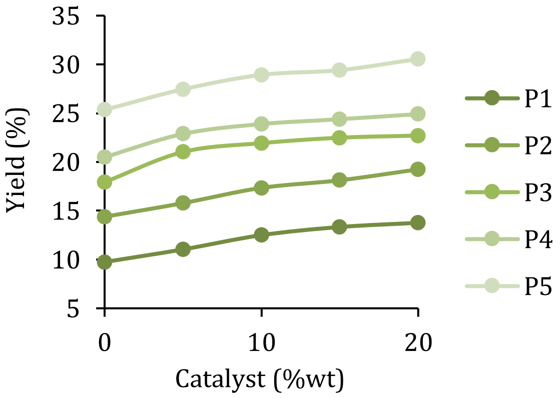

Figure 1. Yield of bio-oil

Nomenclature:
P1 using ratio of PP:LDPE 50:0 g
P2 using ratio of PP:LDPE 37.5:12.5 g
P3 using ratio of PP:LDPE 25:25 g
P4 using ratio of PP:LDPE 12.5:37.5 g
P5 using ratio of PP:LDPE 0:50 g

3.2 Calorific Value

The purpose of the calorific value test is to obtain data on the amount of thermal energy that can be released by a fuel during a combustion reaction or process (Park et al., 2022). Table 2 presents the results of the calorific value analysis for pyrolysis oil derived from rice straw, as well as from PP and LDPE plastics (measured in MJ/kg):

Based on the results presented in Table 2, the calorific value of bio-oil increases with the addition of PP or LDPE plastic content. The highest calorific value was observed at the ratio of 0 PP:50 grams of LDPE. According to previous research by Gummert et al. (2020), the calorific value of bio-oil produced from rice straw typically ranges between 14–16 MJ/kg, which does not meet the ASTM standards. Therefore, the addition of plastic materials aims to enhance the calorific value of the resulting bio-oil. The calorific values obtained from the tests were then compared to ASTM standards and the calorific values of conventional fuels. According to Kim and Lee (2025), the calorific value of kerosene is approximately 24.41 MJ/kg. The calorific value of the bio-oil in this study exceeds that of kerosene but remains below that of petrol (42 MJ/kg) and diesel (45 MJ/kg), as defined by Pertamina fuel standards. Nevertheless, the results align with ASTM standards, which require a minimum calorific value of 17 MJ/kg for bio-oil.

Table 2. Calorific value analysis

Catalyst (%)	PP (gram)	LDPE (gram)	Calorific Value (MJ/kg)
0	50	0	37.450
0	37.5	12.5	38.534
0	25	25	39.202
0	12.5	37.5	39.831
0	0	50	40.539
5	50	0	37.983
5	37.5	12.5	38.789
5	25	25	39.431
5	12.5	37.5	40.155
5	0	50	40.714
10	50	0	38.269
10	37.5	12.5	38.913
10	25	25	39.557
10	12.5	37.5	40.201
10	0	50	40.845
15	50	0	38.273
15	37.5	12.5	39.001
15	25	25	39.729
15	12.5	37.5	30.357
15	0	50	41.185
20	50	0	38.191
20	37.5	12.5	39.104
20	25	25	39.839
20	12.5	37.5	40.663
20	0	50	41.308

