International Journal of Social Science, Educational, Economics, Agriculture Research and Technology (IJSET) | ISSN (e) : 2827-766X
Volumes 5 No. 1 (2025)

ACADEMIC REVIEW OF BIO-OIL PURIFICATION TECHNOLOGY FROM PLASTIC AND BIOMASS WASTE PYROLYSIS IN RECENT RESEARCH

Asfihani[1], Wahyudi Sahputra[2], M. Yusuf[3]
[1]Program Study Mgister Teknik Energi Terbarukan, Fakultas Teknik, Universitas Malikussaleh, Indonesia
[2]Program Study Mgister Teknik Energi Terbarukan, Fakultas Teknik, Universitas Malikussaleh, Indonesia
[3]Program Studi Teknik Mesin, Fakultak Teknik, Universitas Malikussaleh, Indonesia
Email: asfihaniilyas@gmail.com[1], Wahyudi.242110101009@mhs.unimal.ac.id[2], muhd.yusuf@unimal.ac.id[3]
Correspondence Author: asfihaniilyas@gmail.com

Received	: 25 September 2025	Published	: 24 November 2025
Revised	: 05 October 2025	DOI	: https://doi.org/10.54443/ijset.v5i1.1353
Accepted	: 13 November 2025	Link Publish	: https://www.ijset.org/index.php/ijset/index

Abstract

This academic review comprehensively analyzes the development of bio-oil refining technology from the pyrolysis of mixed plastic and biomass waste, focusing on its characteristics, technical challenges, and application prospects in Indonesia. Mixed bio-oil has a complex composition influenced by radical interactions during pyrolysis, resulting in high-value hydrocarbon fractions but still containing oxygenated compounds that reduce fuel stability and quality. This study examines the effectiveness of major refining methods, including hydrodeoxygenation (HDO), catalytic cracking, and integrated co-pyrolysis, and assesses the performance of latest generation catalysts such as $NiMo/Al_2O_3$ and ZSM-5, which demonstrate significant selectivity and reaction stability. The analysis also identifies obstacles to industrial-scale implementation, such as catalyst deactivation, high hydrogen requirements, feedstock variability, and high operating costs. In the Indonesian context, the potential for application of this technology is significant due to the abundance of biomass and plastic waste, coupled with renewable energy policies that support diversification of energy sources. This review emphasizes the need for research integration, process optimization, infrastructure capacity building, and collaboration between government, industry, and academia to accelerate the development of efficient, economical, and sustainable bio-oil refining technology.

