



The Influence of Plastic Waste Types and Ratios on the Characteristics of Alternative Fuels through the Pyrolysis Method

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ABSTRACT

The increasing volume of plastic waste highlights the urgent need for efficient and environmentally sustainable treatment methods. Pyrolysis is recognized as a promising thermochemical process for converting plastic waste into alternative liquid fuels. This study evaluates the use of rice husks, corn cobs, and coconut shells as renewable heat sources in the pyrolysis of polypropylene (PP) and polyethylene terephthalate (PET), applying biomass-to-plastic ratios of 1:8, 1:12, and 1:16. Key parameters assessed include reactor temperature, liquid fuel yield, and fuel properties. The results show that coconut shells produced the highest reactor temperatures and the most optimal yields, reaching 11.95% for PP and 2.74% for PET. PP-derived oil demonstrated the best fuel quality, with a calorific value of 12,038.9 cal/g, density of 0.728 g/cm³, and viscosity of 2.33 cSt, corresponding to the gasoline-kerosene fraction. In contrast, PET-derived oil exhibited a calorific value of 11,348.1 cal/g, density of 0.809 g/cm³, and viscosity of 3.47 cSt, aligning with the kerosene-diesel fraction. These findings confirm the potential of integrating biomass combustion with plastic pyrolysis as a viable pathway for producing alternative liquid fuels while promoting the utilization of agricultural residues as renewable energy sources.

Keywords: alternative energy, biomass, liquid fuel, plastic waste, pyrolysis.

1. INTRODUCTION

Plastic waste is a major source of environmental pollution because it is difficult to decompose naturally and can take an extremely long time to degrade. In addition to polluting the environment, plastic waste also contains microplastics that pose health risks when using plastic-based food utensils. These microplastics can cause digestive disorders, genetic toxicity, and even death [1]. Plastic waste is dominated by polypropylene (PP) and polyethylene terephthalate (PET). According to data from the National Waste Management Information System in 2024, the amount of PET waste reached 111,423.37 tons, and PP waste 13,868.52 tons.

One of the method to reduce plastic waste is converting solid materials into liquid fuel through the pyrolysis process. Pyrolysis is a thermal decomposition process that occurs at

temperatures between 300–500°C with little or no oxygen [2]. During pyrolysis, the polymer chains of PET or PP decompose; these polymers consist of polyolefin and aromatic ester groups. The broken polymer chains become gaseous and are then condensed using a condenser to produce pyrolysis oil, which has characteristics similar to liquid fuels such as gasoline, diesel, or kerosene [3]. The pyrolysis process yields three main products: a liquid product (condensed vapors or smoke), a solid product (char), and a gaseous product (non-condensable gases) [4]. The solid product or char is formed from heavy fractions during pyrolysis; high tar and wax content in plastics, especially PET, does not vaporize and instead condenses into carbon solids. Typically, pyrolysis combustion uses fossil-based gas or liquid fuels to achieve the required temperature. However, in this study,

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biomass such as coconut shells, corn cobs, and rice husks was used as pyrolysis fuels. Replacing fossil fuels with biomass requires consideration of biomass composition such as lignin, cellulose, and hemicellulose and its calorific value. The calorific value of gaseous fuels is around 40 MJ/kg [5], while coconut shells have a calorific value of 30.79 MJ/kg [6], corn cobs 24.76 MJ/kg [7], and rice husks 15.46 MJ/kg [8].

In this study, biomass such as coconut shells, corncobs, and rice husks was used as a heating medium to convert PP and PET plastic waste into liquid pyrolysis fuel. Compared with fossil fuels such as LPG and gasoline, biomass was selected because it is environmentally friendly, renewable, and contributes to mitigating climate change. The growth of plants used as biomass feedstock can absorb carbon dioxide (CO₂) from the atmosphere, which helps offset the CO₂ emissions produced during biomass combustion [9].

The utilization of biomass waste as an energy source remains relatively limited, as it is commonly used directly as fuel without further processing. However, when biomass is processed through thermochemical conversion processes such as pyrolysis, it can produce valuable products including bio-oil, biochar, and gas, which can significantly increase its economic value compared to direct combustion without prior treatment [10]. In addition, biomass can also be combined with plastic waste in a pyrolysis reactor through a co-pyrolysis process, which has been reported to improve the quality of liquid products and reduce gaseous emissions [11].

Biomass contains chemical components including lignin, cellulose, and hemicellulose. Lignin plays an important role in determining calorific value; biomass with high lignin content typically has a calorific value of 23.26–25.58 MJ/kg, while biomass dominated by cellulose and hemicellulose has a lower calorific value of about 18.6 MJ/kg [12]. This is because lignin is rich in

carbon compounds, containing over 60% carbon [13], whereas cellulose contains about 44% [14], and hemicellulose about 24.43% carbon [15].

