

HYDROGEN AND METHANE GAS CONTENT IN SYNGAS FROM THE PYROLYSIS OF MELALEUCA CAJUPUTI AND SHOREA WOOD

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Abstract

The increasing demand for energy and the depletion of fossil energy supplies require research to find renewable energy sources. Biomass is one of the most promising renewable energy sources. Melaleuca cajuputi and Shorea leprosula are two types of wood plants that are widely available in Indonesia. This study aims to explore the potential of biomass derived from these plants, Melaleuca Cajuputi being a swamp-growing plant and Shorea being a land-growing plant, through a gasification process to produce syngas containing hydrogen and methane gases. The pyrolysis of Melaleuca cajuputi and Shorea sawdust was conducted using a fixed bed reactor at temperatures ranging from 200°C to 450°C, with a heating rate of 10°C/minute for a duration of one hour. The hydrogen and methane gases produced from the pyrolysis process were analyzed to determine the syngas characteristics. Additionally, an FTIR test was performed to provide further support for the experimental analysis. The experimental results demonstrate that Melaleuca Cajuputi wood exhibits stronger hydrogen bonds compared to Shorea wood. Consequently, Shorea wood generates hydrogen gas at lower temperatures and produces a greater quantity of methane gas. The peak hydrogen gas content was observed in Melaleuca Cajuputi and Shorea woods at temperatures of 315°C, with concentrations of 1746 ppm and 1503 ppm, respectively. On the other hand, the highest methane gas content was recorded in Shorea and Melaleuca Cajuputi woods at temperatures of 370°C and 318°C, respectively, with concentrations of 200,000 ppm and 63,200 ppm. The intensity of functional groups in biomass has a significant impact on the gas produced during pyrolysis.

Keywords: Biomass; Gasification; Hydrogen; Methane; Pyrolysis

Introduction

Fossil fuels have limited availability and are depleted. The problem of environmental pollution is also a concern associated with their utilization. Excessive use of fossil fuels contributes to global warming. Therefore, research is necessary to explore alternative fuel sources other than fossils. Biomass is one such abundant and renewable energy

source. Biomass energy currently plays a vital role in fulfilling energy and fuel demands due to its renewable and carbon-neutral characteristics. Biomass energy can be obtained through the gasification/pyrolysis process. In biomass thermal conversion technology, pyrolysis/gasification is an effective method for producing syngas (synthetic

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gas, $H_2 + CO$) that can be utilized for heating, generating synthetic chemicals, and producing liquid fuels. This technology has promising prospects for further utilization and development.

Hydrogen can be produced through various methods, including biochemical and thermochemical processes. Thermochemical processes encompass pyrolysis, gasification, hydrolysis, and liquefaction. Among these processes, biomass gasification is a viable method for hydrogen production. Recently, there has been exploration of biomass pyrolysis as a means to generate hydrogen. The production of hydrogen from biomass through gasification and pyrolysis processes demonstrates economic viability and is expected to compete with future technologies (Taipabu *et al.*, 2022; Vuppaladadiyam *et al.*, 2022).

Pyrolysis of biomass is one of the conversion processes carried out thermochemically to decompose biomass at a temperature of 650-800 K at 0.1-0.5 MPa in the absence of air to produce liquid oils, solid charcoal, and gaseous compounds (Vuppaladadiyam *et al.*, 2022). Pyrolysis is an endothermic reaction that is influenced by the composition of the biomass feedstock and the desired distribution of solid, liquid, and gaseous products (Hoang *et al.*, 2021). The conditions of the pyrolysis process such as temperature, heating rate, pressure and residence time, as well as the quality and composition of the biomass feedstock, strongly influence the distribution of output yield and physicochemical properties of the final product (Tripathi *et al.*, 2016). The results of the analysis show the presence of various gases such as H_2 , CH_4 , CO_2 , CO and C_2H_4 in different proportions.

In favor of gaseous products especially in hydrogen production, high temperature, high heating rate and long volatile phase residence time are required (Demirbaş, 2002; Tian *et al.*, 2017). The major light gas species for both the slow and fast pyrolysis experiments (wt% basis) were CO , CO_2 , CH_4 , and H_2 (Safdari *et al.*, 2019). Syngas content is mainly affected by reactor temperature and moisture content in the biomass. Syngas composition varies with increasing temperature. At a temperature of 400°C, a higher concentration of hydrogen is present, with the following composition: CH_4 (methane) 39.1%, H_2 (hydrogen) 28.2%, CO (carbon monoxide) 21.9%, and smaller quantities of other gases (Ramalingam *et al.*, 2022). Syngas from pyrolysis is also affected by wood components. In addition, the higher the lignin content, the higher the yield of H_2 in the gasification process (Yang *et al.*, 2007). The higher the hydrogen and methane gas content in the syngas, the higher the specific energy of the syngas (Suprianto *et al.*, 2020).