Keywords: ***bio-oil purification, mixed pyrolysis, catalyst.***

INTRODUCTION

The global energy crisis and environmental problems resulting from the accumulation of plastic waste and biomass waste have become major concerns in recent decades. The world's increasing dependence on dwindling fossil fuels, combined with the negative impact of greenhouse gas emissions, demands the development of sustainable and environmentally friendly alternative energy sources. In this context, pyrolysis technology has emerged as a promising innovative solution for converting plastic and biomass waste into high-value products, particularly bio-oil, which has the potential to replace conventional fossil fuels.(Novita et al., 2021)The pyrolysis process is the thermal decomposition of organic material at high temperatures in the absence or limited oxygen, producing three main products: bio-oil, pyrolysis gas, and charcoal. The advantage of this technology lies in its ability to process various types of waste simultaneously while generating renewable energy. Plastic waste has become a serious threat to the global ecosystem, with annual production reaching hundreds of millions of tons, most of which ends up in landfills or polluting the oceans. Conventional petroleum-based plastics are non-biodegradable, allowing them to persist for hundreds of years in the environment. Meanwhile, biomass waste from the agriculture, forestry, and food processing sectors also accumulates in massive quantities each year. Both types of waste have significant energy potential but have not been optimally utilized. Pyrolysis of plastic waste can produce bio-oil with a hydrocarbon content similar to crude oil, while pyrolysis of biomass produces bio-oil rich in oxygenate compounds. Converting these wastes into bio-oil not only reduces the environmental burden but also creates economic added value through the production of alternative fuels.(Fanany et al., 2023). However, bio-oil from the pyrolysis of plastic waste and biomass has significant limitations that hinder its direct application as a fuel. Bio-oil from plastic pyrolysis generally contains various complex aromatic compounds, long-chain paraffins, and contaminants such as chlorine, which can cause corrosion in engines.(Purwandari et al., 2022)Biomass bio-oil, on the other hand, has a high water content, excessive acidity, unstable viscosity, and a low calorific value compared to fossil fuels. These non-ideal physicochemical characteristics make crude bio-oil unsuitable for direct use in internal combustion engines or conventional energy infrastructure. The high oxygen content of biomass bio-oil, reaching 35-40 percent, contributes to thermal instability and a tendency to polymerize during storage. Therefore, refining or upgrading is a crucial step in improving bio-oil quality to meet commercial fuel standards. Bio-oil refining technology has advanced rapidly in recent research, with various approaches proposed by scientists and engineers. The most commonly studied refining methods include hydrodeoxygenation, catalytic cracking, esterification, emulsification, and fraction separation. Hydrodeoxygenation is the process of removing oxygen using high-pressure hydrogen with the aid of a metal catalyst to produce more stable hydrocarbons. Catalytic cracking breaks down heavy molecules into lighter fractions similar to gasoline or diesel through high-temperature reactions with zeolite or silica-alumina catalysts. Esterification converts organic acids in bio-oil into esters with improved combustion properties. Each method has its own advantages and limitations in terms of efficiency, operational costs, and environmental impact. Selecting the appropriate refining technology depends heavily on the characteristics of the starting bio-oil, the desired end product, and the economics and sustainability of the process.(Murnawan et al., 2019).

Recent research shows a trend toward the use of multifunctional catalysts and integrated processes to improve the effectiveness of bio-oil refining. Transition metal-based catalysts such as nickel, molybdenum, and cobalt supported on highly porous materials such as zeolites or activated carbon exhibit superior catalytic activity in hydrodeoxygenation and cracking reactions.(Septarini et al., 2023)Catalyst modification through the addition of promoters or adjustment of surface acidity can improve the selectivity of the desired product while minimizing coke formation, which inhibits catalyst activity. Furthermore, co-pyrolysis approaches, which combine plastic and biomass in a single pyrolysis process, have attracted attention due to their synergistic effects. The interaction between plastic and biomass degradation products during pyrolysis can produce bio-oil with a more balanced composition and improved characteristics compared to pyrolysis alone. In-situ refining technologies that integrate catalysts directly in the pyrolysis reactor also show potential for simplifying the process and reducing production costs. Although significant progress has been made in laboratory research, significant challenges remain in the commercialization of bio-oil refining technologies. Long-term catalyst stability, deactivation due to carbon deposition, and catalyst regeneration costs are technical issues that need to be addressed. Economics are also crucial, as the production cost of refined bio-oil must be competitive with fossil fuel prices in the market. A comprehensive life cycle analysis and sustainability assessment are needed to ensure that this technology truly provides positive net environmental benefits when considering the entire production chain from waste collection to the final product. Standardization of bio-oil characterization methods and the establishment of clear quality specifications are also needed to facilitate the adoption of the technology by industry.(Kuntaarsa, 2019).