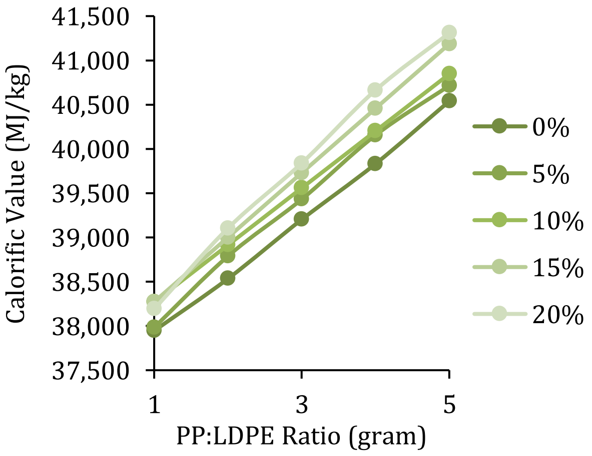

Figure 2. Calorific value analyses of bio-oil

Figure 2 is a presentation of data in the form of a graph to illustrate the impact of the plastic ratios used on the calorific value. According to Wijayanti et al. (2020), the main difference between pyrolysis liquid and fossil fuels is the significant amount of oxygen (O) content, rather than the composition of carbon (C) and hydrogen (H). Consequently, this results in pyrolysis liquid having a lower calorific value and unstable properties, limiting its direct application as a fuel. Therefore, it is investigated that polyethylene contains a large amount of C and H with almost no O content. As a result, its calorific value is approximately 46 MJ/kg, which is higher than that of diesel oil at 42-43 MJ/kg. Meanwhile, according to Al-Maari et al. (2021), the C/H ratio found in polypropylene is lower. Hence, the calorific value of polypropylene is below that of LDPE (low-density polyethylene). The C/H content present in plastics affects the calorific value, which is consistent with the data already presented in Figure 2. The calorific value increases with the addition of the LDPE ratio used. The highest calorific value is obtained at the LDPE plastic ratio of 50 grams, with a calorific value of 41.308 MJ/kg.

3.3 Viscosity Analysis

The purpose of the viscosity analysis is to determine the thickness or flow resistance of the oil at a specific temperature, which indicates its ability to flow under those conditions. The viscosity value was obtained using the Saybolt method at the Yandi Teknik Laboratory in Yogyakarta. Table 3 presents the viscosity of bio-oil.

Table 3. Viscosity of bio-oil

Catalyst (%)	PP (gram)	LDPE (gram)	Viscosity (cSt)
0	50	0	3.762
0	37.5	12.5	3.553
0	25	25	3.204
0	12.5	37.5	3.158
0	0	50	2.528
5	50	0	3.737
5	37.5	12.5	3.560
5	25	25	3.369
5	12.5	37.5	3.363
5	0	50	2.621
10	50	0	3.675
10	37.5	12.5	3.549
10	25	25	3.313
10	12.5	37.5	3.311
10	0	50	2.623
15	50	0	3.703
15	37.5	12.5	3.618
15	25	25	3.421
15	12.5	37.5	3.428
15	0	50	2.705
20	50	0	3.769
20	37.5	12.5	3.631
20	25	25	3.399
20	12.5	37.5	3.370
20	0	50	2.511

Table 4. Quality standards of petroleum fuels

Kerosene	Petroleum	Solar	Our Research
1 - 2 (Anjum & Prakash, 2017)	2 - 4.5 (Pertamina, 2023)	2 - 5 (Pertamina, 2023)	2.5 – 3.7

Based on Tables 3 and 4, the viscosity values of the pyrolysis oil derived from rice straw with varying plastic ratios are found to be close to those of petroleum and diesel. In general, a higher viscosity indicates greater resistance to flow, resulting in slower movement of the substance.

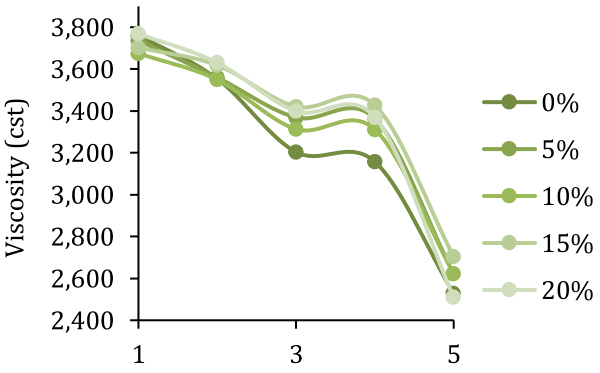

Figure 3. The effect of plastic addition on viscosity

Figure 3 illustrates that viscosity varies with changes in the plastic ratio used. An increase in the proportion of polypropylene (PP) results in a corresponding rise in viscosity. This observation is supported by the findings of Ademiluyi and Adebayo (2010), who stated that the viscosity of oil produced from the pyrolysis of PP is higher than that derived from low-density polyethylene (LDPE). This is attributed to the longer chemical structure of PP, which contributes to greater viscosity. In general, the longer the molecular chains, the higher the viscosity. Additionally, viscosity is influenced by the liquid's density, higher density leads to increased viscosity, as more particles interact and resist flow within the liquid, thereby impeding its movement.

3.4 Density Analysis

Density testing is used to determine the quality of the fuel, particularly in identifying any contamination within a fuel sample. Table 5 shows the results of the density tests on the pyrolysis oil products from plastic waste types PP and LDPE.