In this study, PP and PET plastics were used as feedstocks for producing pyrolysis oil because plastics generally consist mainly of hydrocarbons [16]. Polypropylene, which has a propene monomer [17] has a calorific value of about 45 MJ/kg [18], polyethylene terephthalate, which has terephthalate and ethylene glycol monomers, has a calorific value of around 30 MJ/kg [19], PET also contains aromatic compounds such as benzene and toluene, which can lower the research octane number (RON) of the resulting liquid fuel [20]. However, both PP and PET plastics can produce impurities in the pyrolysis oil, particularly oxygenated and halogenated compounds, which reduce the fuel quality [21]. The quality of the pyrolysis oil was evaluated through calorific value analysis, density, viscosity, and the yield obtained.

The use of fossil-based gaseous or liquid fuels as heat sources in plastic pyrolysis generally produces liquid fuels with characteristics comparable to those obtained when biomass is used as the heating medium. Several studies have reported that the physicochemical properties of plastic pyrolysis oil are mainly influenced by the type of plastic feedstock and the operating conditions of pyrolysis, such as temperature and residence time, rather than the heating source used in the reactor. The heat source primarily functions as an energy supply to achieve the required pyrolysis temperature in the reactor, while the polymer degradation and chain scission reactions occurring inside the reactor depend mainly on the plastic type, temperature, and residence time, which ultimately determine the characteristics of the resulting oil [22]. A comparison of the characteristics of pyrolysis oil reported in previous studies using fossil-fuel-based heating sources and co-pyrolysis processes is presented in Table 1.

Table 1. Comparison of plastic waste pyrolysis oil characteristics with petroleum fuels.

Type of Oil	Type of Plastic	Calorific Value (cal/g)	Viscosity (cSt)	Density (g/mL)	Reference
Pyrolysis Oil from Fossil Fuels	PP	9,751.4	4.1	0.86	[23]
	PET	8,413.0	5.77	0.739	[24]
Pyrolysis Oil from Co- Pyrolysis	PP-Biomass	9,761.0	2.16	0.82	[25]
	PET-Biomass	5,712.2	5.8	0.93	[26]
Kerosene	-	10,874.8	1.2	0.82	[27]
Diesel Oil	-	10,396.8	1.9-4.5	0.87	
Gasoline	-	10,396.8	0.65	0.68	

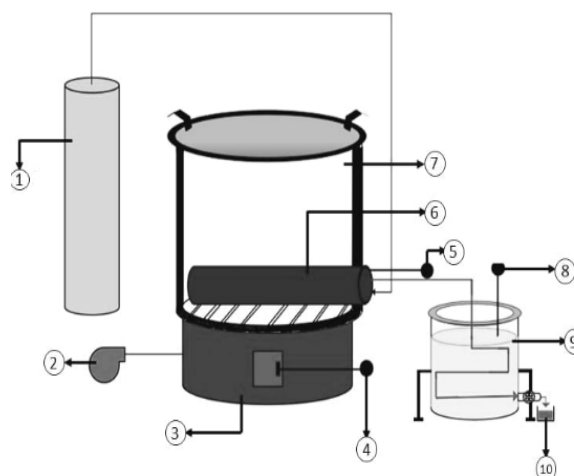
Previous studies on plastic waste pyrolysis have generally used fossil fuel gases as heat sources and have varied between catalytic and non-catalytic processes. Pyrolysis of PET waste at 500°C yields about 49.6% liquid oil [28]. While PP waste without a catalyst produces about 35–38% yield. When zeolite is used as a catalyst, the yield can reach about 43% [29]. The novelty of this research lies in using biomass fuels specifically rice husks, corn cobs, and coconut shells for the pyrolysis process. By using biomass as the fuel source, this study aims to determine the achievable temperature during pyrolysis and the resulting calorific value. Furthermore, by varying both the type of plastic and biomass, the influence of feedstock characteristics on the quality of the resulting liquid fuel can be evaluated.

2. RESEARCH METHODS

2.1. Materials

This study employed a quantitative experimental approach to analyze the effect of plastic waste types on the characteristics of the pyrolysis process using biomass as a co-fuel. The mass of plastic waste was varied in the form of a ratio to the mass of biomass to obtain a better understanding of the interaction between the two materials during pyrolysis. The types of plastic waste used in this study were polypropylene (PP) and polyethylene terephthalate (PET), while the biomass materials consisted of rice husks, corn cobs, and coconut shells. The experimental setup included a set of pyrolysis equipment, as shown in Figure 1, along with

several supporting tools such as sample bottles and an analytical balance.