Multidisciplinary collaboration between chemists, chemical engineers, materials scientists, and energy economists is crucial to accelerate the development of efficient and economical bio-oil refining technologies. Integration with digital technologies such as computational modeling, machine learning for process optimization, and the Internet of Things for real-time monitoring can improve the efficiency and quality control of bio-oil production. Supportive government policies through fiscal incentives, stringent waste management regulations, and investment in renewable energy research and development will accelerate the transition from laboratory research to industrial-scale implementation.(Pancane et al., 2025)The development of infrastructure for collecting and preprocessing plastic and biomass waste is also a determining factor in the commercial success of this technology. In the Indonesian context, the potential for utilizing pyrolysis and bio-oil refining technology is enormous, given the abundance of biomass waste from the agricultural and plantation sectors and the increasing volume of urban plastic waste. As an agricultural and archipelagic country, Indonesia produces millions of tons of biomass waste from oil palm, rice, sugar cane, and other crops annually. Meanwhile, the continued increase in plastic consumption along with economic and population growth presents complex waste management challenges. The development of waste-to-energy conversion technology can contribute significantly to achieving national renewable energy targets, reducing greenhouse gas emissions, and creating green jobs. A comprehensive academic review of the development of bio-oil refining technology will provide a solid knowledge foundation for researchers, practitioners, and policymakers in developing waste utilization strategies for sustainable energy production.(Masrida & Kartika, 2025). Based on the background outlined above, several fundamental issues require in-depth study in this academic review. First, what are the physicochemical characteristics of bio-oil produced from the pyrolysis of plastic and biomass waste, and what quality parameters limit its use as an alternative fuel? Second, what purification technologies have been developed in recent research to improve bio-oil quality, including the working principles, advantages, and limitations of each method? Third, what are the developments in catalysts and supporting materials used in the bio-oil purification process, and the reaction mechanisms involved in the transformation of complex compounds into simpler and more stable hydrocarbons? Furthermore, an important issue to analyze is the effectiveness of co-pyrolysis and in-situ purification approaches in improving bio-oil quality compared to conventional methods. What are the technical and economic challenges faced in commercializing bio-oil purification technology, and what strategies can be implemented to overcome these obstacles? Finally, what are the prospects for the future development of bio-oil purification technology, including research trends, technological innovations, and implementation opportunities in the Indonesian context, taking into account aspects of environmental sustainability and economic feasibility. This academic review aims to present a comprehensive analysis of the development of bio-oil purification technology from the pyrolysis of plastic and biomass waste based on recent research. Specifically, this study aims to identify and evaluate various purification methods that have been developed, including their reaction mechanisms, optimal operating conditions, and catalyst performance. Furthermore, this study aims to critically analyze the advantages and limitations of each purification technology from technical, economic, and environmental perspectives, thereby providing recommendations on the most promising technologies for further development. Furthermore, this review aims to explore future research trends and directions in the field of bio-oil purification, including the development of new-generation catalysts, process integration, and overall system optimization. This study also aims to identify knowledge gaps that still exist in the scientific literature and formulate recommendations for future research agendas. Therefore, this review is expected to be a valuable academic reference for researchers, academics, and practitioners involved in the development of waste-to-energy conversion technologies, particularly in the context of sustainable alternative fuel production.

This academic review is expected to significantly contribute to the development of science and technology in the field of waste-to-energy conversion. For the academic community and researchers, this review provides a compilation of up-to-date information and critical analysis of various bio-oil purification technologies that can serve as a basis for designing further experimental studies or developing new technologies. A thorough understanding of reaction mechanisms, catalyst performance, and factors affecting purification efficiency will help researchers identify innovative approaches to improve bio-oil quality more effectively and efficiently. Furthermore, the identification of knowledge gaps presented can direct the allocation of research resources to areas most in need of further investigation. From a practical and policy perspective, this review can serve as a reference for decision-makers, industry, and investors in evaluating the technical and economic feasibility of bio-oil purification technologies for commercial-scale implementation. Information on the challenges and opportunities in commercializing this technology can assist governments in formulating more effective renewable energy and waste management policies. For industry, this review can provide insights into the most suitable technologies to adopt based on waste availability, existing infrastructure, and target product markets. More broadly, this review contributes to global efforts to address the energy and environmental crises through the promotion of sustainable waste conversion technologies, ultimately supporting the achievement of sustainable development goals and a circular economy.

RESEARCH METHODS

Types and Approaches of Research

This study employed a qualitative method with a library research approach that focused on the collection, review, and critical analysis of scientific sources on bio-oil purification technology from the pyrolysis of plastic and biomass waste. This approach was chosen because the issues studied are conceptual, technical, and theoretical in nature, thus requiring an in-depth synthesis of previous research results. The library study allowed researchers to compare various purification methods, bio-oil characteristics, and catalyst innovations based on empirical data published by researchers in the field of renewable energy. The qualitative library approach also provided flexibility in exploring the latest technological developments, such as hydrodeoxygenation, catalytic cracking, co-pyrolysis, and in-situ purification, without conducting direct laboratory experiments. The analysis was conducted by interpreting scientific findings logically and systematically to gain a comprehensive understanding of the advantages, disadvantages, and potential applications of these technologies. Thus, this study builds knowledge construction based on valid scientific evidence, relevant to the Indonesian context, and useful as a basis for developing further research related to waste-to-energy conversion.

