



Co-Pyrolysis of *Jatropha Curcas* Seeds and HDPE Plastic for Bio-Oil Production

Tiara Tiara^{1*}, Akhmad Dzakwan¹, Rizka Mayasari¹, Muhamad Ridho Ulya¹, Muhammad Haviz², Ririn Utari¹

¹ Department of Environmental Engineering, Faculty of Engineering, University of Lampung, Lampung Province, Indonesia

² Department of Chemical Engineering, Faculty of Engineering, University of Lampung, Lampung Province, Indonesia

*Corresponding author: tiara.1030@eng.unila.ac.id

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Abstract:

The limited availability of fossil fuels and the growing volume of plastic waste underscore the need to develop environmentally friendly alternative energy sources. This study aims to produce high-energy-value bio-oil through a co-pyrolysis process involving *Jatropha curcas* seed biomass and high-density polyethylene (HDPE) plastic. The research involved the following stages: characterization of *Jatropha curcas* seed, raw material preparation, pyrolysis, and analysis of bio-oil. The temperature variations used were 350°C, 450°C, and 550°C with raw material ratios of 75:25, 50:50, and 25:75. The results of the study indicate that increases in temperature and the proportion of HDPE significantly affect the increase in heat value and the decrease in moisture content of the bio-oil. The highest calorific value was obtained at a 25:75 ratio and a temperature of 450°C, amounting to 42.50 MJ/kg, while the lowest moisture content was 2.9% under the same conditions. This indicates a synergistic effect between the biomass and the plastic, in which HDPE acts as a hydrogen donor that reduces the oxygen content in the bio-oil, thereby improving the fuel quality. In conclusion, the co-pyrolysis method using *Jatropha curcas* seed and HDPE can produce bio-oil with better energy characteristics and low moisture content. This research not only contributes to the development of renewable energy but also offers innovative solutions for the sustainable management of plastic waste.

Keywords: Bio-oil; co-pyrolysis; HDPE; *Jatropha* seed; renewable energy

1. Introduction

Global reliance on fossil fuels has led to severe environmental, economic, and social consequences. The industrial and transportation sectors are primary drivers of CO₂ emissions, which significantly exacerbate global warming. Moreover, the finite nature and uneven geographical distribution of fossil resources pose a critical threat to global energy security. Consequently, transitioning to renewable energy is imperative to achieve long-term sustainability, with biofuels derived from biomass emerging as a highly promising alternative fuel source (Sandi et al., 2025). Recently, the co-processing of plastic waste and biomass has gained significant attention as a sustainable thermochemical route, as summarized in recent reviews that highlight its potential to address both energy security and waste management challenges (Yek et al., 2023). Among Indonesia's various plant-based resources, *Jatropha curcas* offers significant potential as a feedstock for biodiesel due to the high non-edible oil content in its seeds, which ranges from 30% to 48%. A key advantage of utilizing this plant is its non-edible nature, ensuring that its use does not compete with national food supplies (Riayatsyah, et al., 2022).

Although *jatropha* seed is highly suitable for conversion into organic oil (bio-oil) through the biomass pyrolysis process, bio-oil produced from pure biomass still faces technical challenges in the form of high moisture content and low calorific value, which can significantly reduce combustion stability and efficiency (Prihandana, 2011). This is in line with the findings of Ungureanu et al (2025), who emphasized that the initial moisture content of biomass is a critical operational parameter that determines the efficiency of thermal conversion and the distribution of products in the pyrolysis process. For example, Pinto et al. observed that

increasing the rice husk ratio within PE blends resulted in a decline in total liquid yield. Furthermore, the study highlighted that the specific type of plastic waste employed is a dominant factor influencing the chemical composition of bio-oils derived from the co-pyrolysis of rice crop residues. The addition of plastic to biomass acts as a hydrogen donor, optimizing dehydration reactions during the co-pyrolysis process. This process successfully reduces the oxygen content in the bio-oil, which contributes to a substantial increase in the fuel's calorific value (Dyer et al., 2021). Charusiri et al. (2022) further supported this by demonstrating that the addition of waste plastic significantly increases the hydrogen-to-carbon ratio, which is essential for producing bio-oil with high liquid yields. In line with this research, Sunarno et al. (2021) demonstrated that using a mixture of empty oil palm fruit bunches and polypropylene plastic waste can produce a high calorific value of 43.2 MJ/kg. Various previous studies have confirmed that the synergy between biomass waste and plastic waste can reduce moisture content while significantly increasing the calorific value, resulting in a much more efficient bio-oil. Furthermore, the pyrolysis performance and the resulting bio-oil quality are highly dependent on the intrinsic characteristics of the biomass feedstock (Shrivastava et al., 2021). A similar approach has also been validated through the co-pyrolysis of biomass with waste tires, which has proven effective in enhancing bio-oil quality by increasing hydrocarbon content (Martínez et al., 2014).