Lignocellulosic biomass is plant-origin biomass that can be classified into the following four categories: hardwood, softwood, agricultural waste, and grass. Cellulose, hemicellulose, and lignin are the three main components of lignocellulosic biomass. Cellulose and hemicellulose are carbohydrates. Among the significant components of biomass, lignin is not a carbohydrate and is the most stubborn constituent of plant cell walls where a natural barrier is formed to protect plant cells from chemical and enzymatic degradation. It plays an important role in linking the other two components and preventing the penetration of other solutions or enzymes (Bichot *et al.*, 2018). Lignin is a three-dimensional polymer containing phenolic groups with cross-linking and structural design that gives structural integrity and rigidity to plant cell walls. (Philippidis, 2018)

Cellulose, lignin, and hemicellulose are three types of plant elements that greatly affect the results of pyrolysis. Different plant varieties will produce different amounts of these elements, which can lead to large differences in the product yields of pyrolysis from different plants (Bourguignon *et al.*, 2017). The varieties of plants have a significant impact on the final product they produce. This is because the plants biomass consists of different elements depending on the soil, cultivation, and climate conditions (Hoang *et al.*, 2021). The type of biomass affects the distribution and arrangement of the phenolic hydroxyl groups.

In softwood lignin, there is a guaiacyl phenolic hydroxyl group unit. Meanwhile, the main content of hardwood lignin sequentially is the aliphatic hydroxyl group, followed by guaiacyl phenolic, syringyl phenolic, and p-hydroxyphenyl. In general, the type of lignin affects the final phenolic pyrolysis product, and the distribution of phenolic hydroxyl groups (Hua *et al.*, 2016). Lignin also contains oxygen-containing groups, specifically carboxyl and carbonyl groups. The structure of lignin has a high degree of complexity and relates to other elements found in organic plant materials.

Pyrolysis of hemicellulose between softwood, hardwood and straw biomass produces different products. Hemicellulose derived from hardwoods and straw yield large amounts of acids and furfurals, as well as five-carbon compounds. Whereas the pyrolysis of hemicellulose of softwood produces many six-carbon compounds. Lignin's reactivity is influenced by oxygen-containing functional groups found in lignin (e.g., carboxyl, carbonyl, hydroxyl, and methoxyl groups). Softwood has a lower number of methoxyl groups that can be found in hardwood (Li *et al.*, 2015).

In the case of softwoods, the main components of hemicellulose are polysaccharides.

Hemicellulose, on the other hand, is hardwood, consisting mainly of (4-O-methyl-D-glucurono-D)-xylan, as well as O-acetyl groups and high levels of uronic acid. Hexose and xylose are two types of monosaccharides found in softwood hemicellulose and hardwood hemicellulose. The maximum temperature attained in the pyrolysis of hemicellulose of softwood is about 310°C and appears to be the highest among those occurring in the pyrolysis of hemicellulose of hardwood and straw. Softwood hemicellulose has higher thermal stability (Wang *et al.*, 2005).

The pyrolysis of hardwood hemicellulose results in a higher yield of charcoal, approximately 33% by weight. Meanwhile, softwood hemicellulose produces 25-30% by weight. The number of pentose units that have more side branches results in an increase in the structural complexity of hemicellulose. This causes the process of breaking glycosidic linkages in this high-structure hemicellulose to form many radicals with large molecular weights. This radical will then be converted into char when it undergoes polymerization (Wang *et al.*, 2015).

Among the raw materials for biomass, *Melaleuca cajuputi* subsp. *Cumingiana* wood and *Shorea leprosula* are types of wood that are abundantly available in Kalimantan and Sumatra, which are the largest islands in Indonesia. One of the characteristics of *Melaleuca cajuputi* wood is that it grows in swampy areas, while *Shorea* wood primarily grows in terrestrial or land areas (Figure 1). With this difference, of course, the characteristics of the gas produced by *Melaleuca cajuputi* wood will be different from the type of *Shorea* wood.