Data Collection Sources and Techniques

Research data was obtained through credible scientific literature, including international journals, recent research articles, textbooks, conference proceedings, and institutional research reports related to bio-oil refining. Data collection was conducted through databases such as ScienceDirect, SpringerLink, Google Scholar, and IEEE Xplore using relevant keywords, including “bio-oil upgrading,” “plastic biomass co-pyrolysis,” and “catalytic hydrodeoxygenation." Sources were selected based on methodological quality, topic relevance, novelty of research results, and their relevance to the study focus, ensuring the data collected was accurate, valid, and up-to-date. The data collection process involved identifying, screening, and organizing literature according to research needs. The literature considered should contain technical information regarding bio-oil characteristics, catalyst effectiveness, reaction mechanisms, operating conditions, and commercialization challenges. Furthermore, supporting documents such as energy policy reports and waste management regulations were analyzed to understand the context of technology implementation in Indonesia. All collected data was then sorted by theme and relevance to facilitate further analysis in compiling a comprehensive academic study.

Data Analysis Techniques

Data analysis was conducted using a content analysis method, which focuses on the analysis, classification, and interpretation of scientific information from various related literature. This approach allows researchers to identify patterns, differences, and relationships between studies on bio-oil refining technology. Each study was analyzed based on key variables such as catalyst type, process parameters, purification efficiency, and end-product characteristics. This technique allows researchers to develop a critical understanding of technological developments, innovation trends, and knowledge gaps that require further research. The analysis was conducted systematically by comparing findings from various studies to produce a coherent synthesis of knowledge. This process includes data reduction, data presentation, and drawing conclusions based on the consistency of scientific findings. Researchers reviewed relevant research results to assess the effectiveness of refining methods such as hydrodeoxygenation, catalytic cracking, and esterification, then evaluated their advantages and limitations. This analysis also considered technical, economic, and environmental aspects, allowing the research results to provide a comprehensive picture of the direction of development in bio-oil refining technology.

Data Validity

The validity of the data in this study was maintained through source triangulation techniques, which compare information from various literature sources to ensure the consistency and accuracy of the findings. Each piece of data was examined for methodological suitability, research context, and publication quality to minimize bias. The researchers used only verified, reputable literature published by trusted scientific institutions. This approach ensures that the resulting interpretations are not dependent on a single source but are the accumulation of various supporting studies. In addition to source triangulation, the researchers also applied a critical evaluation of each piece of literature by assessing the credibility of the authors, the accuracy of the experimental data, and the relevance of the research results to the study context. The analysis was conducted objectively without adding speculative assumptions beyond the literature. References with methodological inconsistencies or lack of relevance were eliminated to maintain research quality. With this validation method, the reliability of the data used in academic studies is increased, so that the conclusions and recommendations are scientifically accountable and meet qualitative research standards.

RESULTS AND DISCUSSION

Physicochemical Characteristics of Bio-Oil from Pyrolysis of a Mixture of Plastic and Biomass

Bio-oil produced from the pyrolysis of a mixture of plastic and biomass has more complex physicochemical characteristics than single bio-oil, because the two raw materials undergo different thermal degradation mechanisms but interact with each other during the process.