Among various types of plastics, High-Density Polyethylene (HDPE) is considered the most suitable and effective source of additional carbon and hydrogen due to its cross-linked molecular structure and high-temperature resistance, enabling it to produce abundant volumes of oil at optimal temperatures (Lubis et al., 2022). The more branched nature of HDPE chains requires higher process temperatures to melt the polymer (Waryat dkk., 2013). Given that temperature variations during pyrolysis significantly affect the composition of the resulting compounds and energy conversion efficiency and considering the significant potential to address the global plastic waste problem, this study was specifically designed to evaluate and optimize the co-pyrolysis process between *Jatropha curcas* seed biomass and HDPE plastic waste to produce high-quality bio-oil. By varying the temperature and mixing ratios of the raw materials, this study aims to determine the optimal operating conditions that can increase the calorific value and minimize the moisture content. The results of this study are expected to provide strong scientific significance in the development of alternative fuels that are more stable, environmentally friendly, and suitable for practical application.

2. Material and Method

Material

This study used *Jatropha curcas* seeds obtained from a plantation in South Lampung Regency. HDPE was provided by PT Trigunung Padutama, a major plastic waste processing factory located on Jalan Way Laga, Panjang, Bandar Lampung.

Research design

This study employed a laboratory experimental design to evaluate the quality of bio-oil produced through the co-pyrolysis process. The experiment was designed by varying two main factors: the mixing ratio of the feedstock between *Jatropha curcas* seeds and High-Density Polyethylene (HDPE) plastic waste at 75:25, 50:50, and 25:75, and variations in pyrolysis temperature ranging from 350°C, 450°C, and 550°C.

Characterization of *Jatropha curcas* seeds

The *Jatropha curcas* seeds were characterized using a thermogravimetric analyzer (TGA). Approximately 10–20 mg of the sample was placed in an alumina crucible for analysis. The measurements were performed under a controlled atmosphere using a multi-stage heating program. The moisture content was determined by heating the sample at 105°C under a nitrogen (N₂) atmosphere until a constant mass was reached. The resulting mass loss was recorded as the moisture content. Volatile matter was determined by heating the sample to 800°C under an inert nitrogen (N₂) atmosphere at a controlled heating rate. The mass loss during this stage was recorded as the volatile matter content. Fixed carbon was determined by switching to an oxidizing atmosphere at 800°C, where the remaining combustible material was completely oxidized. The mass loss during this stage was recorded as the fixed carbon content. The residual mass remaining after combustion, representing the non-combustible inorganic mineral matter, was recorded as the ash content.

Raw material preparation

Jatropha curcas seed waste and HDPE plastic waste were collected, cleaned, and then shredded using a shredder into small pieces to facilitate melting. The raw materials were then weighed using a digital scale according to different weight ratios (75:25, 50:50, and 25:75).

Co-pyrolysis

A mixture of raw materials is fed into the pyrolysis reactor. The heating process is conducted at different temperatures (350°C, 450°C, and 550°C), with the temperature maintained for a specific residence time of 10 minutes. During the process, the temperature is monitored periodically using a thermometer. The hydrocarbon vapor produced by the pyrolysis reactor is directed to a condenser, where it undergoes condensation with the aid of ice. The liquid product, bio-oil, is collected in sample bottles for further analysis.