Table 5. Density of bio-oil

Catalyst (%)	PP (gram)	LDPE (gram)	Density (g/cm^3)
0	50	0	1.048
0	37.5	12.5	1.014
0	25	25	0.980
0	12.5	37.5	0.920
0	0	50	0.860
5	50	0	1.064
5	37.5	12.5	1.007
5	25	25	0.950
5	12.5	37.5	0.875
5	0	50	0.800
10	50	0	1.068
10	37.5	12.5	0.989
10	25	25	0.910
10	12.5	37.5	0.862
10	0	50	0.814
15	50	0	1.072
15	37.5	12.5	1.016
15	25	25	0.960
15	12.5	37.5	0.893
15	0	50	0.826
20	50	0	1.088
20	37.5	12.5	1.009
20	25	25	0.930
20	12.5	37.5	0.893
20	0	50	0.856

Table 6. Quality standards of petroleum fuel

Petroleum	Solar	This Research
0.778 – 1.198 (Pertamina, 2023)	0.815 – 0.86 (Pertamina, 2023)	0.856 – 1.048

Based on Table 5, the density ranges from approximately 1.048 to 0.856 g/cm^3. The density obtained is then compared with the quality standards for fuel oil. The results for the density of the rice straw bio-oil, with the ratio of PP and LDPE plastics, meet the quality standards for petroleum and diesel.

From Figure 4, it can be concluded that the density value decreases as the ratio of LDPE used increases. This is supported by the statement made by Ademiluyi & Adebayo (2010) that this effect is due to the shorter chemical structure bonds in LDPE compared to PP.

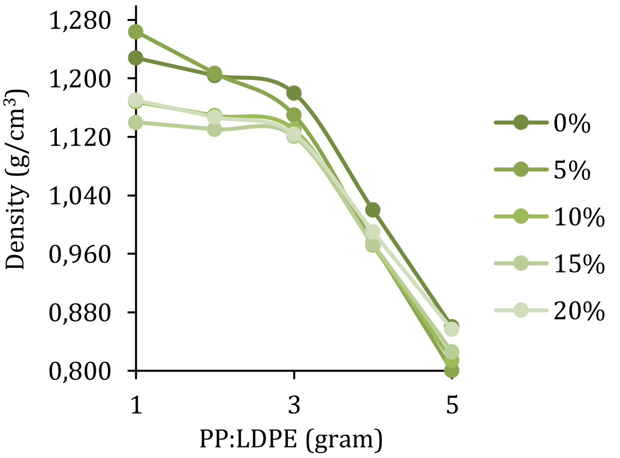

Figure 4. The effect of plastic addition on density

3.5 Gas Chromatography-Mass Spectrometry Analysis

Based on the analysis conducted, the optimal variable was identified as the pyrolysis process using a 20% catalyst concentration with a PP/LDPE ratio of 0:50 grams. This is attributed to the fact that the resulting bio-oil met the ASTM standards, particularly in terms of calorific value. Furthermore, Gas Chromatography-Mass Spectrometry (GC-MS) analysis can be utilized to determine the fuel composition, which is classified into three categories based on carbon chain length: gasoline (C_4–C_{12}), kerosene (C_{13}–C_{15}), and diesel (C_{16}–C_{19}). The classification of the resulting bio-oil can be carried out by quantifying the hydrocarbon content produced from the co-pyrolysis of rice straw and plastic using the Fe/Al_2O_3 catalyst. Therefore, to further assess the quality of the bio-oil, GC-MS analysis is essential, as it identifies and quantifies the types of hydrocarbons present in the sample.

Based on Table 7, it was found that the bio-oil contains 50 distinct hydrocarbon components. Two prominent peaks were observed, with the most dominant compounds being $C_{10}H_{16}$ (19.59%) and $C_{10}H_{14}$ (12.18%). Notably, the GC-MS analysis did not detect the presence of acetic acid (CH_3COOH), due to the strong deoxygenation activity of the Fe/Al_2O_3 catalyst, which plays a crucial role in reducing the oxygen content of bio-oil during pyrolysis. As a result, oxygenated compounds like acetic acid are either converted to lighter gases or further cracked into hydrocarbons. This deoxygenation capability leads to a cleaner, more stable bio-oil with lower acidity and higher calorific value. According to Kim et al. (2022), an excessive acetic acid content can compromise the stability of bio-oil and is unsuitable for engine applications due to its corrosive nature, which may cause rusting. The absence of acetic acid in this study is likely due to the addition of the Fe/Al_2O_3 catalyst. The Fe/Al_2O_3 catalyst facilitates chemical reactions by activating organic molecules, making them more reactive and allowing them to transform into desired products. Iron (Fe) interacts with carbon bonds in the compounds targeted for decarboxylation, thereby promoting the release of CO_2. It also stabilizes the breaking of carbon–carbon and carbon–oxygen bonds. Meanwhile, alumina (Al_2O_3) reduces the required activation energy by adsorbing H_2O, which contributes to an enhanced bio-oil yield. From the analysis, hydrocarbon chains ranging from C_4 to C_{18} were identified in the bio-oil resulting from the pyrolysis process. A quantitative assessment revealed the distribution of hydrocarbon content as follows: gasoline (C_4–C_{12}) with 45 components, kerosene (C_{13}–C_{15}) with 3 components, and diesel (C_{16}–C_{19}) with 2 components. Therefore, it can be concluded that the bio-oil produced from this pyrolysis process is primarily categorized as gasoline (Suharto, 2022).