**Figure 1.** A scheme set of pyrolysis apparatus.

The configuration of the pyrolysis equipment consists of:

1. Nitrogen gas cylinder
2. Blower
3. Lower biomass combustion chamber
4. Thermocouple for measuring the reactor temperature in the pyrolysis unit (T_1)
5. Thermocouple for measuring the combustion chamber temperature (T_2)
6. Plastic waste pyrolysis reactor
7. Upper biomass combustion chamber
8. Thermocouple for measuring the condenser temperature (T_3)
9. Condenser Liquid fuel collection container
10. Condensate collection bottle

2.2. Preparation and Pyrolysis Methods

The first stage of this research was the preparation of raw materials to be used in the pyrolysis process, which involved sorting and selecting polypropylene (PP) and polyethylene terephthalate (PET) plastic waste collected from household waste and final disposal sites. The selected plastic wastes were cut into small pieces to increase the surface area before being placed into the pyrolysis reactor with a total mass of 500 grams. The biomass materials rice husks, corn cobs, and coconut shells were sun-dried to reduce their moisture content before being placed into the combustion chamber as the pyrolysis fuel. The mass ratios of plastic waste to biomass were set at 1:8, 1:12, and 1:16.

After the plastic waste and biomass were loaded into the pyrolysis unit, the reactor was tightly sealed to maintain anaerobic conditions, and nitrogen gas was injected into the reactor. The biomass combustion process was then initiated to heat the reactor until a sufficient temperature was reached to melt and thermally decompose the plastic waste. The pyrolysis process was continued until no more liquid fuel droplets were observed dripping from the condenser. After completion, the liquid fuel products were collected for analysis. The analyses conducted included measurements of density, viscosity, calorific value, and yield percentage.

2.3. Method of Analysis

The analysis of the liquid fuel products consisted of several stages. The first analysis involved determining the calorific value using a Bomb Calorimeter, series 6400, to measure the combustion energy of the pyrolysis-derived liquid fuel. The second analysis was the determination of density using a pycnometer. The density of the liquid fuel was calculated based on the ratio of the mass of the liquid to the volume of the pycnometer, as expressed by the following Equation (1):

$$\rho = \frac{W - W_0}{V} \quad (1)$$

Where:

ρ = density of liquid fuel (g/mL)

W_0 = mass of the empty pycnometer (g)

W = mass of the pycnometer with the sample (g)

V = volume of the pycnometer (mL)

The third analysis was the determination of the kinematic viscosity of the liquid fuel using a viscometer. Measurements were performed three times to ensure accuracy and minimize experimental errors. The kinematic viscosity of the sample was calculated using the following Equation (2) [30]:

$$v = \frac{\mu}{\rho} \quad (2)$$

Where:

μ = dynamic viscosity (cP)

v = kinematic viscosity (cSt)

ρ = density (g/mL)

The fourth analysis was the calculation of the yield percentage obtained from the pyrolysis process. This analysis was conducted to determine the conversion efficiency of the feedstock into pyrolysis products. The yield parameter represents the ratio between the mass of the liquid product obtained and the total mass of the feedstock used. The yield percentage was calculated using the following Equation (3):

$$\text{Yield} = \frac{m_{\text{liquid product}}}{m_{\text{feedstock}}} \times 100\% \quad (3)$$

3. RESULTS AND DISCUSSION

3.1. Effect of Biomass Plastic Ratio on Pyrolysis Temperature

The pyrolysis of PP and PET plastic waste was conducted for a duration of 3 hours. The temperatures recorded as observational data were the pyrolysis temperature and the combustion temperature, as shown in Figure 2. The type of plastic and the type of biomass fuel influenced the pyrolysis temperature. For PP plastic using coconut shell biomass, the resulting pyrolysis temperature reached approximately 243.1°C at a plastic to biomass mass ratio of 1:16. Meanwhile, for PET plastic, the maximum temperature obtained at the same ratio was 308°C.

