JBAT 14(2) (2025) 59 – 66

Jurnal Bahan Alam Terbarukan

p-ISSN 2303 0623
e-ISSN 2407 2370

Accredited SINTA 3 by Ministry of Research and Technology/National Research and Innovation Agency
SK No. 10/C/C3/DT.05.00/2025
http://journal.unnes.ac.id/nju/index.php/jbat

Physical and Chemical Characteristics of Bio-Oil From Pyrolysis of Moringa Oleifera Seeds Using Microwave Technology

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DOI: https://doi.org/10.15294/jbat.v14i2.29284

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Article Info

Article history:
Received
1 July 2025
Revised
15 August 2025
Accepted
27 September 2025
Published
December 2025

Keywords:
Biomass;
Bio-oil;
Characteristics;
Moringa oleifera seeds;
Pyrolysis

Abstract

This research aims to assess the potential of bio-oil from Moringa oleifera seeds through the analysis of physical and chemical characteristics resulting from the pyrolysis process. Raw materials in the form of Moringa oleifera seed powder were pyrolyzed at 400°C using a microwave reactor. To create oxygen free pyrolysis conditions, nitrogen gas was constantly flowed into the system at a rate of 0.15 NL/min. The process temperature was monitored using a K-type thermocouple, and the reaction was stopped when condensed vapor output was no longer observed. The pyrolysis products in the form of bio-oil and bio-char were then collected and weighed to determine the product fraction. Furthermore, the bio-oil was analyzed to determine its physical and chemical properties, including density, pH, and an indication of its constituent compound components. The results showed that pyrolysis under these conditions produced a dominant amount of bio-char (54.3%) and bio-oil of 24.7% of the total weight. The bio-oil obtained had a high density, in the range of 0.97-1.00 g/cm³, with a relatively acidic pH of 4.5-5.5. Although the bio-oil yield is not high, its complex chemical properties, particularly the content of phenolic compounds, nitriles, and amides, show great potential to be developed as a valuable bio-chemical base material such as antioxidants, biophenols, resins, and bioplastic raw materials. These findings strengthen the prospect of Moringa oleifera seeds as a strategic local biomass for sustainable bioindustry.

INTRODUCTION

The global energy crisis has prompted countries to seek alternative solutions to dependence on fossil fuels (Logayah et al., 2023). Fossil fuels such as coal, oil and natural gas are not only non-renewable, but also a major contributor to carbon dioxide emissions that exacerbate global warming (Idroes et al., 2024). Long-term dependence on fossil energy leads to vulnerability to energy price fluctuations, supply limitations and significant environmental impacts. In this context, the development of alternative energy sources that are more environmentally friendly and sustainable is an urgent need (Anis, Lestari, et al., 2018).

Historically, biomass was one of the earliest energy sources used by humans before the fossil fuel era began (Guo et al., 2015). Biomass includes various types of organic materials such as agricultural waste, wood, leaves, grains, and crop residues. Apart from being an energy feedstock, biomass utilization also provides the added advantage of reducing the accumulation of organic waste and increasing the added value of agricultural waste. Therefore, using biomass as a renewable energy feedstock is not only a solution to the energy crisis, but also supports better environmental management (El-Fawal et al., 2025).

One promising energy conversion technology for biomass is pyrolysis. Pyrolysis is the

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process of thermal decomposition of organic matter under conditions of minimal or no oxygen, which produces three main products, namely bio-char (solid), bio-oil (liquid), and pyrolysis gas (Zhang et al., 2023). These three products have different use values according to their characteristics. Bio-char can be used as a solid fuel, carbon sink, or soil ameliorant. Meanwhile, bio-oil serves as a liquid fuel or base material for high-value chemical compounds, and pyrolysis gas can be utilized as heat energy (Awad et al., 2024). These three products have different use values according to their characteristics. Bio-char can be used as a solid fuel, carbon sink, or soil ameliorant. Meanwhile, bio-oil serves as a liquid fuel or base material for high-value chemical compounds, and pyrolysis gas can be utilized as heat energy (Handiso et al., 2024).