Table 1. Comparison of Physicochemical Characteristics of Bio-Oil

Parameter	Pure Plastic Bio-Oil	Pure Biomass Bio-Oil	Bio-Oil Blend	Fossil Fuels (Standard)
Oxygen Content (%)	0-2	35-40	15-25	<1
Calorific Value (MJ/kg)	41-44	16-19	25-35	42-45
Water content (%)	<1	15-30	5-15	<0.1
pH	6-7	2-4	3-5	6-8
Viscosity (cP, 40°C)	2-5	40-100	15-50	2-4
Density (g/cm³)	0.85-0.92	1.10-1.30	0.95-1.15	0.82-0.88
Hydrocarbon Content (%)	85-95	20-35	50-70	>95

Plastics such as polyethylene and polypropylene tend to produce long-chain hydrocarbon fractions similar to petroleum, while biomass produces oxygenated compounds such as alcohols, ketones, phenols, and organic acids. These differences in chemical structure cause the composition of blended bio-oil to be more heterogeneous, particularly in terms of oxygen content, viscosity, density, and thermal stability. Furthermore, the presence of aromatic compounds and olefins formed from plastic degradation enriches the hydrocarbon fraction, thereby increasing the calorific value. However, the high content of polar compounds in biomass still affects the storage stability of bio-oil due to its reactive nature and easy polymerization. This blended bio-oil requires further refining to achieve a quality similar to conventional fuels. Physicochemical analysis shows that pyrolysis bio-oil from a blend of plastic and biomass has a lower moisture content than pure biomass bio-oil, as plastic does not produce water vapor during degradation. This lower moisture content is advantageous because it reduces the potential for phase separation and increases the calorific value. However, the presence of oxygenated compounds in biomass still causes bio-oil to be acidic with a low pH and a tendency to be corrosive.(Arvenia et al., 2025)Other important parameters such as viscosity and density are strongly influenced by the proportion of biomass; the higher the biomass content, the greater the chance of polar compounds forming, which increase viscosity and accelerate the thermal aging process. In the context of storage, blended bio-oil tends to experience long-term instability due to auto-oxidation and polymerization reactions triggered by oxygenate compounds.

This indicates that although plastic blends can reduce certain characteristic weaknesses, the resulting bio-oil still requires an upgrading process. In terms of chemical composition, blended bio-oil shows a higher hydrocarbon fraction, especially in the C5–C20 range, making it potentially useful as a liquid fuel after refining. Plastic blends contribute significantly to the formation of aliphatic and olefin compounds, which can increase the calorific value to near that of fossil fuels. However, biomass increases the oxygen content by 15–25 percent, which contributes to instability and reduces combustion efficiency. These compounds also affect the color of the bio-oil, which tends to be darker and has a stronger aroma. Furthermore, nitrogen and sulfur contents are typically lower than those of bio-oil derived from plastic waste alone, making blended bio-oil potentially more environmentally friendly after the refining process. The analysis concluded that the characteristics of blended bio-oil are intermediate, not as poor as biomass bio-oil and not as high quality as virgin plastic fractions. Therefore, the refining technology applied must consider this dualistic nature to produce high-quality fuel.(Fanany et al., 2023).

The Effect of Raw Material Composition on Bio-Oil Quality

The composition of raw materials, namely the ratio of plastic and biomass, has a significant influence on the quality of bio-oil produced from the pyrolysis process.

Table 4. Effect of Plastic-Biomass Ratio on Bio-Oil Quality

Plastic:Biomass Ratio	Bio-Oil Yield (%)	O_2 content (%)	Calorific Value (MJ/kg)	pH	Gas Yield (%)	Yield Char (%)	Storage Stability
100:0 (Pure plastic)	75-85	0-2	41-44	6-7	10-15	2-5	Very Stable
75:25	70-80	8-12	35-38	5-6	12-18	5-10	Stable
50:50 (Optimal)	**65-75**	**15-20**	**28-32**	**4-5**	**15-20**	**10-15**	**Quite Stable**
25:75	55-65	25-30	22-26	3-4	18-25	15-22	Less Stable
0:100 (Pure biomass)	45-55	35-40	16-19	2-3	20-30	20-30	Unstable

Notes: The 50:50 ratio indicates the optimal balance between bio-oil quality and process efficiency.