Melaleuca cajuputi grows in swamps, but not like a mangrove tree, which has many roots spreading into the water. The wood of *Melaleuca cajuputi* is very resistant to the acid soils found in

swamps. The trunk of this tree also exhibits a characteristic white color, and the old bark appears to peel off. *Melaleuca Cajuputi* has a very wide distribution and is very easy to find at swamps area in Sumatra and Kalimantan with tree heights ranging from 10-20 m (Hartini, 2011). The production of *Melaleuca Cajuputi* wood in 2017 was 12,128.47 m³/year. This wood is a type of hardwood, so it is often used as a support for buildings, construction, firewood, briquettes, and sawn timber (Hayati *et al.*, 2021).

Shorea is a type of light hardwood that comes from the *Shorea* family of the Dipterocarpaceae. In Indonesia, particularly in Kalimantan, *Shorea leprosula* is one of the tree species that holds significant importance in the global timber trade. *Shorea* wood is a primary commodity used in the production of interior furnishings, carvings, and household furniture. The furniture manufacturing process can generate up to 44 % of wood waste. (Tajalla *et al.*, 2019).

Pyrolysis technology offers efficient socio-economic advantages when compared to other thermo-chemical conversion technologies. However, this technology is still in the process of being fully developed and implemented in commercial applications. Further studies are needed to achieve a better understanding of the economics of biomass pyrolysis for biofuels and hydrogen production (Taipabu *et al.*, 2022). One of the disadvantages of biomass conversion through thermochemical methods, such as gasification and pyrolysis, is the high energy consumption required for the conversion process. (Vaidya and Lopez-Sanchez, 2017). Therefore, research is needed to find a method so that the energy needed to produce hydrogen from biomass can be lower. This research uses raw material of biomass waste in the form of sawdust to determine the characteristics of hydrogen gas production and methane gas produced during



(a)



(b)

Figure 1. a. *Melaleuca Cajuputi* forest, b. *Shorea* forest

the pyrolysis process. By understanding the production characteristics of hydrogen gas and methane gas, it is possible to identify the optimal temperature for their generation through the thermochemical process of biomass. This information can help determine the optimal conditions or heat required for biomass to undergo efficient conversion into hydrogen gas and methane., especially Shorea and Melaleuca Cajuputi sawdust waste.

In this study, the pyrolysis process was used to produce syngas from sawdust from Shorea and Melaleuca Cajuputi wood. Research on Melaleuca Cajuputi and Shorea wood as alternative energy has been carried out as a briquette material, but as far as the author knows, research that discusses the quality of the gas produced by gasification of Melaleuca Cajuputi wood has never been done. Additionally, comparative studies have not been conducted between wood species that grow in swamps and those that grow in dry land. Therefore, it is essential to conduct research to explore the potential of Melaleuca cajuputi wood and Shorea wood as alternative energy sources, particularly for the production of syngas, which contains hydrogen gas

and methane through the gasification process. This study aims to determine the characteristics of syngas produced from wood species that grow in swamps and wood species that grow on land. By comparing the properties and composition of the syngas derived from these different wood sources, valuable insights can be gained regarding their suitability as alternative energy sources. Syngas characteristics can be observed through the hydrogen and methane content in the syngas produced during the pyrolysis process of Shorea and Melaleuca Cajuputi wood.

Materials and Methods

Material

The raw materials used in this research were *Melaleuca cajuputi subsp. cumingiana* and *Shorea leprosula* obtained from South Kalimantan, Indonesia. Both types of wood were processed into sawdust with an average particle size of 40 mesh. The sawdust was further dried using solar heat to achieve a moisture content of less than 30%. The composition of the materials used in the study is as follows: (Table 1.)

Experimental setup and procedure

This research was conducted using a fixed-bed reactor (Figure 2). The pyrolysis reactor is made of stainless steel with a diameter of 10 cm and a height of 24 cm. 20 g biomass was placed in the center of the reactor in an aluminum container.

The reactor is heated using fire from LPG (Liquefied Petroleum Gas) by maintaining a constant flame until the temperature reaches 450°C.

The gas produced from the pyrolysis reactor flowed into an ice bath to condense the gas or water vapor. The temperature of the ice bath is maintained within the range of 0-3°C. The condensable gases will condense in the ice bath, while lighter gases such as hydrogen or methane will escape from the ice bath. The gas exits through the cylinder outlet. MQ-8 and MQ-4 sensors are installed at the outlet to detect the concentration of hydrogen and methane gases, which are measured in parts per million (ppm). Type K thermocouple is used to measure the temperature inside the reactor during the pyrolysis process. Data from sensors is recorded in real-time.

