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Influence of Pyrolysis Temperature on the Composition of Bio-Oil Derived from *Cerbera odollam* as a Raw Material

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ABSTRACT

Cerbera odollam is a widely available biomass due to its adaptability to various environments. Although its fruit is inedible, its utilization can be enhanced through pyrolysis, a thermochemical decomposition process conducted at 250°C–600°C in an oxygen-limited environment. This study investigates the effect of pyrolysis temperature on the yield and composition of bio-oil, biochar, and gas, aiming to determine the optimal temperature for producing bio-oil with desirable chemical properties. Pyrolysis was performed in a fixed-bed reactor at temperatures of 350°C, 450°C, and 550°C. The results showed that increasing the pyrolysis temperature led to a higher bio-oil yield, with the maximum yield (28.83%) obtained at 550°C, while biochar production decreased accordingly. Bio-oil produced at 350°C exhibited the lowest pH (2.97), whereas the highest density (1.07 g/mL) was observed at 450°C. GC-MS analysis of bio-oil at 550°C identified butanal, 3-methyl- as the dominant compound (30.52%), along with significant amounts of oleic acid and 9,12-octadecadienoic acid. The novelty of this study lies in optimizing pyrolysis conditions for *Cerbera odollam*, underutilized biomass, by identifying 550°C as the optimal temperature for maximizing bio-oil yield while influencing its chemical composition. These findings provide valuable insights into its potential applications in the biofuel and chemical industries. Further research on catalyst addition and process optimization could enhance bio-oil quality and yield.

Keywords: Bio-oil, *Cerbera odollam*, GC-MS, pyrolysis, temperature

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INTRODUCTION

Cerbera odollam is an abundant source of biomass and has great potential to be widely utilized. This plant thrives in various tropical and subtropical regions and has high adaptability to various environmental conditions, making it easy to cultivate, as can be seen in Figure 1. Apart from that, *Cerbera odollam* cannot be consumed (it is non-edible) (Chan et al., 2016), so its use does not compete with food needs. *Cerbera odollam, which has not been used and is simply thrown away or burned,* can cause environmental pollution problems. Biomass from *Cerbera odollam* contains cellulose (Roy & Abedin, 2022), hemicellulose, and lignin (Ansari et al., 2019). It has a long and complex carbon chain consisting of the elements C, H, and O, so it can be processed further through the pyrolysis process (Wu et al., 2023). Pyrolysis is the thermochemical (Sierra et al., 2023) decomposition of organic materials at a temperature of 250–600°C in the absence of oxygen (Parthasarathy et al., 2023), which produces bio-oil (Mossa et al., 2024), biochar (Corbita et al., 2024), and pyrolysis gas. This process has great potential as an alternative for handling organic waste and biomass management (Akinpelu et al., 2023), producing bio-oil (Ameh et al., 2024), which can be used as raw material for the chemical industry (Bieniek et al., 2023), pharmaceutical (Seo et al., 2023), and renewable energy industries (Letoffet et al., 2024; Kadhem & Wahab, 2024). Thus, the use of *Cerbera odollam* through pyrolysis not only reduces waste and environmental pollution but also produces products that are useful and have high economic value.

Biomass pyrolysis is a process that can provide three different products, namely solid, liquid, and gas, depending on the characteristics (Syuriadi et al., 2022) of the raw material and the pyrolysis reaction conditions, as shown in Figure 2. The solid fraction, or pyrolysis charcoal (biochar), is a carbon-rich residue produced in primary and secondary pyrolysis reactions that can be used as solid fuel for heat (Poomsawat & Poomsawat, 2023) and electricity production (Kadhem & Wahab, 2024), raw material for gasification processes (Clemente-Castro et al., 2023), raw material for the production of activated carbon (Suprianto et al., 2021), soil conditioner, and improving soil quality (Vanapalli et al., 2021).

The liquid fraction, or bio-oil, is another product of biomass pyrolysis, which can be a promising alternative energy source for fuel oil (Rony et al., 2025), diesel (Eraslan & Calhan, 2024)and other chemical derivatives (Zhang et al., 2024). Bio-oil produced from biomass pyrolysis needs to be increased by reducing oxygen (Gao et al., 2024) and residue content. The gas produced during

Figure 1. Cerbera odollam Gaertn

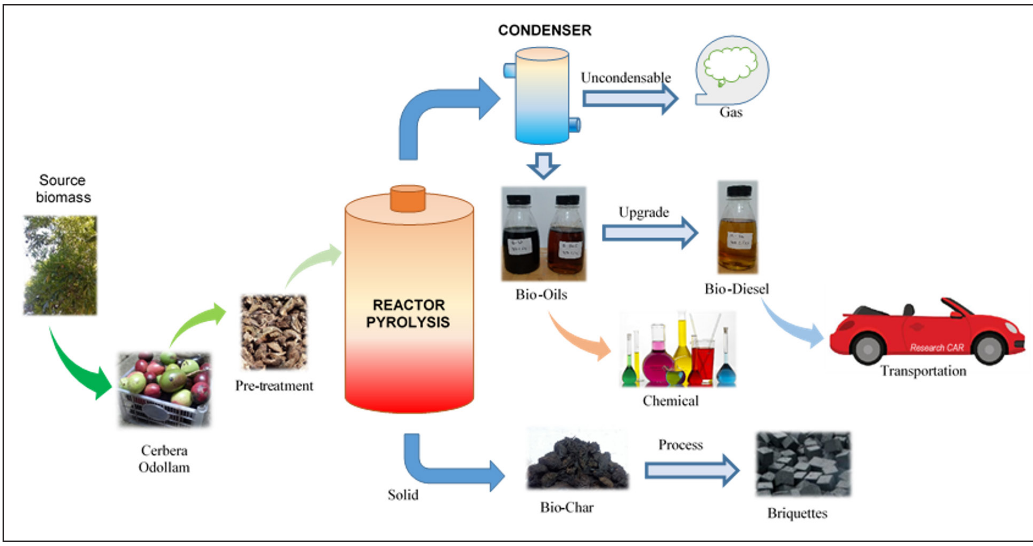

Figure 2. Biomass pyrolysis

the pyrolysis process is another valuable byproduct. Essentially, increasing the reaction temperature in pyrolysis creates a significant increase in gaseous products (Ferdous et al., 2024). These combustible gases can be used as direct fire in boilers for heat production, or in gas turbines or engines for electricity production (Rajpoot et al., 2022). Many factors influence pyrolysis products, such as biomass composition and experimental conditions, including operating temperature, which can be determined based on DTA tests, as shown in Figure 3. Pyrolysis involves the thermal degradation of lignocellulose through a series of complex reactions in an oxygen-free environment.