One of the biomasses that has high potential to be processed through pyrolysis is Moringa oleifera, also known as Moringa. This plant is known for its high resistance to various climatic conditions and thrives in tropical regions. Moringa oleifera seeds contain significant amounts of lipids and carbohydrates that can be converted into liquid fuels such as biodiesel and bio-oil (Sukarni et al., 2024). The seed oil content reaches 36.7% of dry weight, with a very high oleic acid composition (>70%), a cetane number of 67 (Leone et al., 2016), and a thermal stability of about 425–450ºC (Tulashie & Kotoka, 2022). In addition, the lipid content of Moringa oleifera seeds is also reported to be higher than other Moringa species, between 33.3–55.7% (Sukarni et al., 2024), which makes it a superior candidate in the development of renewable fuels.

Numerous studies have been conducted to develop biodiesel from Moringa oleifera seed oil, but attention to the bio-oil fraction from pyrolysis is still very limited. Ahmed (Ahmed, 2023) reported that pyrolysis of Moringa oleifera at 450°C produced bio-oil of 13 wt.% with a pH value of 4.38.

Although these results indicate the potential of bio-oil as a valuable by-product, there have not been many in-depth studies on the physical and chemical characteristics of Moringa oleifera bio-oil, especially in terms of density, pH stability, and the potential content of active compounds such as phenols, aromatics, and organic acids. In addition, most pyrolysis studies are conducted at high temperatures (≥450°C), which generally leads to the decomposition of complex chemical compounds into simpler components. In fact, pyrolysis at lower temperatures such as 400°C has the potential to produce more intact bioactive compounds, with lower energy requirements, making it more thermally efficient. Microwave-assisted pyrolysis technology also offers advantages in terms of heating efficiency and more even heat distribution compared to conventional methods (Anis, Kurniawan, et al., 2018).

Based on the above conditions, this study aims to evaluate the physical and chemical characteristics of bio-oil from pyrolysis of Moringa oleifera seeds at a temperature of 400°C using microwave pyrolysis technology. The focus of the research is directed at measuring density and pH, as well as initial interpretation of the potential chemical compounds contained in bio-oil. This research is important to complete the gap of previous research that still minimally explores Moringa oleifera bio-oil at low pyrolysis temperatures. In addition, the findings of this study are expected to open up opportunities for the utilization of bio-oil not only as fuel, but also as a source of bioactive compounds, such as antioxidants, natural resins, and bioplastic precursors, which are very relevant for sustainable tropical biomass-based industries.

MATERIALS AND METHOD

This research uses Moringa oleifera seeds as raw material. Before use, the raw materials were pulverized into powder, then dried in an oven at 60°C for 24 hours to remove the water content. After drying, the sample powder was sieved to obtain particles with a maximum size of 20 mesh.

The pyrolysis process was carried out using a microwave reactor with a frequency of 2.45 GHz as shown in Figure 1. The use of a microwave oven allows for more homogeneous and faster heating so that it is considered more efficient than conventional heating (Anis et al., 2021; Suyanto & Harahap, 2019). In this study, the microwave technology-based pyrolysis process was carried out using two types of reactors, namely an external reactor made of ceramic (1000 mL) and an internal reactor in the form of a glass beaker (250 mL). The external reactor serves as an absorber that converts microwave energy into heat, while the internal reactor contains the raw materials to be pyrolyzed. The pyrolyzed vapor is flowed out through a stainless-steel pipe that is directly connected to the external reactor. The temperature during the