The rate of hydrogen and methane production is measured based on the rate of increase or decrease in the measured gas concentrations in ppm/s. A positive production rate indicates an increase in concentration, while a negative rate indicates a decrease in gas concentration.

In terms of heating rate, pyrolysis can be divided into three types as shown in Table 2 (Durak and Aysu, 2014). This research was conducted using

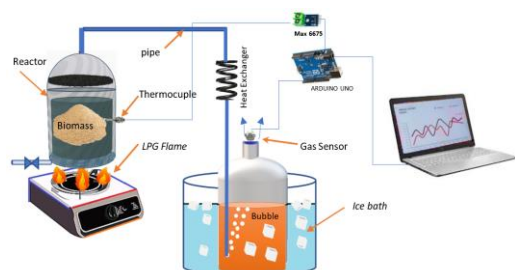


Figure 2. Pyrolyzer fixed bed reactor. Taken from (Suprianto *et al.*, 2020)

Table 1. Chemical components of *Melaleuca Cajuputi* and *Shorea wood*, (Supartini, 2009; Yunanta *et al.*, 2014; Haryati *et al.*, 2017)

Component	Melaleuca Cajuputi (%)	Shorea lerosula (%)
cellulose	47.00	63,97
hemicellulose	27.42	13,37
lignin	18.28	29,39
ash content	1.33	1.4
density (kg/lt)	0.82	0.67

Table 2. Pyrolysis type

Pyro- lysis type	Heating rate (°C s ⁻¹)	Temp. (°C)	Residence Time
Flash	> 1000	500-900	1 s
Fast	1-100	500-900	10-20 s
Slow	0.1-1	300-500	> 30 min

the slow pyrolysis method at temperatures up to 450°C.

Results and Discussion

Based on the conducted experiments, the concentrations of hydrogen and methane in the syngas gas, measured in parts per million (ppm), are presented in Figures 3 and 4, respectively. Figures 5 and 6 illustrate the hydrogen production rate, while Figures 7 and 8 represent the methane gas production rate.

The pyrolysis of *Melaleuca cajuputi* wood results in a two-fold increase in the peak hydrogen concentration, as shown in Figure 3. The first peak is observed at a temperature of 315°C, with a concentration of 1732 ppm, while the second peak occurs at a temperature of 408°C, with a concentration of 1281 ppm. From the perspective of production rate, Figure 6 shows that the production of hydrogen from *Melaleuca cajuputi* wood exhibits two peaks. The first peak occurs at a temperature of 250°C with a rate of 35 ppm/s, while the second peak occurs at a temperature of 402°C.

The high concentration of hydrogen that occurs at a temperature of 315°C can be caused by the decomposition of hemicellulose. While the second

peak at a temperature of 408°C occurs due to the decomposition of cellulose. Hemicellulose decomposition occurs at 220-315°C. While cellulose takes place in the temperature range of 315-400°C. Lignin decomposition occurs slowly between 300-900°C (Yang *et al.*, 2007).

Slightly different from the results of *Melaleuca cajuputi* wood, the concentration of hydrogen gas from *Shorea* wood exhibits a lower peak, 300°C, with a concentration of 1400 ppm.

However, the hydrogen production is already high at a temperature of 230°C. From Figure 5, it can be seen that the hydrogen production rate in the pyrolysis of *Shorea* wood reaches its peak at 230°C, with a rate of 52 ppm/second. Both the peak concentration and peak production rate of hydrogen occur at lower temperatures.

The difference in hydrogen formation temperatures indicates that hydrogen production in *Shorea* wood is primarily attributed to the decomposition of hemicellulose, while in *Melaleuca Cajuputi* wood, it involves the decomposition of both hemicellulose and cellulose. As a hardwood, *Melaleuca Cajuputi* shows a higher yield of hydrogen compared to *Shorea*, which is a light hardwood.