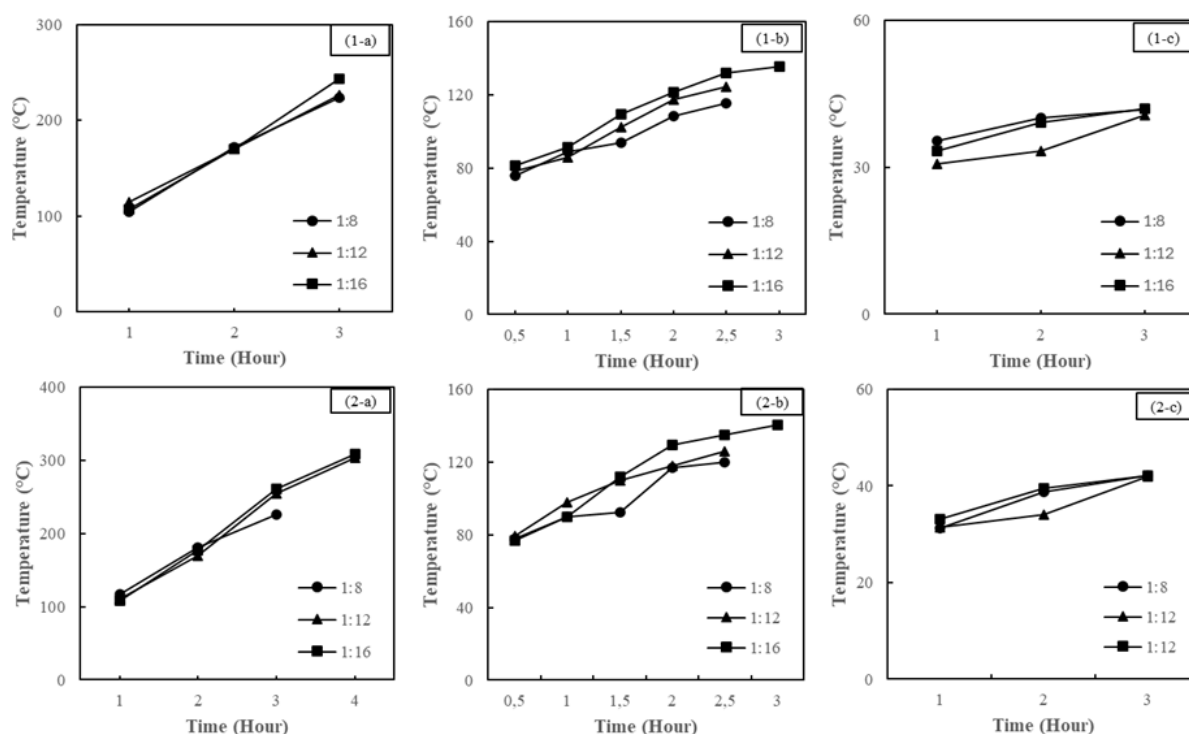


Figure 2. Effect of biomass ratio (a) coconut shell, (b) corncob, and (c) rice husk with plastic waste (1) PP and (2) PET on pyrolysis temperature (T_1).

The temperature increase observed in both plastics indicates that increasing the amount of biomass fuel enhances the heat energy supplied by the coconut shell. The thermal properties of coconut shell, which include a high heating value and stable flame characteristics, support more optimal heat transfer to the pyrolysis reactor. The rate of temperature increase for PET was more significant than for PP, especially at ratios of 1:12 and 1:16. This trend is due to the thermal properties of PET, which, according to Alhulaybi and Dubdub [31], has a thermal decomposition range of 377–477°C and an activation energy of 212 kJ/mol. PET, therefore, exhibits high thermal stability and requires greater energy input to reach its degradation temperature. These findings also confirm that coconut shell is effective as a combustion medium for achieving optimal pyrolysis temperature, supported by its high heating value [6], particularly for plastics with high melting and degradation points such as PET.

For both PP and PET, combustion using corncob biomass produced a pyrolysis temperature in the range of 135–145°C.

However, corncob has a shorter combustion duration compared to coconut shell only around 2.5 hours at ratios of 1:8 and 1:12, though pyrolysis duration could reach 3 hours at a ratio of 1:16. The temperatures achieved with corncob were lower because of its silica ash content [32] which acts as an insulating material and produces slag that impedes heat transfer inside the furnace [33]. Similarly, rice husk biomass produced relatively low pyrolysis performance, with a maximum pyrolysis temperature of only 42°C, far below the minimum temperatures required to break PP polymer chains, approximately 200–370°C [34,35], and PET above 290°C [36]. The low temperature prevented liquid fuel formation, resulting in products dominated entirely by char with zero percent liquid fraction.

3.2. Effect of Biomass-Plastic Ratio on Reactor Temperature

The selection of biomass fuel influences not only the pyrolysis temperature but also the internal reactor temperature containing PP and PET plastics as shown in Figure 3. Coconut shell achieved the highest

combustion temperature inside the reactor, ranging from 410.9–514.5°C, at all ratios (1:8; 1:12; 1:16) for both PP and PET. This is attributed to the high heating value of coconut shell, stable and prolonged combustion due to its high fixed carbon content [37], and low ash content. The low ash level prevents the formation of deposits on the outer reactor walls, ensuring uniform and continuous heat transfer across the reactor surface [6].