The pyrolysis temperature plays a crucial role in optimizing bio-oil production, as it directly influences the composition and quality of the final product. Lower temperatures favor bio-oil formation with a higher oxygenate content, which decreases stability and calorific value. Higher temperatures enhance the decomposition of organic compounds, leading to bio-oil with a greater hydrocarbon content and reduced oxygenates, improving fuel quality (Wahyudi et al., 2024). Excessive temperatures promote gas formation and decrease overall bio-oil yield. The selection of an appropriate pyrolysis temperature is essential to balance bio-oil quantity and quality. Temperature variations also affect the distribution of specific chemical compounds in bio-oil, influencing their applicability in liquid fuel and chemical production. A comprehensive understanding of the effects of pyrolysis temperature enables process optimization in both research and industrial applications.

The pyrolysis process of lignocellulosic biomass consists of several main stages, including the release of water vapor, cellulose decomposition, and lignin decomposition (Chen et al., 2022), where temperature plays a crucial role in the decomposition of each

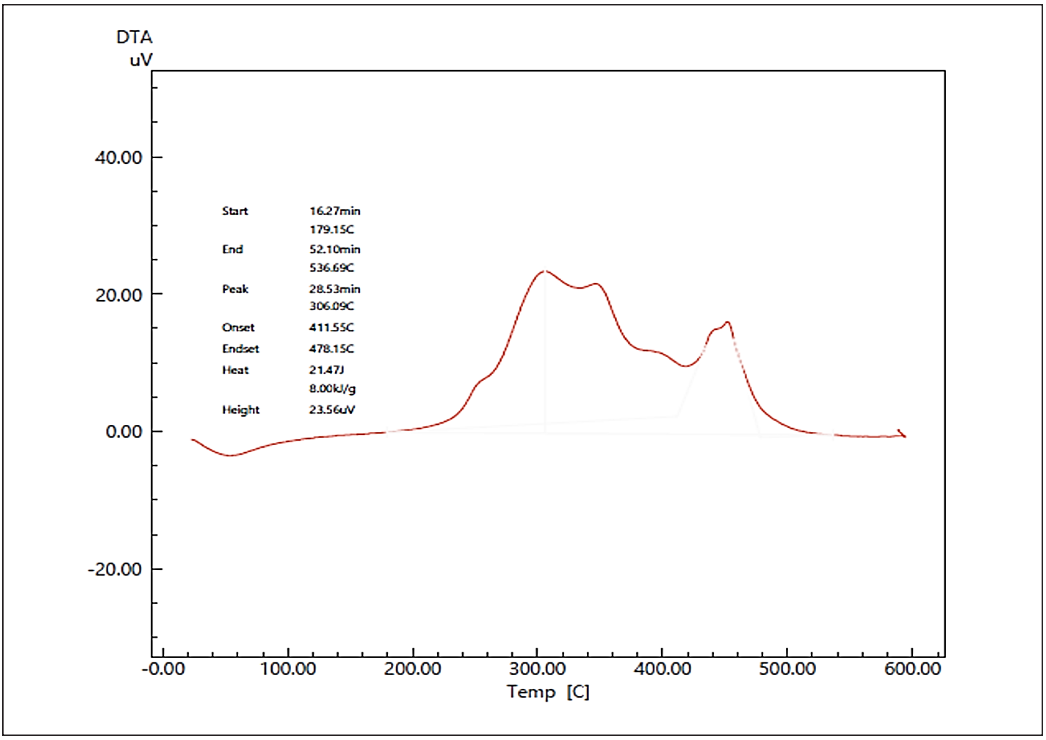

Figure 3. Cerbera odollam thermogravimetric differential test

component. Chen et al. (2022) reported that lignin decomposition occurs at 450°C, while hemicellulose and cellulose degrade at 250–350°C temperatures. However, some studies suggest that the decomposition temperature range of lignin may vary depending on the structure and origin of the biomass. During pyrolysis, organic materials undergo thermal decomposition, resulting in a vapor phase and a solid residue in the form of char or biochar (Arregi et al., 2023), with pyrolysis products typically consisting of approximately 35% biochar, 30% bio-oil, and 35% gas. However, variations may occur depending on the heating method and the characteristics of the raw material. Bio-oil derived from pyrolysis has been studied as an alternative fuel for various applications, including turbines (Hasanzadeh et al., 2023), diesel engines (Onwudili et al., 2023), and boilers (Szufa et al., 2023), but the high oxygen content in bio-oil can affect thermal stability, necessitating further refining processes before it can be optimally used as a substitute for fossil fuels.

In addition to temperature and processing methods, the chemical composition of biomass also influences the pyrolysis yield, where, according to Melikoglu et al. (2023), biomass with a high lignin content tends to produce phenols, while cellulose-rich biomass yields levoglucosan, an organic compound containing carbohydrate acid, with the efficiency of production and utilization of these pyrolysis products remaining a topic of ongoing research, particularly regarding their potential applications in the energy and chemical industries.

For instance, *Cerbera odollam* contains 41.8% cellulose and 58.2% lignin, which has been analyzed using FTIR to identify the functional groups present, where FTIR analysis results indicate that the highest intensity originates from the carboxylic acid (C-O) group, while other groups such as C-H (aromatic and aliphatic), C=O, and O-H exhibit lower intensities (Rosalina et al., 2018). The interpretation of these results provides insights into the characteristics of pyrolysis products and their relationship to the initial chemical structure of the biomass, highlighting that with various factors influencing the pyrolysis process of lignocellulosic biomass, the optimization of parameters such as temperature, heating rate, and raw material size remains a critical aspect in improving efficiency and product quality.

Although extensive research has been conducted on pyrolysis and bio-oil production from various biomass sources, a significant gap remains in understanding how temperature variations influence bio-oil composition from less-explored feedstocks. Most previous studies have focused on common materials such as wood, straw, and agricultural waste, while limited attention has been given to unconventional biomass with unique characteristics (Khan et al., 2024). Among these, *Cerbera odollam* exhibits promising potential as a bio-oil feedstock, yet studies on optimizing its pyrolysis conditions, particularly temperature effects, are still scarce. This study addresses this gap by examining the impact of temperature variations on bio-oil yield and composition. The findings are expected to contribute to advancing more efficient pyrolysis technologies and diversifying sustainable bio-oil sources while enhancing the utilization of underexploited biomass. Specifically, this research investigates the influence of pyrolysis temperature on product distribution (bio-oil, biochar, and gas), identifies optimal conditions for maximizing bio-oil yield, and characterizes the chemical composition of the resulting bio-oil.