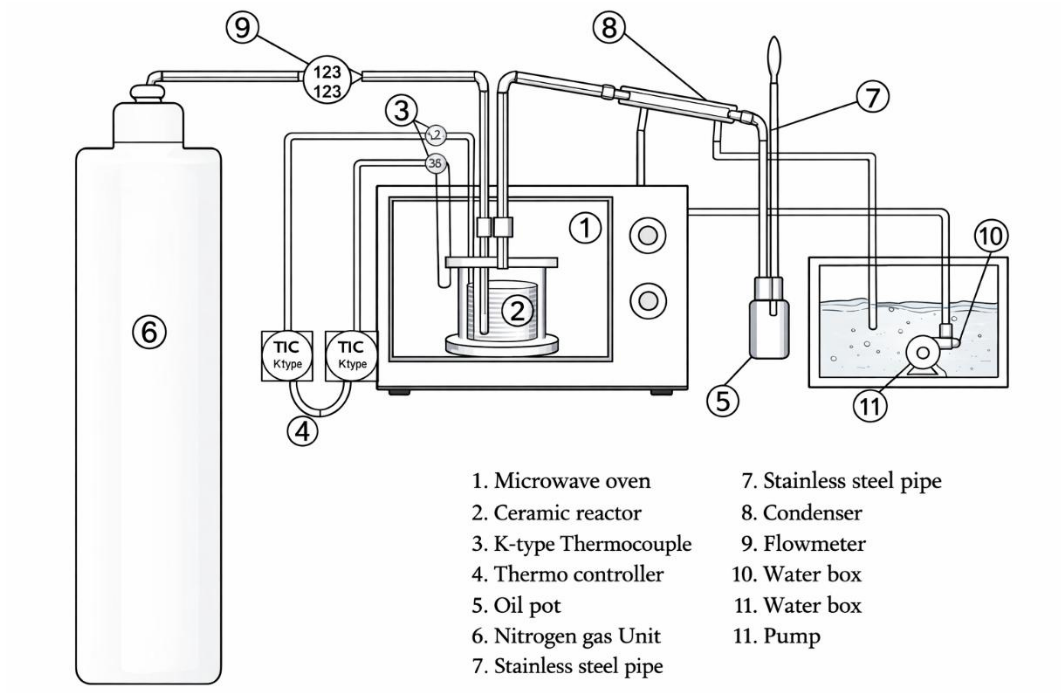

Figure 1. Schematic of microwave technology-based pyrolysis process (Anis, Lestari, et al., 2018).

pyrolysis process is measured and monitored using two K-type thermocouples, each placed inside the internal reactor and microwave oven chamber. These two thermocouples are connected to a thermos controller that serves to maintain temperature stability during the process. As an inert carrier gas, nitrogen was flowed into the reactor at a flow rate of 0.15 NL/min, both before and during the pyrolysis process, to create the oxygen-free conditions required for the pyrolytic reaction.

Pyrolysis was conducted by placing 100 g of feedstock powder in the internal reactor, and 100 g of granular activated carbon as microwave absorber in the external reactor. The pyrolysis process was carried out at a fixed temperature of 400°C. Once the target temperature is reached, the temperature is maintained constantly until no more vapor is condensed to ensure the pyrolytic reaction takes place optimally. The vapor produced during the pyrolysis process is drained through an outlet pipe and then condensed using a 300 mm Liebig condenser cooled by a stream of water. The condensed bio-oil was collected in a 500 mL glass container.

The product yields of bio-oil and bio-char were weighed using a scale, while the gases were evaluated based on their differences. Furthermore, the study focused on analyzing the physical and chemical characterization of pyrolysis bio-oil products, namely density, pH, and bio-oil compound composition. Density and pH of bio-oil were measured using a pycnometer and pHmeter, respectively. While the composition of bio-oil compounds was analyzed using GC-MS Shimadzu QP 2010 SE.

RESULTS AND DISCUSSION

Figure 2 shows the temperature profile of the Moringa oleifera seed pyrolysis process using a microwave reactor with a target temperature of 400°C. The data shows a significant trend of temperature increase from minute to minute to reach the target temperature in 21 minutes.

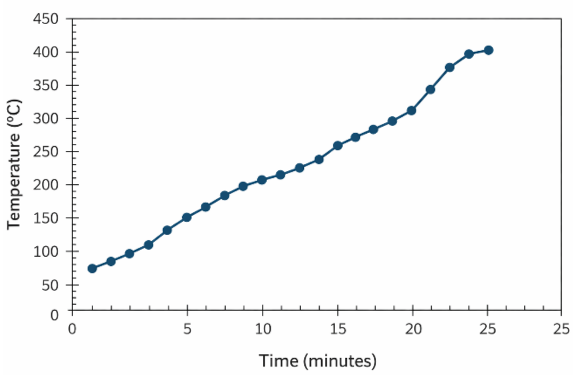

Figure 2. Pyrolysis temperature profile with target temperature 400°C.

Table 1. Bio-oil and bio-char yields from pyrolysis of Moringa oleifera seeds and comparison with other bimass feedstocks at 400°C.