Table 7. GC-MS analysis of bio-oil

No	Compound	Area (%)	No	Compound	Area (%)
1	C_4H_8	1.04	26	$C_{11}H_{18}O$	1.35
2	C_5H_8	8.09	27	$C_{10}H_{18}$	4.02
3	C_6H_{12}	0.93	28	C_9H_{12}	1.05
4	C_6H_{12}	3.2	29	$C_{10}H_{16}$	0.97
5	C_6H_{10}	3.1	30	$C_{10}H_{16}$	1.61
6	C_6H_6	1.01	31	C_9H_{12}	1.07
7	C_8H_{18}	0.92	32	$C_{10}H_{14}$	10
8	C_7H_{12}	1.42	33	$C_{10}H_{16}$	14.85
9	C_7H_{12}	1.87	34	C_9H_8	0.8
10	$C_6H_{12}O$	1.28	35	$C_{10}H_{14}$	0.89
11	C_7H12	1.58	36	$C_{10}H_{14}$	1.09
12	C_7H_8	1.04	37	$C_{10}H_{16}$	1.57
13	C_7H_{12}	1.23	38	$C_{10}H_{12}$	1.12
14	C_8H_{14}	3.02	39	$C_{11}H_{16}$	0.86
15	C_9H_{14}	0.96	40	$C_{10}H_{12}$	0.88
16	C_8H_{10}	1.18	41	$C_{11}H_{14}$	0.87
17	C_8H_{10}	2.11	42	$C_{11}H_{14}$	0.85
18	$C_{10}H_{16}O$	0.85	43	C_7H_5NS	1.16
19	C_8H_{10}	1.18	44	$C_{12}H_{12}$	1.15
20	$C_{10}H_{16}$	0.77	45	$C_{11}H_{11}N$	1.42
21	$C_9H_{11}NO_3$	1.11	46	$C_{15}H_{24}$	1.91
22	$C_{10}H_{16}$	1.19	47	$C_{15}H_{22}$	0.9
23	C_9H_{12}	1.16	48	$C_{17}H_{36}$	3.91
24	C_9H_{12}	1.08	49	$C_{13}H_{14}$	1.01
25	C_9H_{12}	1.02	50	$C_{18}H_{35}N$	2.06
Total			100		

Hydrocarbons can be classified into several categories, namely saturated hydrocarbons, unsaturated hydrocarbons, cycloalkanes, aromatic hydrocarbons, and alicyclic hydrocarbons. The composition of these hydrocarbon types in bio-oil significantly influences its overall quality. An imbalance, whether an excess or deficiency of certain hydrocarbon types, can adversely affect the performance and applicability of the bio-oil. For instance, the presence of aromatic hydrocarbons contributes to an increased octane rating and enhances fuel stability. However, if present in excessive quantities, they can cause corrosion, instability, and environmental pollution due to incomplete combustion, which also poses health risks.

Similarly, cyclic hydrocarbons can increase the viscosity of bio-oil. While moderate viscosity may be beneficial for specific applications, an excessive concentration of cyclic hydrocarbons may lead to reduced fuel quality by exceeding standard viscosity limits and diminishing the stability of the bio-oil. In light of these factors, a classification of the hydrocarbon compounds found in the bio-oil based on their type is presented in Table 8.

Table 8. Classification of GC-MS results

Compounds	% Area
Saturated Hydrocarbon	3.91
Unsaturated Hydrocarbon	32.48
Aromatic	29.8
Cyclic	28.93
Alcohol	3.48
Amino Acid	1.11
Total	**100**

The classification of hydrocarbon types was determined by categorizing the components listed in Table 7. Each component was classified based on its hydrocarbon type, resulting in the following composition: saturated hydrocarbons accounted for 3.91%, unsaturated hydrocarbons for 32.48%, aromatic hydrocarbons for 29.8%, cyclic hydrocarbons for 28.93%, alcohols for 3.48%, and amino acids for 1.11%. From the results presented in Table 8, it can be concluded that the aromatic content complies with the ASTM D5769 standard, which sets a maximum limit of 35% for aromatic compounds. Therefore, it can be inferred that the bio-oil produced in this study meets the ASTM standards for gasoline fuel.