MATERIALS AND METHODS

The research equipment is a pyrolysis reactor fixed bed type with a volume capacity of 25 L and equipped with a water-cooled 2-stage condenser, universal oven, analytical balance, Ostwald pyrex, and a 5 mL pyrex pycnometer. The material used is *Cerbera odollam* with a diameter of ±7.5–9 cm obtained from the coastal area of Probolinggo district, East Java province, Indonesia.

Initial treatment of the ingredients was carried out to reduce the size of the *Cerbera odollam* by chopping it using a chopping machine until it was 4-5 cm small, then drying it in the hot sun for 3 days, and finally putting it in the oven at a temperature of 105°C for 3 hours. One thousand five hundred grams of dried *Cerbera odollam* were put into the reactor for each batch. The pyrolysis process was carried out three times with varying pyrolysis temperatures of 350°C, 450°C, and 550°C. Each pyrolysis process lasts 1.5 hours. The bio-oil product is obtained after the gas formed from the heating process in the reactor flows into the condenser and undergoes condensation at a cooling water temperature of ±

25°C. The resulting condensate is collected in a flask installed under the condenser (Noor et al., 2025). Some of the gas products are gases that do not condense when they pass through the condenser, then pass through the bio-oil storage container, and exit the system. Biochar remaining from the pyrolysis process will be left behind in the reactor (Ajagbe et al., 2025). The process scheme can be seen in Figure 4.

The batch reactor has a temperature control setting via the reactor panel box so that the temperature of the pyrolysis process can be regulated (Wijayanti et al., 2021). Bio-oil density is calculated using a 5 mL Pirex pycnometer. The mass of each product is obtained using Equations 1 and 2.

[Bio-oil mass] = [bio-oil volume] x [ρ (bio-oil density)] [1]

[Gas mass] = [feed mass] – [bio-oil mass] – [char mass] [2]

Bio-oil at each temperature variation was analyzed for pH values using pH Metter, and bio-oil at a temperature of 550°C was analyzed for chemical compound content using GCMS (Shimadzu GCMS-QP2020NX). This temperature was selected based on previous studies, which indicated that the highest bio-oil yield was obtained at 550°C. A higher temperature also leads to a more complex composition of compounds due to the further decomposition of lignocellulose in biomass. Theoretically, an increase in

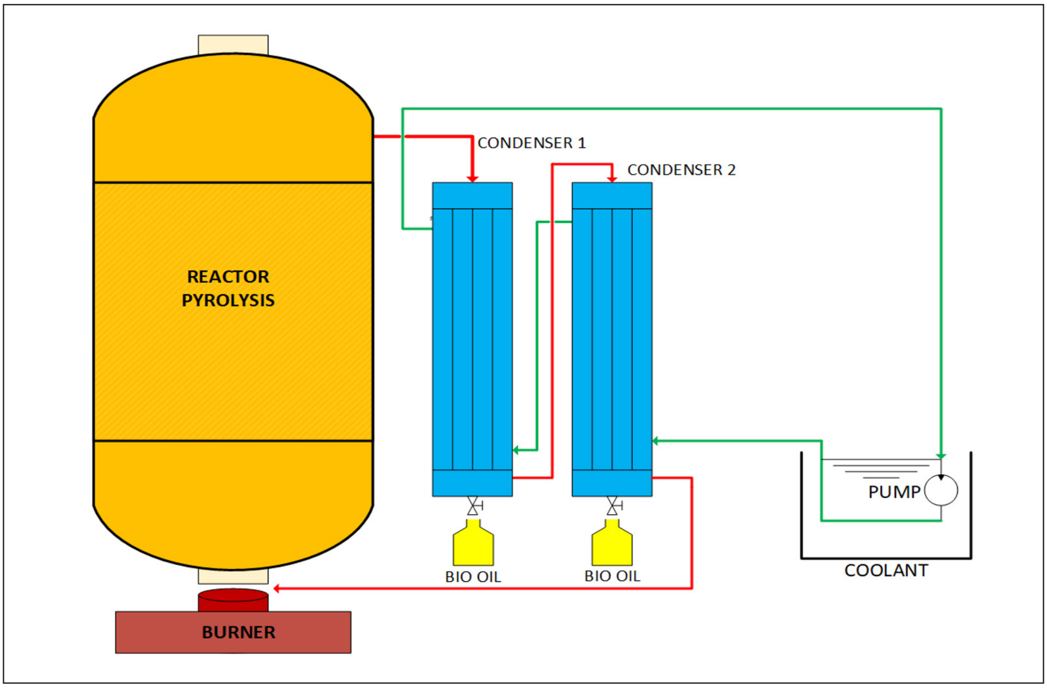

Figure 4. Pyrolysis process scheme

pyrolysis temperature enhances the conversion of biomass into volatile compounds, which subsequently condense into bio-oil. At 550°C, the decomposition of major biomass components, such as cellulose, hemicellulose, and lignin, occurs more extensively, resulting in bio-oil with a broader range of compounds.

Biochar Mass Determination

After the pyrolysis process is complete and the reactor has cooled down, the remaining biochar is carefully removed to avoid mass loss due to debris that may remain. The biochar is then weighed using an analytical balance (OHAUS NV2201) to determine its mass accurately with the following steps: First after the pyrolysis process, the reactor is allowed to cool to a safe temperature before being opened. Second, the biochar is removed from the reactor and collected in a closed container to prevent mass loss due to exposure to air or moisture. Third, the biochar is weighed using an analytical balance with a high degree of accuracy. Fourth, the mass of the biochar obtained is recorded for analysis in calculating the pyrolysis mass balance.

RESULTS AND DISCUSSION

Effect of *Cerbera odollam* Pyrolysis Temperature on Pyrolysis Products

Pyrolysis of *Cerbera odollam* produces three products: solid products called biochar, liquid products called bio-oil, and gas. Table 1 shows the mass balance in the pyrolysis of *Cerbera odollam*: the feed that enters the reactor is 1,500 gr for each temperature variation (350, 450, and 550°C), and the sum of the masses of each product (biochar, bio-oil, and gas) has a total output of 1,500 gr for each temperature.

The data in Table 1 show the mass distribution of pyrolysis products (biochar, bio-oil, and incondensable gas) across different temperatures. As the pyrolysis temperature increases from 350°C to 550°C, there is a notable decrease in the mass of biochar, from 821.25 g at 350°C to 650.58 g at 550°C. Conversely, the mass of bio-oil increases significantly with temperature, reaching a maximum of 432.52 g at 550°C. The mass of incondensable gas also increases slightly with temperature but shows a less pronounced trend compared to the other products. These results suggest that higher pyrolysis temperatures favor the decomposition of the biomass into liquid and gaseous products, reducing the solid biochar yield.