Raw Material	Bio-oil (wt.%)	Bio-char (wt.%)	Reference
Moringa oleifera seeds	24.7	54.3	This research
Sugarcane bagasse	42.43	36.48	(Stegen & Kaparaju, 2020)
Coffee husk	336	40.5	(Del Pozo et al., 2022)
Grape pulp	21.1	54.1	(Del Pozo et al., 2022)
Olive mill waste	42.1	38.8	(Del Pozo et al., 2022)
Durian peel	32.1	36.0	(Manmeen et al., 2023)

In the first minute, the temperature was recorded at 50°C and increased gradually until reaching the final temperature of 400°C at the 21st minute. The temperature rise was not constant, but varied depending on the heating phase. In the initial phase (minutes 1 to 5), the temperature increased rapidly, with a rise of 64°C in just 4 minutes. The middle phase (minutes 6 to 17) showed a relatively stable heating rate with a temperature increase range of 13-38°C per minute, indicating high heat transfer efficiency. Towards the end (minutes 18 to 21), the rate of temperature increase began to decrease significantly, with only a 5°C increase in the last minute, indicating that the system was approaching the target temperature and entering a stable phase. This pattern illustrates the general characteristics of the pyrolysis process, where the initial temperature rises rapidly to reach optimal conditions, then stabilizes to maintain efficient thermochemical reactions on the biomass of Moringa oleifera seeds.

The results of pyrolysis of Moringa oleifera seeds at 400 ° C produced the main product fraction in the form of bio-oil of 24.7 wt.%, bio-char of 54.3 wt.% as shown in Table 1. In addition to bio-oil and bio-char, this study also produced pyrolysis gas products, which were evaluated based on different fractions of 21.0 wt.%. This composition shows that Moringa oleifera seeds tend to produce more solid residue (bio-char) than the liquid fraction, indicating a high content of lignin and stable carbon structure in the raw material.

The low bio-oil yield compared to bio-char indicates that the pyrolysis process at this temperature may not optimize the conversion of volatile matter components into liquid, or it is also possible that the chemical characteristics of Moringa oleifera seeds are more dominant in forming bio-char. However, high levels of bio-char actually provide added value, considering that bio-char has great potential for agricultural applications, activated carbon materials, and even long-term carbon storage in the context of climate change mitigation (Fakhar et al., 2025).

Compared to other biomasses, the pyrolysis product profile of Moringa oleifera seeds has distinctive characteristics. For example, bagasse and olive milling waste produced significantly higher bio-oil (42.43% and 42.1%, respectively) and lower bio-char, indicating suitability for renewable liquid fuel production. Coffee husk and durian peel have a more balanced product distribution between bio-oil and bio-char, with bio-oil around 32-34% and bio-char around 36-41%, making them multifunctional feedstocks (Kiruthika et al., 2013). Meanwhile, grape pulp has the most similar composition to Moringa oleifera seeds with 54.1% bio-char and 21.1% bio-oil, indicating similarities in lignocellulose content and material structure. This suggests that Moringa oleifera seeds are more suitable for applications that emphasize solid products, rather than as a primary source of bio-oil like bagasse or olive waste.

In terms of potential, bio-char from Moringa oleifera seeds has a distinct advantage in its high and stable carbon structure, making it an excellent material for waste adsorbent, soil quality improvement, and long-term carbon sequestration (Bekchanova et al., 2024). Despite the relatively low yield of bio-oil, the quality of the compounds in it (such as phenols, ketones and organic acids) can still have high chemical value, especially if further fractionation or upgrading is performed. Thus, although not the best candidate for bio-oil production, Moringa oleifera seeds have strategic value as a chemical feedstock for a variety of purposes (Bagheri et al., 2020).

Table 2. Density comparison of Moringa oleifera seed bio-oil with bio-oil from other biomasses.

Raw Material	**Density (g/cm^3)**	**Reference**
Moringa oleifera seeds	0.97-1.00	This research
Sugarcane bagasse	0.89-0.93	(Stegen & Kaparaju, 2020)
Coffee husk	0.91-0.95	(Del Pozo et al., 2022)
Grape pulp	0.92-0.96	(Manmeen et al., 2023)

Table 2 shows the density measurement results of bio-oil from Moringa oleifera seeds and its comparison with bio-oil from other biomasses. The density of bio-oil is an important parameter that reflects the chemical characteristics and material quality of the liquid product. Bio-oil from pyrolysis of Moringa oleifera seeds at 400°C has a density of 0.97-1.00 g/cm^3, which is higher than bio-oil from other biomasses such as bagasse (0.89-0.93 g/cm^3), coffee skin (0.91-0.95 g/cm^3), and durian skin (0.92-0.96 g/cm^3). This high density indicates that the bio-oil from Moringa oleifera seeds has a more dominant concentration of heavy and complex compounds, such as aromatic compounds, phenolics, and high molecular weight organic acids. This property indicates that Moringa oleifera seed bio-oil is more energy-dense, but also tends to be more viscous than bio-oils with lower density, which usually contain more light compounds such as alcohols and aldehydes.