Melaleuca Cajuputi and *Shorea* wood exhibit significant differences in the composition of lignin

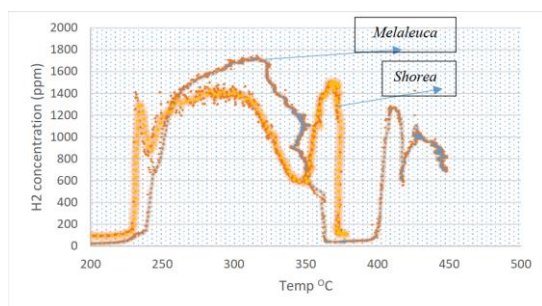


Figure 3. The concentration of hydrogen produced during the pyrolysis process

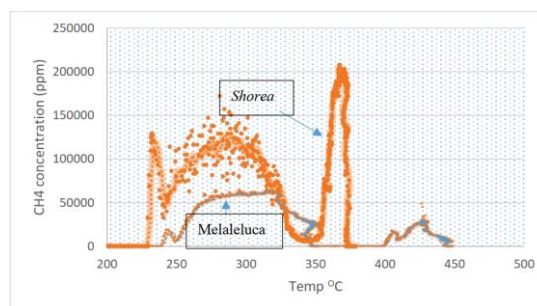


Figure 4. The concentration of methane produced during the pyrolysis process

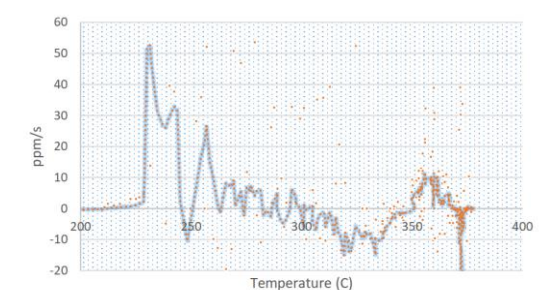


Figure 5. The concentration of hydrogen produced during the pyrolysis process

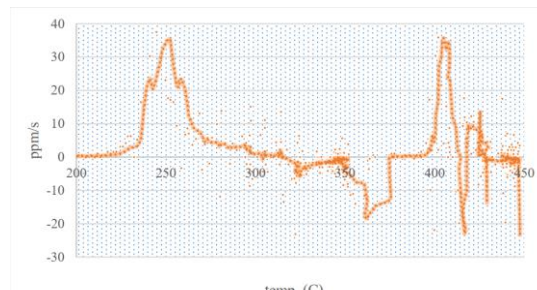


Figure 6. Hydrogen production rate on pyrolysis from *Melaleuca Cajuputi* wood

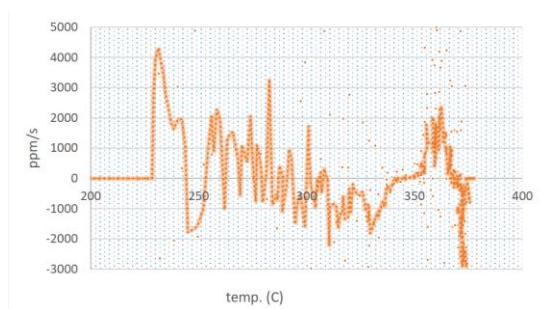


Figure 7. Methane production rate on pyrolysis from Shorea wood

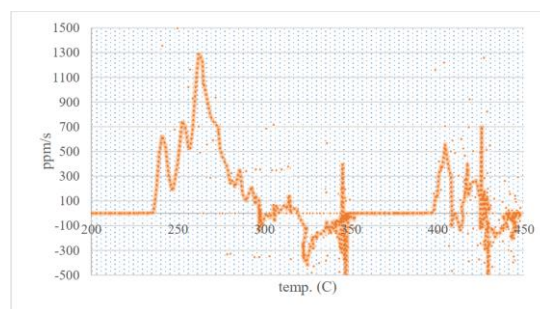


Figure 8. Methane production rate on pyrolysis from Melaleuca Cajuputi wood

and hemicellulose. This finding is consistent with previous studies that have reported variations in the products obtained from the pyrolysis of hemicellulose in different types of biomass, such as softwood and hardwood. (Hoang *et al.*, 2021).

Based on Figure 4, it can be observed that the concentration of methane follows a similar trend as the hydrogen gas production. The production of methane from *Melaleuca cajuputi* wood exhibits two peaks in methane gas concentration. The first peak occurs at a temperature of 318°C, with a concentration of 63,200 ppm, while the second peak is observed at a temperature of 426°C, with a concentration of 33,714 ppm. Figure 7 illustrates the methane production rate in *Melaleuca cajuputi* wood, with the highest peak occurring at a temperature of 264°C at a rate of 1290 ppm/s. This result differs from *Shorea* wood, which exhibits its peak methane production at a lower temperature of 231°C, with a rate of 4300 ppm/s (Figure 8).