Table 1
Cerbera odollam *pyrolysis products based on mass at various pyrolysis temperatures*

Pyrolysis Temperature (°C)	Biochar (gr)	Bio-oil (gr)	Incondensable gas (gr)	Total (gr)
350	821.25	282.94	395.81	1500.0
450	705.31	375.92	418.77	1500.0
550	650.58	432.52	416.90	1500.0

In calculating the mass of gas using the mass balance method, several potential uncertainties need to be considered. One of the main factors is the possibility of mass loss due to gas leakage during the pyrolysis process. The gas produced from pyrolysis is light and can easily escape through small gaps in the reactor system, especially if the system is not completely sealed. In addition, undetected secondary reactions can also cause differences in the calculation of gas mass. Some volatile compounds formed during pyrolysis can undergo further reactions, either with other components in the system or with the reactor wall, which can change the total amount of gas produced. Another factor that can affect the accuracy of the calculation is the efficiency of bio-oil condensation, where a small portion of the gas components may be condensed with the bio-oil, causing slight differences in the mass balance calculation.

The characteristics of the pyrolysis bio-oil were analyzed and are summarized in Table 2. This table presents the key properties of bio-oil, including its density and pH, which are critical for assessing its suitability as a raw material source.

Table 2
Density and pH values in Cerbera odollam *pyrolysis bio-oil products*

Pyrolysis Temperature (°C)	Volume mL)	Density (gr/mL)	pH
350	299.92	1.06	2.97
450	402.23	1.07	3.26
550	454.15	1.05	3.33

Based on the data presented in Table 2, it is evident that the volume of the bio-oil product increases with the rising pyrolysis temperature. At 350°C, the produced volume is 299.92 mL; at 550°C, the volume increases to 454.15 mL. This indicates that higher pyrolysis temperatures tend to yield a greater amount of bio-oil, likely due to more extensive decomposition of the raw material into volatile products that subsequently condense into bio-oil. Furthermore, the density of the bio-oil shows a slight decrease with increasing pyrolysis temperature, from 1.06 g/mL at 350°C to 1.05 g/mL at 550°C. This decrease in density may suggest a change in the chemical composition of the bio-oil, where higher temperatures potentially lead to more decomposition reactions that produce compounds with lower molecular weights and higher water content. Regarding the pH values, all bio-oil products exhibit acidic characteristics with a $pH < 7$.

The increase in pyrolysis temperature also results in a slight increase in pH from 2.97 at 350°C to 3.33 at 550°C. This rise in pH could indicate that some acidic compounds may decompose or form in lesser quantities at higher temperatures, making the bio-oil slightly less acidic. The relationship between pH and FTIR results, which highlight the presence of C-O groups, particularly those associated with carboxylic acid groups, supports the observation that the bio-oil contains significant acidic compounds. Overall, these data suggest that pyrolysis temperature influences the volume, density, and acidity (pH) of the produced bio-oil, which is closely related to its chemical composition and water content in the final product.

Based on Figure 5, the results 1.500 gr of *Cerbera odollam* pyrolysis products in percent show that *Cerbera odollam* pyrolysis carried out at a temperature of 350°C produces 54.75% biochar, 18.86% bio-oil, and 26.39% gas. Pyrolysis at a temperature of 400°C produced 47.02% biochar, 25.06% bio-oil, and 27.92% gas. At a temperature of 550°C, it produces 43.37% biochar products, 28.83% bio-oil products, and 27.79% gas products. Figure 5 shows that the higher the pyrolysis temperature, the lower the biochar product, and vice versa for gas products: the higher the pyrolysis temperature, the more gas product.

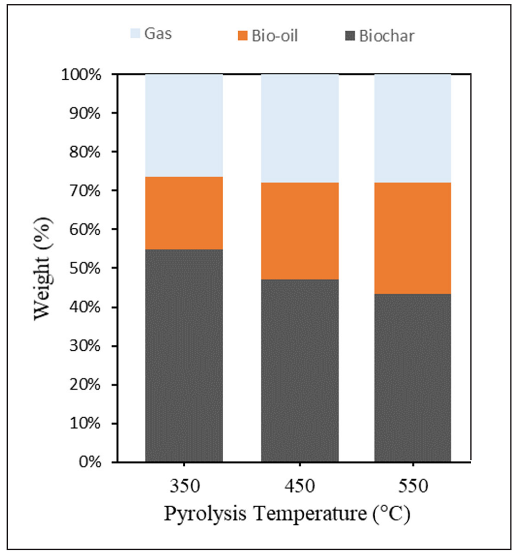

Figure 5. *Cerbera odollam* pyrolysis products

GC-MS Analysis of Bio-Oil products

The bio-oil product at a temperature of 550°C has the highest yield, so it is analyzed using a Shimadzu QP2020NX GCMS to determine the chemical elements contained in the bio-oil. Produce the data in Table 3.

The main products from bio-oil at a temperature of 550°C are butanal and 3-methyl, the systematic name of an organic compound known as isovaleraldehyde. It is a branched aldehyde with the molecular formula $C_5H_{10}O$; Butanal, 3-methyl- has the highest area percentage, 30.52%. *Cerbera odollam* has 32.0%–38.6% cellulose and 19.7%–35.7% hemicellulose. Degradation of hemicellulose and cellulose produces organic acids such as acetic and formic acids. However, hemicellulose degradation impacts the high value of volatile matter, as well as small amounts of tar and charcoal production. Meanwhile, 13.5%–24.4% is the lignin content, and the ash content of *Cerbera odollam* is 10%–17%. Ash in biomass is usually formed from alkaline elements such as potassium, calcium, magnesium, and silica (W. Wang et al., 2022), which influences the conversion and selectivity of the pyrolysis reaction (Ge et al., 2023). High ash content also reduces the calorific value of biomass.