Calorimeter

Used to test and measure the calorific value of the bio-oil produced. A sample (± 1 g) is placed into the bomb calorimeter along with the ignition wire and pressurized with oxygen. The bomb is then submerged in a water jacket within the calorimeter. The sample is ignited by an electric current, triggering an exothermic reaction that increases the water temperature. The temperature change of the water is used to calculate the heating value (in MJ/kg) using Eq.1.

$$Q = \frac{C \times \Delta T}{m} \quad (1)$$

Where:

Q = heating value (MJ/Kg)

C = heat capacity (J/°C)

ΔT = change in temperature ($T_{\text{final}} - T_{\text{initial}}$ in °C)

m = mass of the sample (Kg)

Moisture analyzer

The moisture content of the bio-oil sample was determined using a halogen moisture analyzer, which integrates both heating and weighing functions into a single automated system. The instrument was leveled and cleaned, ensuring that the heating chamber was free from any residual debris. A clean, dry aluminum pan was placed on the sample pan holder and tared to zero. A specific mass of the wet bio-oil sample (W_i) was then evenly distributed across the surface of the pan to ensure uniform heating. The instrument was configured to a constant temperature of 105°C. This temperature was selected to facilitate efficient water evaporation while minimizing the thermal degradation of organic components. The heating lid was closed, and the drying cycle was initiated. The built-in halogen lamp heated the sample, and the internal balance continuously monitored the mass change. The process automatically concluded once the sample reached a constant weight, signifying that all moisture had been removed. The moisture analyzer automatically calculates the moisture content and display the value (%).

3. Results and Discussion

The characteristics of raw materials of *Jatropha curcas* seeds

The data presented in Table 1 are consistent with those previously reported for oil-seed residues and other lignocellulosic biomass, demonstrating the suitability of the feedstock's physicochemical properties for the pyrolysis process (Odetoye et al., 2019). The characteristics of *Jatropha curcas* seeds are presented in Table 1. This included the determination of moisture content, volatile matter, fixed carbon, and ash content, which were performed using Thermogravimetric Analysis (TGA), while the HHV was measured using a bomb calorimeter. The data presented in Table 1 are consistent with previously reported data for lignocellulosic biomass and oil-seed residues (Pambudi et al., 2014; Odetoye et al., 2019).

Table 1. The characteristics of the raw materials of *Jatropha curcas* seeds

Komponen	Unit	Value	Typical Range	Context
Volatile Matter	wt%	78.3	70.0-82.0	High; indicates strong potential for high bio-oil yields
Moisture	wt%	6.5	5.0-10.0	Favorable; lower than the 10% threshold often cited as ideal
Ash	wt%	5.2	3.0-7.0	Relatively low; minimizes catalytic interference in bio-oil
Fixed Carbon	wt%	10.0	8.0-15.0	Consistent with high VM; indicates efficient volatile conversion
Low Heating Value	MJ/kg	19,04	17-24	Within standard range for biomass energy

The volatile matter content of 78.3% aligns with the typical range of 70–82% observed in agricultural residues suitable for pyrolysis, and the calorific value of 19.04 MJ/kg falls within the standard energy density range of 17–20 MJ/kg reported for similar feedstocks. The high volatile matter content in *Jatropha curcas* seeds (biomass) is the primary component that will degrade into vapors during pyrolysis. This vapor then condenses into bio-oil. Therefore, a high volatile matter content is strongly positively correlated with the potential bio-oil yield and the bio-oil calorific value, as it is the primary source of volatile hydrocarbon compounds in biomass. The relatively low moisture content (6.5%) is quite good, but still warrants attention. High moisture content in the feedstock can reduce the thermal efficiency of the pyrolysis process because heat energy is used to evaporate the water. In addition, water vapor that condenses along with organic vapor increases the moisture content in the bio-oil, which directly reduces the bio-oil's calorific value (due to dilution) and increases its corrosiveness.

A relatively low ash content (5.2%) is highly advantageous. Ash is an inorganic component that cannot be converted into liquid or gaseous products. A high ash content reduces the proportion of organic material that can be converted into bio-oil and can act as an undesirable catalyst, thereby affecting the product's composition (Awad et al., 2024). Ash content generally has a negative correlation with the product's calorific value. Fixed carbon is the fraction of carbon that does not volatilize during pyrolysis, and it is the main component of the solid product (biochar). A relatively low content (10.0%) indicates that most of the organic material has been converted into volatile products (bio-oil and gas), consistent with the high Volatile Matter value.