Compared to other feedstocks, the density of bio-oil from Moringa oleifera seeds indicates significant differences in chemical composition. Sugarcane bagasse, for example, produces a lower density bio-oil which means it contains more volatile and flammable compounds, suitable for application as a fuel. Coffee husk and durian peel produce relatively stable medium-density bio-oil, but not as dense as Moringa oleifera seed bio-oil. This difference illustrates that Moringa oleifera seed bio-oil, although not as large in quantity as the other materials, has more complex chemical qualities and has the potential to be further processed into high-value chemical compounds such as bio-phenols, resins, antioxidants, and bioplastic base materials (Pandey et al., 2023). The potential is considerable, especially in the chemical and energy industries. Bio-oil from Moringa oleifera seeds can be used as feedstock in the production of aromatic chemicals through upgrading processes such as hydrodeoxygenation or fractional distillation. In addition, due to its high content of aromatic compounds, this bio-oil can potentially be used as a feedstock for the solvents, adhesives, or specialty chemicals industries. Thus, bio-oil from Moringa oleifera seeds offers high added value even in smaller volumes, and is highly relevant for the development of a bio-industry based on renewable materials.

Table 3 shows the pH value of Moringa oleifera seed bio-oil and its comparison with bio-oil from other biomasses. The results of bio-oil pH analysis at a pyrolysis temperature of 400°C show that all types of biomasses produce acidic bio-oil. Bio-oil from Moringa oleifera seeds has a pH in the range of 4.5-5.5, slightly higher than that of corn cob (pH 4-5) and cassava (pH 4.0) as reported by Shah et al., (2012) and Rueangsan et al., (2021). This difference reflects variations in the initial chemical composition of the biomass, particularly the content of lignin and aromatic compounds that can produce different volatile compounds during the pyrolysis process. The relatively higher pH of Moringa oleifera seed bio-oil indicates lower volatile organic acid content and possibly more stable phenolic and alkaline compounds. These characteristics are positive indicators as near-neutral bio-oils tend to be more stable, less corrosive and easier to handle than highly acidic bio-oils, which usually require additional neutralization processes before use (Daniel Valdez et al., 2023).

Table 3. Comparison of the pH of *Moringa oleifera* seed *bio-oil* with *bio-oil* from other biomasses

Raw Material	**pH**	**Reference**
Moringa oleifera seeds	4.5-5.5	This research
Corn cobs	4-5	(Shah et al., 2012)
Cassava	4.0	(Rueangsan et al., 2021)

These characteristics of Moringa oleifera seed bio-oil provide distinct advantages in the context of non-energy applications, especially as a source of antioxidant active ingredients. Phenolic

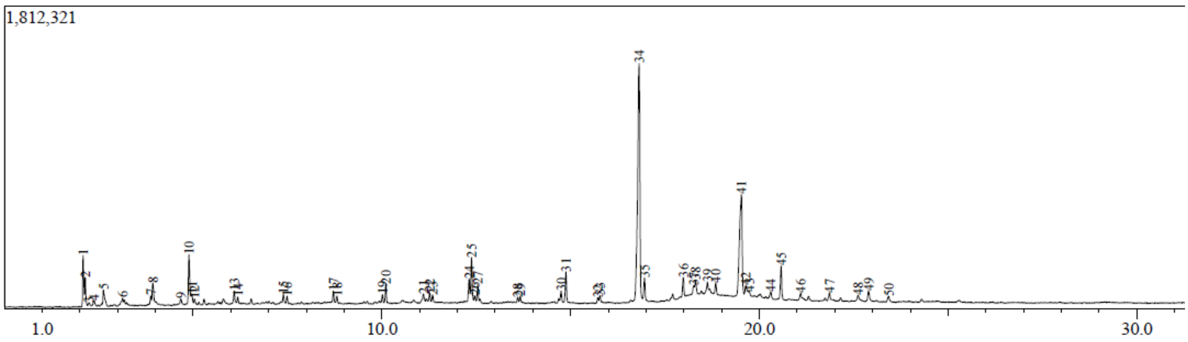

Figure 3. TIC of bio-oil from pyrolysis of Moringa oleifera seeds at 400°C.