Pyrolysis at a temperature of 350–550°C decreases biochar yield as the pyrolysis temperature increases, and the yield of the gas product increases. In slow pyrolysis, the main product is biochar, which still contains ash (L. Wang et al., 2022). In this study, the

Table 3
GC-MS analysis of bio-oil

Ret. Time	Area%	Name
1.379	30,52	Butanal, 3-methyl-
34.825	18,00	Oleic Acid
35.994	15,69	9,12-Octadecadienoic acid (Z,Z)-
1.342	11,26	1,6-Anhydro-2,4-dideoxy-.beta.-D-ribo-hexop
30.514	6,75	n-Hexadecanoic acid
34.250	4,62	Octadecanoic acid
21.002	4,51	Hexadecanoic acid, ethyl ester
1.528	1,67	Ethyl Acetate
36.470	1,62	Dodecanedioic acid, dimethyl ester
8.540	1,18	Diethyl sulfate
24.547	1,12	Octadecanoic acid, ethyl ester
30.925	0,77	n-Hexadecanoic acid
39.212	0,71	Eicosanoic acid
33.564	0,36	2(3H)-Furanone, dihydro-5-tetradecyl-
1.654	0,26	Propanoic acid, ethyl ester
30.815	0,19	Hexyl (3S)-3-hydroxy-5-methoxy pentanoate
27.899	0,15	Eicosanoic acid, ethyl ester
1.841	0,12	Butanoic acid, ethyl ester
24.186	0,06	9-Octadecenoic acid, methyl ester
23.358	0,05	4-Ethyl-2,6-dimethoxyphenol

pyrolysis process lasted 1.5 hours, which was slow because it took over an hour. Pyrolysis at a temperature of 350°C produces the most biochar products and the least gas products because (Selvarajoo & Oochit, 2020), at this temperature, complete decomposition has not occurred in the *Cerbera odollam*. Apart from that, pyrolysis at a temperature of 300°C can be said to be torrefaction (Richa et al., 2023) because torrefaction is a type of biomass processing that involves heating without oxygen or using inert gas at a low temperature of 200–300°C. Torrefaction aims to increase the calorific value (Parvej et al., 2022) of biomass by heating it to less than 300°C, with the main product being biochar, which can be used as a solid fuel. The largest bio-oil product was obtained at a temperature of 550°C with an amount of 28.83%. This is because, at this temperature, complete decomposition has occurred in *Cerbera odollam*; the main elements that make up *Cerbera odollam* are 28.5%–41% cellulose, 15.3%–25.9% hemicellulose, and lignin between 6.2%–12.6%. Hemicellulose decomposition occurs at a temperature of 250–350°C, whereas cellulose and lignin decomposition requires a temperature of more than 300°C (Mahakhant et al., 2021). This causes the bio-oil product to be less at a temperature of 350°C, and the optimum product for bio-oil is at a temperature of 450°C. At a temperature of 450°C, Cellulose and hemicellulose have experienced decomposition. In contrast, lignin decomposition only occurs partially because it requires an even higher temperature, more than 400°C. Cellulose is the main source of generating condensable vapor. Hemicellulose has the lowest degradation temperature at 250–300°C. Hemicellulose produces many non-condensable gases, and cellulose produces many bio-oil products.

Conversely, at higher temperatures, particularly 550°C, the bio-oil yield peaks at 28.83%. This increase in bio-oil production is attributed to the complete decomposition of the biomass components at elevated temperatures. The primary constituents of *Cerbera odollam* biomass include 28.5%–41% cellulose, 15.3%–25.9% hemicellulose, and 6.2%–12.6% lignin. Hemicellulose decomposes between 250–350°C, cellulose between 300–400°C, and lignin at temperatures above 400°C. Therefore, at 550°C, the decomposition of cellulose and hemicellulose is almost complete (Mahakhant et al., 2021), enhancing bio-oil formation. In GC-MS analysis, various organic compounds indicated the complexity of bio-oil produced at 550°C. Compounds such as butanal, 3-methyl-, which had the highest percentage area (30.52%), indicated that most of the bio-oil components were derived from the decomposition of hemicellulose and cellulose (Usino et al., 2021). The presence of compounds such as Hexadecanoic acid and Octadecanoic acid indicated that most of the fatty acids were present in the bio-oil, which could be potential precursors in biodiesel production. Comparison between pyrolysis results at 350°C and 550°C highlighted the significant difference in the products produced. At lower temperatures (350°C), biomass decomposition was still incomplete, which led to more dominant biochar production, while at 550°C, a significant increase in bio-oil products occurred. This fact supports the idea that temperature is crucial in determining pyrolysis results and final products.

It should be noted that the high content of Oleic acid (18%) and 9,12-Octadecadienoic acid (15.69%) in the bio-oil produced indicates the presence of unsaturated fatty acids that have the potential to be used in chemical industry applications, for example, in the manufacture of lubricants or surfactants. On the other hand, compounds such as Diethyl sulfate (1.18%), although in relatively small amounts, may be of concern in terms of toxicity and need to be carefully managed in further processing. In further research, it would be interesting to explore how other pyrolysis conditions, such as heating rate, atmosphere, or variations in the particle size of the feedstock, can affect the distribution of compounds in the bio-oil. Such research could optimize richer bio-oil yield in high-value compounds while minimizing contaminants or unwanted byproducts. In addition, a more in-depth analysis of the effect of biomass ash content on pyrolysis products could provide additional insights into the relationship between the mineral composition of the biomass and the selectivity of the pyrolysis reaction. Further research on optimizing pyrolysis temperature and time can also focus on obtaining higher bio-oil yields and improving bio-oil quality in terms of thermal stability, energy, and chemical component purity.

Decomposition Pathways and Product Distribution

Hemicellulose's decomposition at 250–350°C releases volatile gases and tar (Niksa, 2022a), producing non-condensable gases. This degradation pathway results in a significant portion of the volatile matter escaping as gas, crucial for energy recovery through gasification processes. Cellulose, decomposing at temperatures above 400°C, is a primary source of condensable vapors (Niksa, 2022b). Its decomposition produces a substantial amount of bio-oil, as it converts into a range of volatile organic compounds. At 550°C, the breakdown of cellulose is well-advanced, leading to increased bio-oil production compared to lower temperatures. Lignin decomposition requires temperatures above 500°C (Folgueras et al., 2023), where it breaks down into smaller molecules, primarily phenolic compounds (Zhang et al., 2023). At 550°C, lignin decomposition is partial, contributing to bio-oil formation, but at a slower rate compared to cellulose and hemicellulose.

The optimal temperature for maximizing bio-oil yield in this study is identified as 550°C. At this temperature, the decomposition of cellulose and hemicellulose is significant, while lignin decomposition is not complete. This balance enhances bio-oil production, making 550°C a critical temperature for optimizing bio-oil yield. The decomposition kinetics at this temperature ensure a high yield of condensable vapors, favoring bio-oil production over gases and solid residues. Pyrolysis produces significant amounts of bio-oil at this temperature, with optimal decomposition of hemicellulose and cellulose. Hemicellulose degraded at 250–350°C produces volatile gases and tar, which contribute to non-condensable gas products, making gasification a potential pathway for energy recovery (Ward et al., 2014). Cellulose, which begins to decompose at temperatures above 400°C, is the main source of condensed vapors that make up bio-oil. This explains why, at 550°C, the increase in bio-oil production occurs due to further decomposition of cellulose.