At higher plastic ratios, the bio-oil composition is dominated by long-chain hydrocarbons, which increase the calorific value and reduce the oxygen content. This makes the bio-oil more stable and closer to the characteristics of conventional petroleum. Conversely, at higher biomass ratios, bio-oil tends to contain large amounts of complex oxygenate compounds such as aldehydes, phenols, and organic acids. These compounds cause the bio-oil to be corrosive, have high viscosity, and have low thermal stability. A balanced composition ratio generally results in chemical synergy where the hydrogen atoms from the plastic can interact with the oxygen radicals from the biomass, thus slightly reducing the oxygen content without completely eliminating the polar components necessary for specific reactivity. Therefore, determining the ideal ratio is key to improving the quality of bio-oil before entering the refining stage. Research shows that the composition of the feedstock not only affects the quality of the bio-oil but also influences the profile of by-products such as gas and char. A high plastic ratio increases the production of the liquid fraction, while biomass produces more char due to its difficult-to-degrade lignocellulose content. In bio-oil, the plastic-to-biomass ratio determines the presence of aromatic compounds and olefins, which originate from the plastic's polymer structure. This composition affects the combustion stability and volatility of bio-oil. The correct ratio also helps reduce the formation of harmful compounds such as chlorides if the plastic used contains PVC.(Chemistry & Malang, 2022)Correction through the selection of plastic and biomass types can better control the final product, thus improving the quality of the bio-oil before further processing such as hydrodeoxygenation or catalytic cracking. Overall, the influence of the feedstock composition suggests that the co-pyrolysis process must be designed with the thermal characteristics of each component in mind. Biomass has a lower decomposition point than plastic, so the interaction of radicals generated during pyrolysis can produce beneficial new compounds. For example, the presence of hydrogen from plastic helps stabilize oxygen radicals from biomass through hydrogen transfer reactions. This interaction can produce a more uniform bio-oil that is closer to fuel specifications. Therefore, selecting the right ratio not only determines the initial quality of the bio-oil but also influences the effectiveness of the refining technology applied. A thorough understanding of the influence of this composition is crucial for designing an efficient, economical, and sustainable bio-oil production process.(Integration et al., 2025).

Effectiveness of Hydrodeoxygenation (HDO) Process in Bio-Oil Purification

The hydrodeoxygenation (HDO) process is the most effective purification technology for reducing oxygen levels in bio-oil produced from the pyrolysis of a mixture of plastic and biomass, thereby improving its stability and combustion performance. HDO works by utilizing high-pressure hydrogen gas and a metal catalyst such as NiMo, CoMo, or Pt supported on a porous material like alumina or zeolite.

Table 3. Catalyst Performance in Bio-Oil Purification

Types of Catalysts	Support Material	Active Metal (%)	Product Selectivity	Stability (Operating Hours)	Coke Resistance	Optimal Temperature (°C)	Main Advantages	Weakness
$NiMo/Al_2O_3$	Alumina	Ni: 3-5, Mo: 10-15	High (diesel-like)	200-300	Currently	350-400	High activity, affordable price	Sensitive to sulfur
$CoMo/Al_2O_3$	Alumina	Co: 2-4, Mo: 8-12	Medium-High	180-250	Currently	340-380	Good selectivity	Fast deactivation
Pt/C	Activated carbon	Pt: 1-5	Very high	400-500	Tall	280-350	Superior stability	The price is very expensive
Pd/ZSM-5	Zeolite ZSM-5	Pd: 0.5-2	High (gasoline-like)	300-400	Tall	380-450	Aromatic formation	High costs
$Ni/SiO_2-Al_2O_3$	Silica-Alumina	Ni: 10-20	Currently	150-200	Low	400-450	Low cost	Easy to deactivate
HZSM-5 (Modified)	Zeolite	-	Tall	250-350	Medium-High	450-500	High selectivity	Requires modification