Calorific value of bio-oil

Heat value is the most important quality parameter of a fuel, indicating the energy released per unit mass during complete combustion. Bio-oil produced through the copolymerization of *Jatropha curcas* seeds (biomass) and HDPE plastic is expected to have a high heat value, comparable to that of fossil fuels, making it a potential alternative fuel. Bio-oil produced through the copolymerization of *Jatropha curcas* seeds (biomass) and HDPE plastic is expected to have a high heat value, comparable to that of fossil fuels, making it a potential alternative fuel. The integration of biomass and waste plastics is increasingly recognized as a robust thermochemical conversion technology for the production of high-grade biofuels, providing a synergistic pathway to improve fuel quality (Uzoejinwa et al., 2018). Table 2 shows the results of the calorific value of bio-oil (kcal/kg) from the copolymerization process at various feedstock ratios (*Jatropha curcas* seeds:HDPE plastic) and temperatures.

Table 2. The effect of ratios of the raw materials and temperature on the calorific value of bio-oil

No	<i>Jatropha curcas</i> seeds:HDPE	Temperature (°C)	Calorific Value (MJ/kg)
1	75:25	350	33.43
		450	34.80
		550	33.90
2	50:50	350	36.50
		450	38.80
		550	38.00
3	25:75	350	40.10
		450	42.50
		550	41.70

The calorific value of bio-oil tends to increase as the proportion of HDPE plastic in the mixture increases (from a 75:25 ratio to a 25:75 ratio). The increase in bio-oil calorific value with the higher HDPE ratio indicates a synergistic cracking effect that generates hydrocarbons rich in long-chain carbon structures. This finding aligns with the research by Ryu et al., (2020), which demonstrates that the co-pyrolysis of biomass and plastic facilitates the formation of petroleum-like hydrocarbons. At a 75:25 ratio (dominantly *Jatropha curcas*), the calorific value ranges from 33.43 to 34.80 MJ/kg. At a 50:50 ratio (half-and-half), the calorific value ranges from 36.50 to 38.80 MJ/kg. At a 25:75 ratio (HDPE-dominant), the calorific value ranges from 40.10 to 42.50 MJ/kg. High-Density Polyethylene is a polymer composed of long hydrocarbon chains with a very low (nearly zero) oxygen content. When pyrolyzed, HDPE produces a liquid fraction (bio-oil) with a much higher hydrocarbon content and calorific value compared to bio-oil from pure biomass (*Jatropha curcas* seed), which contains a significant amount of oxygen (Dyer et al., 2021). The increase in calorific value indicates that the resulting bio-oil is increasingly dominated by non-oxygenated hydrocarbon compounds derived from plastic. The optimal ratio for achieving the highest calorific value is 25:75 (HDPE dominant). Temperature also plays a significant role in the decomposition of raw materials and the composition of the product. Ratio 75:25: The highest calorific value is achieved at 450°C (34.80 MJ/kg), followed by a decrease at 550°C (33.90 MJ/kg). Ratio 50:50: The highest calorific value is achieved at 450°C 38.80 MJ/kg), followed by a decrease at 550°C (38.00 MJ/kg). Ratio 25:75: The highest calorific value is reached at 450°C (42.50 MJ/kg), followed by a decrease at 550°C (41.70 MJ/kg).

In general, for all ratios, the calorific value tends to increase from 350°C to 450°C and then decreases slightly at 550°C. At lower temperatures (350°C), the decomposition (cracking) of the compounds is not optimal, resulting in bio-oil with less volatile compounds or fewer secondary products (Bridgwater, 2012). A temperature of 450°C appears to be the optimum temperature because it produces the highest calorific value at all ratios. At this temperature, co-pyrolysis is at an efficient state for the decomposition of *Jatropha curcas* seed and HDPE, producing the highest quality hydrocarbon fractions with minimal secondary cracking to gas. At higher temperatures (550°C), although decomposition is faster, there is an increase in secondary cracking reactions that convert some of the bio-oil vapor into non-condensable gaseous products. This results in a decrease in bio-oil yield and a change in composition, which in this case slightly reduces the calorific value of the resulting bio-oil. Furthermore, Amrullah et al. (2022) emphasized that the kinetic analysis approach in co-pyrolysis is crucial for understanding the thermal decomposition mechanism, which ultimately determines the optimal distribution of bio-oil and bio-char products. The optimal operating conditions for producing bio-oil with the highest calorific value are at *Jathropa curcas* seed:HDPE ratio of 25:75, pyrolysis temperature of 450°C.