Meanwhile, lignin degraded at temperatures above 500°C is slower in making a significant contribution to bio-oil production. Phenolic molecules produced from lignin decomposition at 550°C enrich the composition of bio-oil (Soldatos et al., 2024), but in a smaller proportion compared to the results of hemicellulose and cellulose decomposition. Considering the characteristics of the decomposition pathway of each biomass component, a temperature of 550°C was shown to be the optimum point to maximize the bio-oil yield. At this temperature, the balance between the decomposition of hemicellulose, cellulose, and lignin provides a bio-oil product rich in volatile compounds with added value. These results open up great opportunities for further exploration in optimizing pyrolysis conditions to improve bio-oil quality and quantity and increase energy efficiency in biomass conversion.

CONCLUSION

The pyrolysis temperature of *Cerbera odollam* in the batch reactor affects the pyrolysis products (char, bio-oil, and gas) produced. Pyrolysis of *Cerbera odollam* at a temperature of 350°C produces the most char products and the least gas products. Pyrolysis at a temperature of 450°C produces the most gas products and the least char products. The higher the pyrolysis temperature, the higher the gas product and the lower the char product. Likewise, the lower the pyrolysis temperature, the more char products there are and the fewer gas products. The optimum temperature for producing bio-oil from the pyrolysis of *Cerbera odollam* is 550°C, so it has the most chemical components analyzed using GC-MS to determine the chemical components contained. Based on GC-MS analysis, the butanal, 3-methyl-product has the highest percentage area, around 30.52%. So, it can be concluded that more bio-oil can be produced using the fast pyrolysis method or by adding a catalyst. Finally, the pyrolysis process of *Cerbera odollam* biomass exhibits distinct product distributions across different temperatures. Understanding the decomposition pathways and their temperature dependencies is essential for optimizing the yield and quality of biochar, bio-oil, and gases. This knowledge can guide the development of efficient biomass conversion technologies, enhancing the sustainability and economic viability of biomass utilization. In the future, research can focus on deeper investigations into the effects of pyrolysis time, heating rate, and biomass feedstock modification, hoping to increase bio-oil yield and reduce unwanted byproducts. Further investigations into phenolic compounds derived from lignin can also open up opportunities for developing bio-oil applications in industrial chemistry.

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REFERENCES

Ajagbe, C. A., Zainuddin, M. F., Manaf, L. A., Rahim, N. N. R. N. A., & Anguruwa, G. T. (2025). Comparative analysis of carbonized hybrid briquettes produced from cassava peel and sawdust for cooking application. *Pertanika Journal of Science and Technology*, *33*(1), 531–555. https://doi.org/10.47836/pjst.33.1.25

Akinpelu, D. A., Adekoya, O. A., Oladoye, P. O., Ogbaga, C. C., & Okolie, J. A. (2023). Machine learning applications in biomass pyrolysis: From biorefinery to end-of-life product management. *Digital Chemical Engineering*, *8*, Article 100103. https://doi.org/10.1016/j.dche.2023.100103

Ameh, V. I., Ayeleru, O. O., Nomngongo, P. N., & Ramatsa, I. M. (2024). Bio-oil production from waste plant seeds biomass as pyrolytic lignocellulosic feedstock and its improvement for energy potential: A review. *Waste Management Bulletin*, *2*(2), 32–48. https://doi.org/10.1016/j.wmb.2024.03.002

Ansari, K. B., Arora, J. S., Chew, J. W., Dauenhauer, P. J., & Mushrif, S. H. (2019). Fast pyrolysis of cellulose, hemicellulose, and lignin: Effect of operating temperature on bio-oil yield and composition and insights into the intrinsic pyrolysis chemistry. *Industrial and Engineering Chemistry Research*, *58*(35), 15838–15852. https://doi.org/10.1021/acs.iecr.9b00920

Arregi, A., Santamaria, L., Lopez, G., Olazar, M., Bilbao, J., Artetxe, M., & Amutio, M. (2023). Appraisal of agroforestry biomass wastes for hydrogen production by an integrated process of fast pyrolysis and in line steam reforming. *Journal of Environmental Management*, *347*, Article 119071. https://doi.org/10.1016/j.jenvman.2023.119071

Bieniek, A., Sieradzka, M., Jerzak, W., & Magdziarz, A. (2023). Fast pyrolysis of agricultural biomass in drop tube reactor for bio-oil production: Numerical calculations. *Journal of Analytical and Applied Pyrolysis*, *176*, Article 106241. https://doi.org/10.1016/j.jaap.2023.106241

Chan, E. W. C., Wong, S. K., Chan, H. T., Baba, S., & Kezuka, M. (2016). Cerbera are coastal trees with promising anticancer properties but lethal toxicity: A short review. *Journal of Chinese Pharmaceutical Sciences*, *25*(3), 161–169. https://doi.org/10.5246/jcps.2016.03.019

Chen, D., Cen, K., Zhuang, X., Gan, Z., Zhou, J., Zhang, Y., & Zhang, H. (2022). Insight into biomass pyrolysis mechanism based on cellulose, hemicellulose, and lignin: Evolution of volatiles and kinetics, elucidation of reaction pathways, and characterization of gas, biochar and bio-oil. *Combustion and Flame*, *242*, Article 112142. https://doi.org/10.1016/j.combustflame.2022.112142

Clemente-Castro, S., Palma, A., Ruiz-Montoya, M., Giráldez, I., & Díaz, M. J. (2023). Comparative study of the combustion, pyrolysis and gasification processes of *Leucaena leucocephala*: Kinetics and gases obtained. *Heliyon*, *9*(7), Article e17943. https://doi.org/10.1016/j.heliyon.2023.e17943

Corbita, J. N., Pabilona, L., & Villanueva, E. (2024). Energy audit on two 22-TPH coal-fired boilers of a pineapple processing plant. *Pertanika Journal of Science and Technology*, *32*(4), 1919–1937. https://doi.org/10.47836/pjst.32.4.25

Eraslan, U., & Calhan, R. (2024). Investigation of the performance and emissions of a diesel engine fuelled with bio-oil generated through microwave-assisted pyrolysis of a blend of hazelnut, walnut, and polyethylene terephthalate waste. *Industrial Crops and Products*, *214*, Article 118560. https://doi.org/10.1016/j.indcrop.2024.118560

Ferdous, J., Hossain, M. S., Rahman, M. S., Kader, M. A., & Islam, M. R. (2024). Experimental investigation of optimum bio-oil production parameters through co-pyrolysis of three organic wastes. *Journal of Analytical and Applied Pyrolysis*, *177*, Article 106308. https://doi.org/10.1016/j.jaap.2023.106308