For corncob biomass, the highest reactor temperatures achieved ranged from 301.2–365.6°C. Increasing the corncob to plastic ratio extended the pyrolysis duration, with a maximum of 3 hours at a 1:16 ratio. These reactor temperatures were lower than those produced by coconut shell combustion due to the high silica ash content of corncob. The silica ash forms deposits on the outer reactor surface, reducing heat transfer efficiency and preventing the temperatures required for PET

polymer chain degradation. For rice husk biomass, reactor temperatures were notably low, only 100°C for PP and 120°C for PET. These temperatures indicate that the heat generated from rice husk combustion is insufficient to reach optimal pyrolysis conditions, especially for PET, which requires higher temperatures for effective degradation. The poor combustion performance of rice husk is influenced by its physical and chemical properties: rice husk ash contains 80–90% silica [38], which creates an insulating layer that restricts heat transfer from the combustion zone to the reactor. Additionally, rice husk burns quickly without a stable flame, resulting in discontinuous heat supply. Consequently, heat distribution is uneven, and peak temperatures remain low, making rice husk ineffective as an external heat source for plastic pyrolysis.

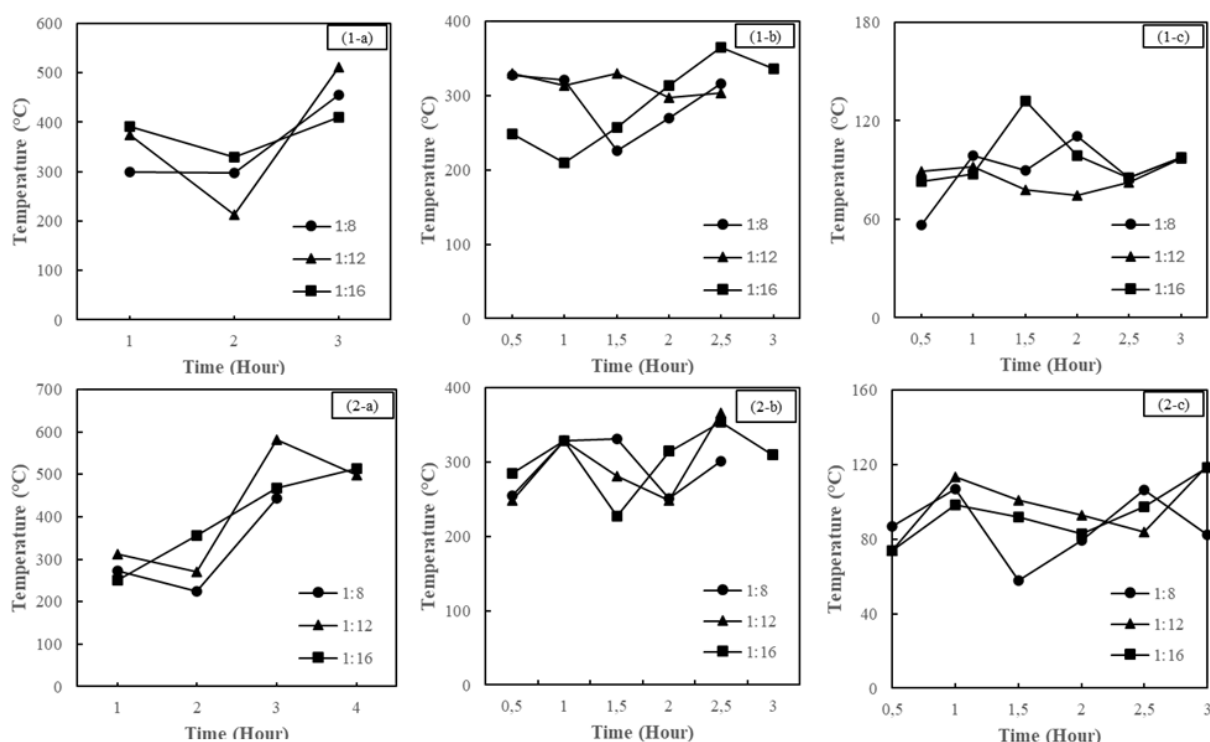


Figure 3. Effect of biomass ratio (a) coconut shell, (b) corncob, and (c) rice husk with plastic waste (1) PP and (2) PET on reactor temperature (T_2).

The increase in temperature in both the combustion reactor and the pyrolysis reactor influences polymer chain scission and the production of liquid fuel. Higher temperatures provide greater energy required to break polymer chains, whereas lower temperatures result in slower degradation processes. The C–C and C–O bonds in polymer compounds break during thermal decomposition, generating free radicals that subsequently undergo further reactions to form hydrocarbon molecules such as alkanes and alkenes [39].