Meanwhile, the production of methane gas from *Shorea* wood exhibits significantly higher peaks at lower temperatures. It reaches a concentration of 119,000 ppm at a temperature of 233°C, and 200,000 ppm at a temperature of 370°C. In terms of temperature, *Melaleuca cajuputi* wood produces methane at a higher temperature compared to *Shorea* wood, specifically at 318°C and 233°C, respectively. This trend is consistent with the hydrogen production discussed earlier. Additionally, the methane gas production rate in *Shorea* wood is highest at 230°C, with a rate of 4300 ppm/s.

Fluctuations in the rate of methane production occur due to differences in the decomposition temperature of the biomass components. Hemicellulose decomposition occurs at 220-315°C. The decomposition of cellulose occurs at a higher temperature range of 315-400°C while lignin is the most difficult to break down. Decomposition occurs slowly from 300-900°C.

At temperatures ranging from 300 to 395°C, the production rates of hydrogen and methane in

Melaleuca Cajuputi wood decrease and even become negative (Figure 6 and 8). The negative values indicate that the production rate of hydrogen is lower than the temperatures below it. From a temperature perspective, this range corresponds to the temperature at which cellulose undergoes decomposition. This suggests that the decomposition of cellulose results in a relatively low production of hydrogen. Similarly, when looking at Figures 5 and 8, the production rates of hydrogen and methane gases in *Shorea* wood also decrease within the temperature range of 300 to 350°C. However, the decrease is slightly lower compared to *Melaleuca Cajuputi* wood.

FTIR Analysis

The functional group analysis using Fourier-transformed infrared (FTIR) spectroscopy on the sample is shown in Figure 7. The wave numbers 3406, 2923, 2856, 1728, 1629, 1504, 1461, 1159, and 896 cm^{-1} show the O-H, C-H, C groups. =O, C=C, C-H, and C-O which indicated the presence of lignin, hemicellulose, and cellulose of *Melaleuca cajuputi* and *Shorea* wood.

When comparing the results of pyrolysis between *Melaleuca cajuputi* and *Shorea* wood, it can be observed that the production of hydrogen gas from *Melaleuca cajuputi* wood occurs at a higher temperature compared to *Shorea* wood. However, the amount of hydrogen gas produced is greater in the case of *Melaleuca cajuputi* wood. This indicates that *Melaleuca cajuputi* wood has a higher potential for hydrogen gas production compared to *Shorea* wood. The differences in hydrogen gas production between *Melaleuca Cajuputi* wood and *Shorea* wood can be attributed to variations in the intensity of certain chemical bonds present in the woods, such as O-H, C-H, C=O, C=C, C-H, and C-O bonds. From Figure 8, it can be observed that the FTIR transmittance of *Shorea* wood is lower. A lower FTIR transmittance indicates an increase in the intensity of infrared radiation absorbed by the material. This can be influenced by factors such as

an increasing dipole moment and an increase in the distance between atoms (Othman, 2023). When the distance between atoms is longer, the bond intensity in a material becomes weaker. With low intensity, the hydrogen bonds in *Shorea* wood molecules are weaker than wood so that lower decomposition temperature.

The production of methane gas was found to be higher in *Shorea* compared to *Melaleuca Cajuputi*. This observation suggests that *Melaleuca Cajuputi* primarily generates a greater amount of hydrogen gas, while the production of methane gas is relatively lower. In both slow and fast pyrolysis experiments, the major light gas species observed, based on weight percentage (wt%), included CO, CO₂, CH₄, and H₂. During the pyrolysis of *Melaleuca Cajuputi*, there is a higher production of hydrogen gas, which leads to a decrease in other constituents, including methane (CH₄). As a result, the overall amount of methane gas decreases. In contrast, in the pyrolysis process of *Shorea*, a smaller proportion of volatile gases is This study was conducted experimentally on a laboratory scale using a conventional slow pyrolysis technique. To achieve more optimal gas production, further research using fast and flash pyrolysis methods is needed. However, this study has demonstrated that the pyrolysis of *Melaleuca cajuputi* wood, which grows in swamp areas, results in a higher production of hydrogen gas compared to wood from land areas. On the other hand, *Shorea* wood produces a higher amount of methane gas compared to *Shorea* wood.