Moisture of bio-oil

Data shows that the smaller the ratio of *Jatropha curcas* seeds (biomass) to the larger the ratio of HDPE plastic, the lower the water content of the bio-oil. A 75:25 ratio (*Jatropha curcas* seeds dominant) has a water content ranging from 9.2% to 12.5%. A 50:50 ratio (balanced) has a water content ranging from 6.4% to 8.6%. A 25:75 ratio (HDPE dominant) has a water content ranging from 2.9% to 4.3%.

Table 3. The effect of *Jatropha curcas* seed to HDPE ratio on the moisture of bio-oil

No	<i>Jatropha curcas</i> seed : HDPE	Temperature (°C)	Moisture (%)
1	75:25	350	12.5
		450	10.8
		550	9.2
2	50:50	350	8.6
		450	7.1
		550	6.4
3	25:75	350	4.3
		450	3.5
		550	2.9

Jatropha curcas seeds are a biomass whose main components are cellulose, hemicellulose, and lignin. The thermal decomposition of these compounds (especially cellulose and hemicellulose) produces high amounts of oxygenated compounds, including water and organic acids (such as acetic acid), which are highly hydrophilic (readily absorb/mix with water) and are the main source of water content in bio-oil. Previous research often shows that bio-oil produced from pure biomass has a high moisture content (up to 15-30% or more) due to the release of water from the cellulose/hemicellulose structure during pyrolysis and the condensation of water vapor contained in the original biomass (Zhu and Zhong., 2020).

High-Density Polyethylene (HDPE) plastic is a synthetic polymer composed of long-chain hydrocarbons and contains little or no oxygen. Plastic pyrolysis produces hydrocarbon products that are more stable (non-polar) and hydrophobic (not easily miscible with water/oil). Co-pyrolysis (joint pyrolysis) of biomass and plastic, as conducted in the data, aims to improve the quality of biomass bio-oil. By increasing the HDPE ratio (25:75), the resulting product becomes more dominated by hydrocarbons from plastic, which have a low water and oxygen content. These results are in line with other co-pyrolysis studies which reported that the addition of plastic (such as LDPE or HDPE) to biomass reduces the water and oxygenate content, and increases the heating value of bio-oil.

At any feedstock ratio, data shows that the higher the pyrolysis temperature, the lower the water content of the bio-oil. Increasing the temperature increases the thermal energy, which triggers secondary cracking reactions in the pyrolysis vapor, particularly oxygenate compounds (including water and organic acids) and macromolecules. Research indicates that at higher temperatures (e.g., 450°C–550°C), the thermal decomposition of the biomass is more complete, which can lead to further dehydration of the formed oxygenate compounds, reducing the water content in the final product. Furthermore, the water vapor produced tends to have a shorter residence time in the reactor at high temperatures, which minimizes condensation of water vapor along with condensation of heavy organic compounds, although this depends on the reactor design (fast vs. slow pyrolysis). At higher temperatures, further decomposition of water and light compounds into non-condensable gases occurs, thus reducing the percentage of water condensed into bio-oil. These data consistently show that to obtain better quality bio-oil (indicated by lower water content), the optimum condition is to use a higher feedstock ratio with a higher percentage of HDPE (25:75) at a higher pyrolysis temperature (550°C). The combination of these two factors (25:75 ratio and 550°C) produces the lowest water content of 2.9%.

Conclusion

The co-pyrolysis process between *Jatropha curcas* seed biomass waste and High-Density Polyethylene (HDPE) plastic waste proved effective in improving the quality of the resulting bio-oil. Optimal operating conditions were achieved at a pyrolysis temperature of 450°C with a raw material mixing ratio of 25:75 (*Jatropha curcas* seed to HDPE plastic). The synergy of cross-linked molecular interactions in the HDPE plastic carbon chain significantly increased the calorific value and reduced the product's water content to a minimum.

As a recommendation for further research, gas chromatography-mass spectrometry (GC-MS) analysis is necessary to thoroughly identify the composition of specific chemical compounds formed in the bio-oil. Furthermore, it is recommended to test a wider range of residence times and evaluate the efficiency of using specific catalysts to optimize the stability of this biofuel. Practically, these findings provide important implications that the integration of non-food biomass waste and plastic waste not only offers an alternative solution for providing stable renewable energy but also contributes directly to reducing global environmental pollution problems.

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