Temperature also affects the yield of pyrolysis oil. This can be observed in this study where a maximum temperature of 308°C was sufficient to produce liquid hydrocarbon fractions. However, if the pyrolysis temperature increases further, secondary cracking may occur, converting the liquid fractions into lighter gases and consequently reducing the liquid yield.

3.3. Analysis of Liquid Fuel Products from Pyrolysis

The analyzed parameters of the pyrolysis product included yield, heating value, density, and viscosity. The highest yield was obtained using coconut shell biomass for both PP and PET plastics, due to the achievement of sufficient pyrolysis and reactor temperatures required for polymer chain cracking. While higher heating value contributes to increased liquid fuel yield, the type of plastic also affects yield performance. For PP plastic, the highest yield was 2.74% at a 1:16 ratio as shown in Figure 4. For PET plastic, the highest yield was 11.95% at the same ratio. This difference results from the distinct thermal properties and molecular structures of PP and PET. Polypropylene (PP) consists of simple carbon chains with methyl groups and no aromatic rings, making its C–C bonds relatively easy to thermally degrade. As a result, thermal cracking occurs at lower temperatures, producing short-chain fragments that readily condense into liquid hydrocarbons. Thus, PP typically generates higher liquid fractions than structurally complex plastics such as PET [18].

Meanwhile, with corncob biomass, only PP plastic produced liquid fuel, and the yield was lower than that produced using coconut shell. Increasing the biomass-to-plastic ratio increased the yield, as greater heat availability enhanced PP thermal decomposition, resulting in higher liquid fraction formation. The absence of yield when using rice husk biomass indicates insufficient combustion temperature to support effective PP pyrolysis.

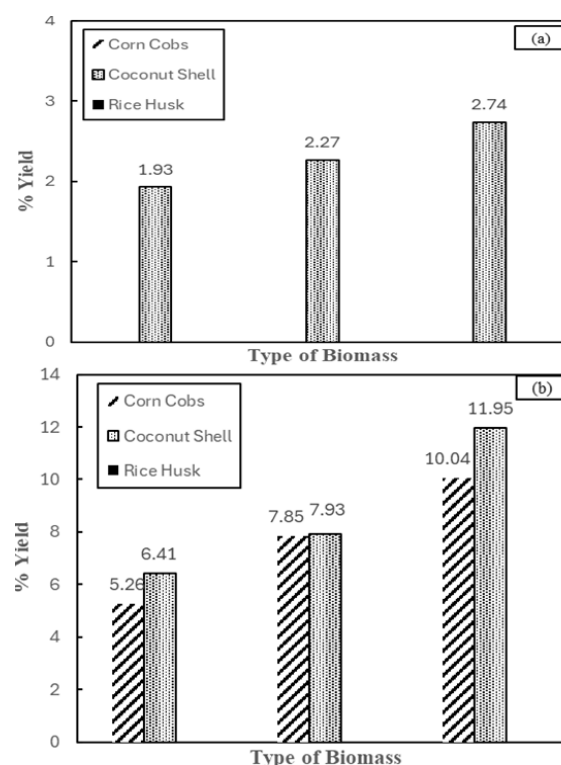


Figure 4. Liquid fuel yield from plastic waste (a) PP and (b) PET.

Heating value is one of the most important parameters for assessing the quality of liquid fuel, as it describes the amount of heat energy released during the complete combustion of a unit mass of fuel [40]. Figure 5 shows that the heating value of PP-derived liquid fuel was higher than that of PET for all biomass ratios. The highest heating value for PP was 12,038.9 cal/g at a ratio of 1:12, while for PET, the highest value was 11,348.1 cal/g, also at a ratio of 1:12 with coconut shell biomass. At a ratio of 1:16, the heating values decreased due to excessive biomass, which

accelerates secondary cracking reactions that convert heavy fractions into gas [41]. PP tends to produce high-energy, high-density liquid fractions because of its simple polymer structure and high carbon content, forming medium- to long-chain hydrocarbons. PET-derived liquid fuel was not produced when using corncob biomass. The heating values of PP and PET liquid fuels generated using coconut shell were comparable to those of gasoline and diesel, approximately 11,000 cal/g [42, 43].