Folgueras, M. B., Gómez-Martín, J. M., & Diez, M. A. (2023). How height-related variations in hybrid poplars affect composition and pyrolytic behaviour: The key role of lignin maturity during woody-biomass pyrolysis. *Journal of Analytical and Applied Pyrolysis*, *169*, Article 105861. https://doi.org/10.1016/j.jaap.2023.105861

Gao, G., Zhang, S., Shao, Y., Li, C., Zhang, L., Gao, W., Ding, K., Huang, Y., Gholizadeh, M., & Hu, X. (2024). Oxidative pyrolysis of spirulina: Impacts of oxygen on bio-oil and property of biochar. *Journal of Environmental Chemical Engineering*, *12*(3), Article 112506. https://doi.org/10.1016/j.jece.2024.112506

Ge, Y., Ding, S., Zhang, W., Kong, X., & Kantarelis, E. (2023). Impacts of fresh bed materials on alkali release and fuel conversion rate during wood pyrolysis and char gasification. *Fuel*, *353*, Article 129161. https://doi.org/10.1016/j.fuel.2023.129161

Hasanzadeh, A., Mehrara, M., Irani, M., Chitsaz, A., & Parham, K. (2023). An innovative biomass-fueled gas turbine-ORC system equipped with electrochemically mediated amine regeneration (EMAR) for CO_2 capture. *Journal of CO2 Utilization*, *68*, Article 102365. https://doi.org/10.1016/j.jcou.2022.102365

Kadhem, A. A., & Wahab, N. I. A. (2024). Effects of unavailability of conventional energy units on power generation system adequacy. *Pertanika Journal of Science and Technology*, *32*(4), 1687–1706. https://doi.org/10.47836/pjst.32.4.13

Khan, A. A., Zaidi, S., Qureshi, F., Yusuf, M., Al-Kahtani, A. A., Kamyab, H., Gupta, M., Pandit, B., Gill, H. S., & Ibrahim, H. (2024). Response surface optimization and support vector regression modeling of microwave-assisted essential oil extraction from cumin seeds. *Industrial Crops and Products*, *208*, 1–9. https://doi.org/10.1016/j.indcrop.2023.117895

Letoffet, A., Campion, N., Böhme, M., Jensen, C. D., Ahrenfeldt, J., & Clausen, L. R. (2024). Techno-economic assessment of upgraded pyrolysis bio-oils for future marine fuels. *Energy Conversion and Management*, *306*, Article 118225. https://doi.org/10.1016/j.enconman.2024.118225

Mahakhant, A., Attanatho, L., & Suemanotham, A. (2021). Thermal decomposition of biomass wastes derived from palm oil production. *Journal of Analytical and Applied Pyrolysis, 155*, Article 105069. https://doi.org/10.1016/j.jaap.2021.105069

Melikoglu, M., Ozdemir, M., & Ates, M. (2023). Pyrolysis kinetics, physicochemical characteristics and thermal decomposition behavior of agricultural wastes using thermogravimetric analysis. *Energy Nexus, 11*, Article 100231. https://doi.org/10.1016/j.nexus.2023.100231

Mossa, M. A., Hairuddin, A. A., Aziz, N. A., & Tobib, H. M. (2024). The green energy effect on an HCCI engine from used cookinoil-based biodiesel from Malaysia. *Pertanika Journal of Science and Technology*, *32*(4), 1565–1589. https://doi.org/10.47836/pjst.32.4.07

Niksa, S. (2022a). On the primary devolatilization of hemicellulose. *Journal of Analytical and Applied Pyrolysis*, *164*, Article 105515. https://doi.org/10.1016/j.jaap.2022.105515

Niksa, S. (2022b). Predicting the rapid devolatilization of mineral-free cellulose. *Journal of Analytical and Applied Pyrolysis*, *161*, Article 105402. https://doi.org/10.1016/j.jaap.2021.105402

Noor, M. F., Sumarlan, S. H., Hendrawan, Y., Argo, B. D., & Abdillah, H. (2025). Implementation and analysis of temperature and gas sensor datalogger in multi-stage condenser pyrolysis. *Indonesian Journal of Electrical Engineering and Computer Science, 37*(3), 1497–1505. https://doi.org/10.11591/ijeecs.v37.i3.pp1497-1505

Onwudili, J. A., Sharma, V., Scaldaferri, C. A., & Hossain, A. K. (2023). Production of upgraded fuel blend from fast pyrolysis bio-oil and organic solvent using a novel three-stage catalytic process and its combustion characteristics in a diesel engine. *Fuel*, *335*, Article 127028. https://doi.org/10.1016/j.fuel.2022.127028

Parthasarathy, P., Zuhara, S., Al-Ansari, T., & McKay, G. (2023). A review on catalytic CO_2 pyrolysis of organic wastes to high-value products. *Fuel*, *335*, Article 127073. https://doi.org/10.1016/j.fuel.2022.127073

Parvej, A. M., Rahman, M. A., & Reza, K. A. (2022). The combined effect of solar assisted torrefaction and pyrolysis on the production of valuable chemicals obtained from water hyacinth biomass. *Cleaner Waste Systems*, *3*, Article 100027. https://doi.org/10.1016/j.clwas.2022.100027

Poomsawat, W., & Poomsawat, S. (2023). Pyrolysis kinetic behavior of composite polypropylene-biomass solid fuels derived via co-hydrothermal carbonization process. *Thermal Science and Engineering Progress*, *43*, Article 101953. https://doi.org/10.1016/j.tsep.2023.101953

Rajpoot, L., Tagade, A., Deshpande, G., Verma, K., Geed, S. R., Patle, D. S., & Sawarkar, A. N. (2022). An overview of pyrolysis of de-oiled cakes for the production of biochar, bio-oil, and pyro-gas: Current status, challenges, and future perspective. *Bioresource Technology Reports*, *19*, Article 101205. https://doi.org/10.1016/j.biteb.2022.101205

Richa, L., Colin, B., Pétrissans, A., & Wallace, C. (2023). Catalytic and char-promoting effects of potassium on lignocellulosic biomass torrefaction and pyrolysis. *Environmental Technology & Innovation*, *31*, Article 103193. https://doi.org/10.1016/j.eti.2023.103193

Rony, Z. I., Rasul, M. G., Jahirul, M. I., & Hasan, M. M. (2025). Properties of pyrolysis oils derived from different organic wastes for assessing their suitability for engine fuel. *Energy Conversion and Management: X*, *25*, Article 100875. https://doi.org/10.1016/j.ecmx.2025.100875

Rosalina, R., Henny, R., Lestari, P. S., Tedja, T., Etty, R., & Sugiarti, S. (2018). The influence of phosphoric acid activation of carbon from Bintaro fruit (Cerbera odollam Gaertn) on the adsorption of chromium in various conditions of pH. *International Journal of Chemical Studies, 6*(1), 443–448.