Conclusion

Based on the results of the study, it can be concluded as follows:

1. The highest concentrations of hydrogen and methane gases in the syngas from the slow pyrolysis of *Melaleuca cajuputi* wood occurred at two different temperatures. The highest concentration of hydrogen gas was observed at 318°C, while the highest concentration of methane gas occurred at 408°C.
2. The production of hydrogen gas from *Melaleuca cajuputi* wood occurs at a higher temperature compared to *Shorea* wood. However, the amount of hydrogen gas produced is greater in the case of *Melaleuca cajuputi* wood.

The intensity of functional groups in biomass affects the production of H₂ and CH₄. As the bond intensity weakens in the biomass, H₂ and CH₄ are formed at lower temperatures.

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References

- Bichot, A., Delgenès, J.P., Méchin, V., Carrère, H., Bernet, N., and García-Bernet, D. (2018). Understanding biomass recalcitrance in grasses for their efficient utilization as biorefinery feedstock. *Reviews in Environmental Science and Biotechnology*, 17(4):707-748. <https://doi.org/10.1007/s11157-018-9485-y>
- Bourguignon, M., Moore, K.J., Brown, R.C., Kim, K.H., Baldwin, B.S. and Hintz, R. (2017). Variety Trial and Pyrolysis Potential of Kenaf Grown in Midwest United States. *Bioenergy Research*, 10(1):36-49. <https://doi.org/10.1007/s12155-016-9773-8>
- Demirbaş, A. (2002). Gaseous products from biomass by pyrolysis and gasification: Effects of catalyst on hydrogen yield. *Energy Conversion and Management*, 43(7):897-909. [https://doi.org/10.1016/S0196-8904\(01\)00080-2](https://doi.org/10.1016/S0196-8904(01)00080-2)
- Durak, H. and Aysu, T. (2014). Effects of catalysts and solvents on liquefaction of *Onopordum heteracanthum* for production of bio-oils. *Bioresource Technology*. Elsevier Ltd, 166:309-317. <https://doi.org/10.1016/j.biortech.2014.05.051>
- Hartini, S. (2011). Jenis-Jenis Myrtaceae (Jambu-Jambuan) Berdaun Wangi Koleksi Kebun Raya Bogor. *Prosiding Seminar Nasional Hari Lingkungan Hidup*, 30-35.
- Haryati, S., Yulhan, A.T. and Asparia, L. (2017). Pembuatan Karbon Aktif dari Kulit Kayu Gelam (*Melaleuca leucadendron*) Yang Berasal dari Tanjung Api-Api Sumatera Selatan. *Teknik Kimia*, 23(2):77-86.
- Hayati, W.A., Erwin, N., Husien, N., Wahyuni, S., Wardhani, I.Y., and Budi, A.S. (2021). Patterns of Iron Stain on Gelam Wood (*Melaleuca cajuputi* Powell), *Proceedings of the Joint Symposium on Tropical Studies (JSTS-19)*, p. 11. <https://doi.org/10.2991/absr.k.210408.067>
- Hoang, A.T., Ong, H.C., Fattah, I.M.R., Chong, C.T., Cheng, C.K., Sakthivel, R., and Ok, Y.S. (2021). Progress on the lignocellulosic biomass pyrolysis for biofuel production toward environmental sustainability. *Fuel Processing Technology*, 223:106,997 <https://doi.org/10.1016/j.fuproc.2021.106997>
- Hua, W., Liu, C., Wu, S., and Li, X.H. (2016). Analysis of Structural Units and Their Influence on Thermal Degradation of Alkali Lignins., *BioResources*, 11(1):1,959-1,970. <https://doi.org/10.15376/biores.11.1.1959-1970>
- Li, C. Zhao, X., Wang, A., Huber, G. W., and Zhang, T. (2015). Catalytic Transformation of Lignin for the Production of Chemicals and Fuels., *Chemical Reviews*, 115(21):11,559-11,624. <https://doi.org/10.1021/acs.chemrev.5b00155>
- Othman, N. (2023). IR Spectroscopy in Qualitative and Quantitative Analysis. 1st Edition. *Infrared Spectroscopy - Perspectives and Applications*. <https://doi.org/10.5772/intechopen.106625>
- Philippidis, G.P. (2018). Cellulose Bioconversion Technology. 1st Edition. *Handbook on Bioethanol*, 253-285p. <https://doi.org/10.1201/9780203752456-12>