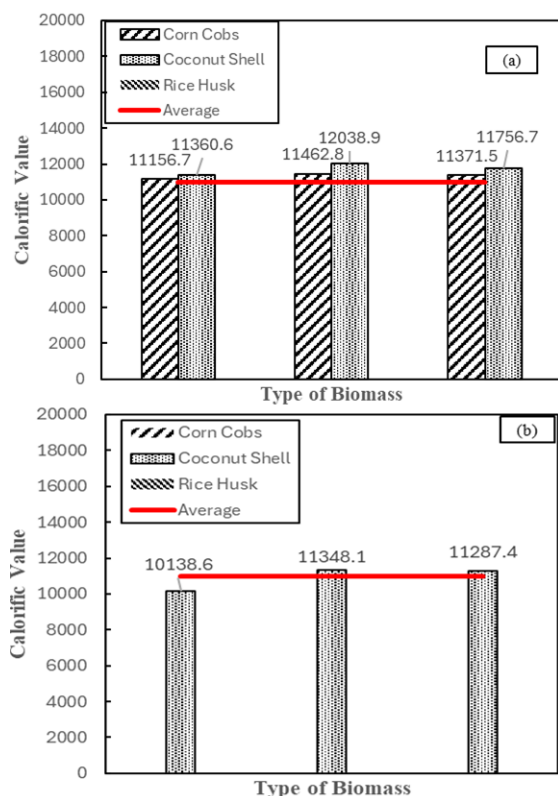


Figure 5. Heating value of liquid fuel from plastic waste (a) PP and (b) PET.

Viscosity is an important parameter for determining the quality of liquid fuel. High viscosity indicates the presence of waxes, resins, or long-chain aromatic fractions, while very low viscosity indicates dominance of short-chain hydrocarbons and volatile compounds. Excessively low viscosity can cause premature evaporation, resulting in incomplete combustion and elevated hydrocarbon and CO emissions [44].

Based on the results shown in the Figure 6, PP-derived pyrolysis oil exhibited lower

viscosity than PET-derived oil for both coconut shell and corncob biomass, except that PET produced no oil when using corncob. These differences arise from the distinct chemical characteristics of each polymer. The highest viscosity was obtained at a ratio of 1:12, but it decreased at 1:16 due to the higher biomass loading, which increased the temperature and reduced the proportion of heavy fractions responsible for higher viscosity. All pyrolysis oil samples fell within the kinematic viscosity range of conventional fuels. The viscosity of PP-derived oil using coconut shell and corncob matched the viscosity of kerosene, approximately 1.48 cSt at 20°C [45], while PET-derived oil corresponded to diesel viscosity, approximately 3.5 cSt at 40°C [46].

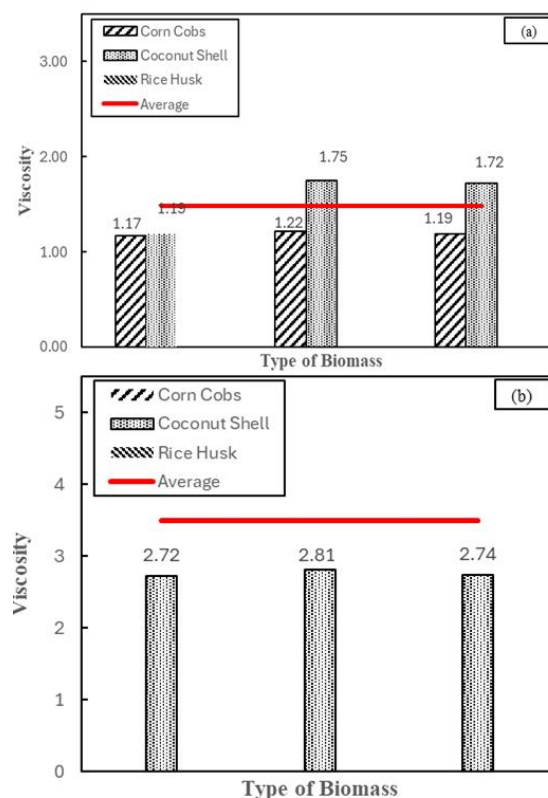


Figure 6. Viscosity of liquid fuel from plastic waste (a) PP and (b) PET.

Density analysis of PP-derived pyrolysis oil yielded values of 0.7285–0.7485 g/cm³, similar to gasoline density, whereas PET-derived oil showed densities of 0.803–0.809 g/cm³, comparable to kerosene [45]. This difference results from the heavier molecular

weight components present in PET pyrolysis oil, as PET contains aromatic and ester groups that degrade into heavier fractions, while PP produces mostly saturated hydrocarbon chains with lower density.

Figure 7 shows an initial increase from the 1:8 ratio to 1:12, followed by a decrease in density at the 1:16 ratio. The initial increase is attributed to the additional heat supply, which leads to the formation of intermediate molecular hydrocarbons, while the polymer chains have not yet been completely broken. As a result, heavier oil fractions are produced, particularly in PET-derived pyrolysis oil, which exhibits a higher density compared to PP-derived oil. This occurs because PET-derived pyrolysis oil contains aromatic compounds, whereas PP is predominantly aliphatic. When the ratio is further increased to 1:16, the higher heating rate promotes the cracking of heavy fractions into lighter and more volatile hydrocarbons, as evidenced by the decrease in density observed in all types of pyrolysis oil.