Roy, D. K., & Abedin, M. Z. (2022). Potentiality of biodiesel and bioethanol production from feedstock in Bangladesh: A review. *Heliyon*, *8*(11), Article e11213. https://doi.org/10.1016/j.heliyon.2022.e11213

Selvarajoo, A., & Oochit, D. (2020). Effect of pyrolysis temperature on product yields of palm fibre and its biochar characteristics. *Materials Science for Energy Technologies*, *3*, 575–583. https://doi.org/10.1016/j.mset.2020.06.003

Seo, J. C., Lee, J. G., Kang, S. H., & Kwon, C. Y. (2023). Suicidal use of East Asian traditional herbal medicine: A systematic review of observational studies and implications for regulation. *European Journal of Integrative Medicine*, *62*, Article 102276. https://doi.org/10.1016/j.eujim.2023.102276

Sierra, I., Ayastuy, J. L., Gutiérrez-Ortiz, M. A., & Iriarte-Velasco, U. (2023). A study on the impact of the reaction mechanism of the thermochemical activation of bone char (by pyrolysis and carbonization). *Journal of Analytical and Applied Pyrolysis*, *171*, Article 105973. https://doi.org/10.1016/j.jaap.2023.105973

Soldatos, P., Margellou, A., Pappa, C., Torofias, S., Matsakas, L., Rova, U., Christakopoulos, P., & Triantafyllidis, K. (2024). Conversion of beechwood organosolv lignin via fast pyrolysis and *in situ* catalytic upgrading towards aromatic and phenolic-rich bio-oil. *Sustainable Chemistry for the Environment*, *6*, Article 100107. https://doi.org/10.1016/j.scenv.2024.100107

Suprianto, T., Winarto, Wijayanti, W., & Wardana, I. N. G. (2021). Synergistic effect of curcumin and activated carbon catalyst enhancing hydrogen production from biomass pyrolysis. *International Journal of Hydrogen Energy*, *46*(10), 7147–7164. https://doi.org/10.1016/j.ijhydene.2020.11.211

Syuriadi, A., Siswantara, A. I., Nurhakim, F. R., Irbah, Y. N., Al Rizky, B., Zulfa, F. A., Devitra, F. A., Permana, S., & Susanto, I. (2022). Analysis of the effect of biomass variants (fish waste, tamanu waste and duckweed) on the characteristics of syngas, bio oil, and carbon charcoal produced in the pyrolysis process. *Eastern-European Journal of Enterprise Technologies*, *3*(6(117)), 41–46. https://doi.org/10.15587/1729-4061.2022.253750

Szufa, S., Piersa, P., Junga, R., Błaszczuk, A., Modliński, N., Sobek, S., Marczak-Grzesik, M., Adrian, & Dzikuć, M. (2023). Numerical modeling of the co-firing process of an in situ steam-torrefied biomass with coal in a 230 MW industrial-scale boiler. *Energy*, *263*, Article 125918. https://doi.org/10.1016/j.energy.2022.125918

Usino, D. O., Ylitervo, P., Moreno, A., Sipponen, M. H., & Richards, T. (2021). Primary interactions of biomass components during fast pyrolysis. *Journal of Analytical and Applied Pyrolysis*, *159*, Article 105297. https://doi.org/10.1016/j.jaap.2021.105297

Vanapalli, K. R., Bhattacharya, J., Samal, B., Chandra, S., Medha, I., & Dubey, B. K. (2021). Single-use LDPE - Eucalyptus biomass char composite produced from co-pyrolysis has the properties to improve the soil quality. *Process Safety and Environmental Protection*, *149*, 185–198. https://doi.org/10.1016/j.psep.2020.10.051

Wahyudi, D., Wignyanto, Hendrawan, Y., & Hamidi, N. (2024). Bernoulli distillation system (BDS) for bioethanol sorghum stalk purification. *Pertanika Journal of Science and Technology, 32*(6), 2421–2440. https://doi.org/10.47836/pjst.32.6.02

Wang, L., Olsen, M. N. P., Moni, C., Dieguez-alonso, A., Rosa, D., Stenr, M., Liu, X., & Mao, L. (2022). Comparison of properties of biochar produced from different types of lignocellulosic biomass by slow pyrolysis at 600 ◦C. *Applications in Energy and Combustion Science, 12*, Article 100090. https://doi.org/10.1016/j.jaecs.2022.100090

Wang, W., Lemaire, R., Bensakhria, A., & Luart, D. (2022). Review on the catalytic effects of alkali and alkaline earth metals (AAEMs) including sodium, potassium, calcium and magnesium on the pyrolysis of lignocellulosic biomass and on the co-pyrolysis of coal with biomass. *Journal of Analytical and Applied Pyrolysis*, *163*, Article 105479. https://doi.org/10.1016/j.jaap.2022.105479

Ward, J., Rasul, M. G., & Bhuiya, M. M. K. (2014). Energy recovery from biomass by fast pyrolysis. *Procedia Engineering*, *90*, 669–674. https://doi.org/10.1016/j.proeng.2014.11.791

Wijayanti, W., Musyaroh, Sasongko, M. N., Kusumastuti, R., & Sasmoko. (2021). Modelling analysis of pyrolysis process with thermal effects by using Comsol Multiphysics. *Case Studies in Thermal Engineering*, *28*, Article 101625. https://doi.org/10.1016/j.csite.2021.101625

Wu, Y., Gui, Q., Zhang, H., Li, H., Li, B., Liu, M., Chen, Y., Zhang, S., Yang, H., & Chen, H. (2023). Effect of biomass components' interaction on the pyrolysis reaction kinetics and small-molecule product release characteristics. *Journal of Analytical and Applied Pyrolysis*, *173*, Article 106039. https://doi.org/10.1016/j.jaap.2023.106039

Zhang, C., Xiong, Y., Liu, Q., Wang, X., Syed-Hassan, S. S. A., Deng, W., Xu, K., Wang, Y., Hu, S., & Xiang, J. (2024). Effects of Interactions among cellulose, hemicellulose, and lignin on the formation of heavy components in bio-oil during oxidative pyrolysis. *Energy and Fuels, 38*(21), 20831-20838. https://doi.org/10.1021/acs.energyfuels.4c04330

Zhang, H., Liu, M., Yang, Y., Chen, W., Zhu, J., Zhang, S., Yang, H., Chen, H., & Chen, Y. (2023). Mechanism study on the interaction between holocellulose and lignin during secondary pyrolysis of biomass: In terms of molecular model compounds. *Fuel Processing Technology*, *244*, Article 107701. https://doi.org/10.1016/j.fuproc.2023.107701