The elements formed during the pyrolysis process of bio-oil can be classified into several key components, namely carbon (C), hydrogen (H), oxygen (O), sulfur (S), and nitrogen (N). These elements are formed as a result of the combustion reaction occurring in an oxygen-deficient environment (pyrolysis), and their concentrations significantly influence the quality of the resulting bio-oil. According to the American Society for Testing and Materials (ASTM) fuel standards, the average elemental composition in bio-oil includes 56% carbon, 6% hydrogen, 38% oxygen, 0.2% nitrogen, and

0.02% sulfur by weight. In comparison, Li et al. (2021), who studied the enhancement of bio-oil through fast pyrolysis, reported an average composition of 85% carbon, 11% hydrogen, 1% oxygen, and 0.3% nitrogen by weight. Based on these reference parameters, elemental composition analysis was performed, and the results are presented in Table 9.

Table 9. Content of C, H, O, S, and N in pyrolysis oil

Ultimate Analysis	(%wt)
C	87.01
H	11.65
O	0.57
S	0.29
N	0.47
Total	100

The elemental composition of the bio-oil was found to be as follows: 87.01% carbon (C), 11.65% hydrogen (H), 0.57% oxygen (O), 0.29% sulfur (S), and 0.47% nitrogen (N). The high content of carbon and hydrogen contributes to an increased calorific value of the bio-oil and gas. However, excessive concentrations of oxygen, sulfur, and nitrogen can have negative effects, such as causing corrosion and increasing emissions of harmful gases (Brown, 2021). Therefore, the obtained composition must comply with established standards. Based on the data in Table 8, it can be concluded that the bio-oil meets the relevant ASTM standards.

3.6 Characteristics of Bio-Oil on the Best Variables

The results from the data processing presented in the previous subsection are summarized, and the best variables are selected. These optimal variables are subsequently tested using GC-MS to analyze the bio-oil contents. The findings are presented in Table 10.

In the bio-oil produced, the percentage of catalyst weight influences both the yield and the level of acid generated. As the catalyst percentage increases, the bio-oil yield rises while the concentration of acetic acid decreases. In this study, the optimal catalyst weight percentage was found to be 20%, resulting in a bio-oil yield of 30.56% and an amino acid content of 1.11%. The addition of LDPE and PP plastic during the pyrolysis of rice straw affects both the calorific value and the viscosity of the bio-oil. Plastics, which are composed of hydrocarbons (C and H), contribute to a higher calorific value. Additionally, the type of plastic used influences the viscosity by altering the molecular chain structure. In this study, the bio-oil produced with the addition of LDPE plastic exhibited a viscosity that met ASTM standards, measuring 2.511. The most optimal bio-oil characteristics were achieved with a catalyst weight percentage of 20% and the addition of plastic with a PP/LDPE ratio of 0:50 grams.

Table 10. Characteristic of the bio-oil at the best variable

	Rice Straw (Gummert et al., 2020)	Our Research	ASTM D7544
Yield (%)	9.40	30.56	-
HHV (MJ/kg)	14.09	41.308	17
Density (g/ml)	1.02	0.856	1.2
Viscosity (cSt)	36.6	2.511	2-5
Acid (%)	5.81	1.11	Max. 5
Aromatic (%)	22,49	29.80	35
Alcohol (%)	40.23	3.48	max 15
C (%)	33.70	87.01	50– 87
H (%)	3.91	11.65	6–12
O (%)	36.26	0.57	max 40
S (%)	0.03	0.29	0.1–0.5
N (%)	0.71	0.47	Max. 2.5

4. CONCLUSION

The yield and quality of bio-oil from rice straw pyrolysis are influenced by catalyst weight and plastic addition. A 20% catalyst weight increases bio-oil yield to 30.56% and reduces acetic acid content to 1.11%. Adding LDPE plastic, rich in hydrocarbons, improves the bio-oil's calorific value and resulting in a viscosity of 2.511, meeting ASTM standards. Interestingly, LDPE alone is sufficient to produce bio-oil with the desired viscosity and quality. If polypropylene (PP) is added, a more refined approach, such as optimizing the co-pyrolysis process or adjusting catalyst conditions, may be required to improve yield without compromising bio-oil quality. Future studies should focus on reducing aromatic content through hydrodeoxygenation or catalytic cracking, with transition metal catalysts enhancing stability and reducing aromatic compounds.

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