- Ramalingam, S., Subramanian, S., and Subramanian, A. (2022). Utilization of pyrolytic oil and hydrogen enriched syngas from single feedstock (delonix regia) through pyrolysis process and its influence on performance and emission characteristics in CI engine. *International Journal of Hydrogen Energy*, 47(87):36,749-36,762. <https://doi.org/10.1016/j.ijhydene.2022.08.262>
- Safdari, M.S., Amini, E., Weise, D.R., and Fletcher, T.H. (2019). Heating rate and temperature effects on pyrolysis products from live wildland fuels. *Fuel*, 242:295-304. <https://doi.org/10.1016/j.fuel.2019.01.040>
- Supartini, S. (2009). Komponen Kimia Kayu Meranti Kuning (Shorea Macrobalanos). *Journal Penelitian Dipterokarpa*, 3(1):43-50. <https://doi.org/10.20886/jped.2009.3.1.43-50>
- Suprianto, T., Wijayanti, W., and Wardana, I.N.G. (2020). Synergistic effect of curcumin and activated carbon catalyst enhancing hydrogen production from biomass pyrolysis. *International Journal of Hydrogen Energy*, 46(10):7,147-7,164. <https://doi.org/10.1016/j.ijhydene.2020.11.211>
- Taipabu, M.I., Viswanathan, K., Wu, W., Hattu, N., and Atabani, A.E. (2022). A critical review of the hydrogen production from biomass-based feedstocks: Challenge, solution, and future prospect. *Process Safety and Environmental Protection*, 164:384-407. <https://doi.org/10.1016/j.psep.2022.06.006>
- Tajalla, G.U.N., Humaira, S., Parmita, A.W.Y.P., and Zulfikar, A. (2019). Pembuatan dan Karakterisasi Selulosa dari Limbah Serbuk Meranti Kuning (Shorea macrobalanos). *Jurnal Sains Terapan*, 5(1):142-147. <https://doi.org/10.32487/jst.v5i2.704>
- Tian, T., Li, Q., He, Rong., Tan, Z., and Zhang, Y. (2017). Effects of biochemical composition on hydrogen production by biomass gasification. *International Journal of Hydrogen Energy*, 42(31):19,723-19,732. <https://doi.org/10.1016/j.ijhydene.2017.06.174>
- Tripathi, M., Sahu, J.N., and Ganesan, P. (2016). Effect of process parameters on production of biochar from biomass waste through pyrolysis: A review. *Renewable and Sustainable Energy Reviews*, 55:467-481. <https://doi.org/10.1016/j.rser.2015.10.122>
- Vaidya, P.D., and Lopez-Sanchez, J.A. (2017). Review of Hydrogen Production by Catalytic Aqueous-Phase Reforming. *ChemistrySelect*, 2(22):6,563-6,576. <https://doi.org/10.1002/slct.201700905>
- Vuppaladadiyam, A.K., Vuppaladadiyam, S.S.V., Awasthi, A., Sahoo, A., Rehman, S., Pant, K.K., Murugavelh, S., Huang, Q., Anthony, E., Fennel, P., Bhattacharya, S., and Leu, S.Y. (2022). Biomass pyrolysis: A review on recent advancements and green hydrogen production. *Bioresource Technology*, 364:128,087. <https://doi.org/10.1016/j.biortech.2022.128087>
- Wang, S., Ru Bin, Dal, G., Sun, W., Qiu, K., and Zhou, J. (2015). Pyrolysis mechanism study of minimally damaged hemicellulose polymers isolated from agricultural waste straw samples. *Bioresource Technology*, 190:211-218. <https://doi.org/10.1016/j.biortech.2015.04.098>
- Wang, S., Ru, B., Lin, H., and Sun, W. (2005). Pyrolysis behaviors of four O-acetyl-preserved hemicelluloses isolated from hardwoods and softwoods. *Fuel*, 150:243-251. doi: 10.1016/j.fuel.2015.02.045
- Yang, H., Yan, R., Chen, H., Lee, DH., and Zheng, C. (2007). Characteristics of hemicellulose, cellulose and lignin pyrolysis. *Fuel*, 86(12-13):1,781-1,788. <https://doi.org/10.1016/j.fuel.2006.12.013>
- Yunanta, R.R.K., Lukmandaru, G., and Fernandes, A. (2014). Chemical Properties of Shorea retusa, Shorea macroptera, and Shorea macrophylla Woods. *jurnal penelitian ekosistem dipterokarpa*, 8(1):15-24. <https://doi.org/10.20886/jped.2014.8.1.15-24>