compounds, which are often produced from pyrolysis of biomass with high lignin content such as Moringa oleifera seeds, have the ability to capture free radicals and inhibit oxidative reactions. With a pH that is not too acidic and a chemical composition that tends to be stable, Moringa oleifera seed bio-oil can be developed as a raw material for natural antioxidants in the pharmaceutical, cosmetic, and fuel additive industries. These properties also enable storage and handling of bio-oil with lower risk of degradation and corrosion (Abatyough et al., 2022), making it a more economical and environmentally friendly alternative to bio-oil from other biomasses. Thus, Moringa oleifera seeds offer strategic prospects as a sustainable source of tropical biomass-based antioxidant compounds.

The bio-oil produced from pyrolysis of Moringa oleifera seeds at 400°C was analyzed using gas chromatography-mass spectrometry (GC-MS) method to identify the profile of volatile and semi-volatile compounds contained therein. Based on the total ion chromatogram (TIC) as shown in Figure 3, a total of 50 chromatographic peaks were detected, reflecting the presence of complex chemical compounds resulting from the thermal decomposition of lipidic and lignocellulosic biomass.

The analysis results show that Moringa oleifera seed bio-oil contains a variety of complex chemical compounds. The most dominant main compounds are 9-Octadecen-1-ol (Z) at 32.63% and 9-Octadecenamide (Z) at 16.41%. These two compounds are long-chain compounds from the alcohol and amide groups that are known to have important biological activities such as antioxidants and antimicrobials, and are widely used in cosmetics, pharmaceuticals, and natural lubricants. In addition, bio-oil also contains phenolic compounds such as phenol and 2-methylphenol that contribute to its antioxidant properties. Phenolic compounds have the ability to counteract free radicals, so they are often used in the food industry as natural preservatives, as well as in health and cosmetics as antioxidant active ingredients.

This shows that bio-oil from Moringa oleifera seeds has high potential to be developed as a source of bioactive chemicals, especially as natural antioxidants. Bio-oil from Moringa oleifera seeds also contains hydrocarbons such as dodecane, tetradecane, and hexadecane, but in relatively small and scattered amounts. This results in a low calorific value of bio-oil, making it unsuitable for use as a direct fuel. Additionally, the high density and low pH indicate that this bio-oil is slightly acidic, making it non-potent for fuel applications.

However, the presence of nitrile and amide compounds such as hexadecanenitrile and hexadecanamide opens up opportunities for utilization in the chemical industry, for example, as a base material for solvents, resins, or intermediate compounds for the production of other chemicals. Overall, bio-oil from Moringa oleifera seeds at a temperature of 400°C is more potential to be used as a raw material for natural antioxidants and high-value chemical products than as a fuel. The composition of compounds rich in active compounds makes it prospective to be developed in the pharmaceutical, cosmetic, and environmentally friendly additive industries.

CONCLUSION

The bio-oil resulting from pyrolysis of Moringa oleifera seeds at a temperature of 400°C shows complex and promising chemical characteristics, despite its lower yield compared to the bio-char fraction. The high density of bio-oil, which is 0.97-1.00 g/cm^3, reflects the high concentration of heavy organic compounds.

Additionally, the pH value in the range of 4.5-5.5 indicates its relatively acidic nature. The GC-MS analysis results show that bio-oil contains a variety of compounds from different groups, such as alcohols, phenols, alkenes, alkanes, fatty acids, amides, and nitriles. The largest fraction consists of alcohols and amides (>60%), which are known to have important biological activities such as antioxidant, antimicrobial, and anti-inflammatory properties. The presence of phenolic compounds further strengthens the potential of this bio-oil as a source of natural antioxidants. With its high-value compound composition, bio-oil from Moringa oleifera seeds has prospects as a raw material for bioactive chemicals in various industries, including pharmaceuticals, cosmetics, and as an environmentally friendly additive in fuel formulations. These results show that the tropical biomass of Moringa oleifera seeds has great opportunities to be developed in sustainable bioindustry, while contributing to reducing dependence on fossil-based synthetic chemicals.

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