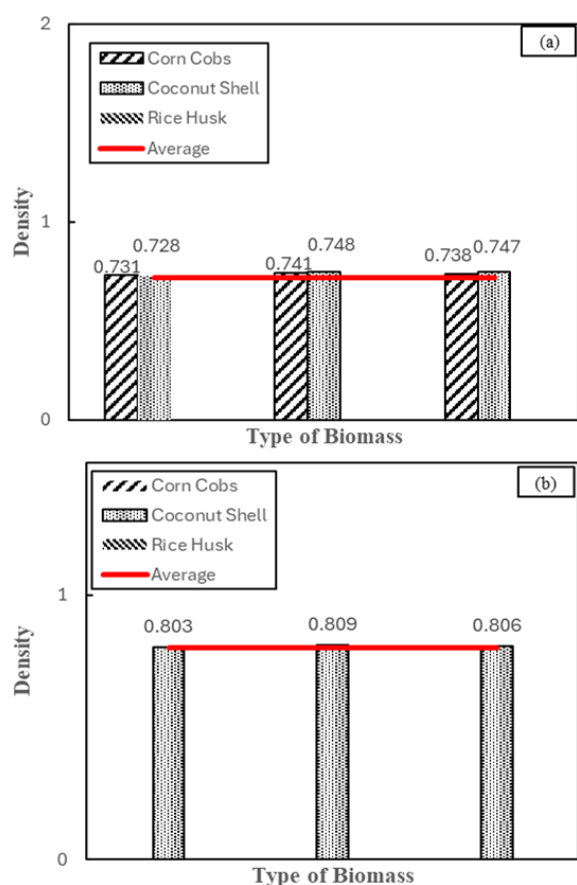


Figure 7. Density of liquid fuel from plastic waste (a) PP and (b) PET.

Overall, the characterization results indicate that the three pyrolysis oils require different upgrading approaches based on their fractional and chemical compositions.

PP pyrolysis oil using corncob biomass, dominated by light components, requires vacuum distillation to obtain a more stable middle fraction. If the yield is limited, catalytic upgrading such as oligomerization or hydrocracking can be applied to increase diesel-range fractions. PP pyrolysis oil using coconut shell biomass shows a distribution closer to gasoline-kerosene range; therefore, batch vacuum distillation is the primary method to isolate the diesel fraction that meets standard viscosity and density requirements, followed by hydrotreating if polar compounds or contaminants are present. PET pyrolysis oil using coconut shell biomass is more affected by oxygenates and polymer residues. Quality improvement is more effectively achieved through physical purification methods such as filtration, dewatering, and adsorption. Mild hydrotreating is only necessary when oxygen or sulfur levels exceed diesel specifications. Conversely, if gasoline-like properties are desired, the addition of a zeolite catalyst during pyrolysis is necessary to shift the product distribution toward lighter fractions, supported by GCMS analysis, boiling point profiling, and flash point measurement to reinforce the classification of the resulting fuel fractions.

4. CONCLUSION

This study demonstrates that the biomass-to-plastic ratio plays a critical role in governing the thermal behavior of the pyrolysis process and the properties of the resulting liquid fuel. Among the conditions evaluated, coconut shell at a 1:16 ratio generated the highest reactor temperature and the greatest liquid fuel yield. Pyrolysis oil derived from PP corresponds more closely to light fuel fractions, whereas PET-derived oil exhibits characteristics associated with medium to heavy fractions. This distinction is supported by property measurements, in which PP oil aligns with the gasoline-kerosene range,

while PET oil shows similarity to the kerosene-diesel range in terms of density and viscosity. These findings underscore the potential of agricultural biomass as a renewable heat source for plastic waste pyrolysis, contributing to sustainable energy production.

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AUTHOR CONTRIBUTIONS

M.A.I.I.: Conceptualization, data curation, validation, writing – original draft, review & editing. **E.N.:** Investigation, data curation, data validation, writing – review & editing. **W.Z.:** Methodology, formal analysis, writing – review & editing. **L.R.:** Validation, writing – review & editing. **M.M.:** Validation, writing – review & editing. **A.T.:** Writing – review & editing. All authors read and approved the final manuscript.

CONFLICTS OF INTEREST

The authors declare no competing financial interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES

During the preparation of this manuscript, the authors used OpenAI's Claude to assist with language editing and to improve the clarity, conciseness, and readability of the manuscript. The authors critically reviewed and revised the AI-assisted text and take full responsibility for the accuracy, integrity, and final content of the published article.

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