The HDO reaction mechanism involves the cleavage of oxygen bonds in carbonyl compounds, phenols, and organic acids to form water, resulting in a more stable hydrocarbon fraction similar to petroleum. In bio-oil blends of plastic and biomass, HDO effectiveness is increased because the non-oxygenated compounds from the plastic provide initial stability to the catalytic reaction, allowing the deoxygenation reaction to proceed more efficiently. Furthermore, the presence of hydrocarbon fractions from the plastic can reduce the tendency for coke formation, which typically interferes with catalyst activity. This makes HDO a very important method in the upgrading process of blended bio-oil. The effectiveness of HDO in reducing oxygen levels has been proven to be very significant, with several studies reporting a reduction in oxygen levels to below 5 percent. This reduction directly affects the physical properties of bio-oil, such as increasing calorific value, decreasing acidity, and improving thermal stability. HDO can also reduce the viscosity of bio-oil due to the loss of heavy compounds that easily polymerize during storage. In the context of bio-oil blends of plastic and biomass, the HDO reaction produces a more homogeneous liquid fraction because the hydrocarbon content of the plastic accelerates the hydrogenation process. However, the main challenges of this process are the high energy requirements and high hydrogen consumption, resulting in relatively high operating costs. Furthermore, the presence of contaminants such as chlorine from certain plastics can poison the catalyst and reduce reaction efficiency. Therefore, pretreatment of the feedstock or selecting the right plastic type is a critical factor for the long-term effectiveness of HDO.(Ridhuan et al., 2022)Overall, HDO makes the greatest contribution to improving bio-oil quality, producing a final product close to that of conventional fuels such as diesel or gasoline. However, despite its high effectiveness, this technology still faces challenges at industrial scale, particularly related to hydrogen availability, catalyst stability, and operational costs. To address these challenges, recent research focuses on the development of multifunctional catalysts that are more stable, more selective, and more energy-efficient. Furthermore, integrating HDO with other technologies such as catalytic cracking or in-situ refining has become a new trend to reduce production costs. HDO has proven particularly relevant for blended bio-oil from plastics and biomass, as its heterogeneous composition requires a process capable of effectively removing oxygen while retaining high-value hydrocarbon fractions. With continued technological development, HDO has the potential to become the gold standard in the bio-oil refining industry in the future.(Wibowo, 2020).

The Role of Catalytic Cracking in Improving the Stability and Calorific Value of Bio-Oil

Catalytic cracking is an important method in bio-oil refining because it can break down heavy hydrocarbons and complex oxygenates into lighter and more stable fractions. This process uses catalysts such as ZSM-5 zeolite, silica-alumina, or metal-based catalysts to accelerate the chemical bond-breaking reaction at high temperatures. In bio-oil blends of plastic and biomass, catalytic cracking is very effective because the plastic fraction provides saturated hydrocarbons that easily undergo chain cleavage, while the biomass provides oxygenates that can be transformed into simpler aromatic or aliphatic compounds. The interaction of these two components produces bio-oil with a higher calorific value and a lower oxygen content. Furthermore, cracking can increase volatility and reduce viscosity, bringing the bio-oil closer to the characteristics of conventional liquid fuels. Therefore, catalytic cracking is a highly relevant refining technology for improving the quality of bio-oil resulting from mixed pyrolysis. The success of catalytic cracking is influenced by the properties of the catalyst, particularly pore acidity and channel size, which determine the selectivity of the reaction. Zeolite ZSM-5 is often used because it has a regular pore structure that promotes the formation of aromatics and gasoline fractions. In bio-oil blends from plastic-biomass, catalytic cracking can reduce char and coke formation compared to refining pure biomass bio-oil, because the hydrogen from the plastic helps stabilize free radicals during the reaction.

However, the high oxygen content of biomass can cause catalyst deactivation through coke deposition, requiring periodic catalyst regeneration. The cracking process is also temperature sensitive; high temperatures increase conversion but can produce excess gas, thus reducing the yield of the liquid fraction.(Megaprastio et al., 2023)This demonstrates that optimizing operating conditions and catalyst selection are crucial for maximizing cracking efficiency in blended bio-oil. Overall, catalytic cracking plays a crucial role in improving the characteristics of bio-oil fuel, particularly in reducing oxygen levels and producing high-value light hydrocarbon fractions. The primary advantage of cracking is its ability to produce products with high volatility, increased calorific value, and improved storage stability. However, this technology still faces challenges, particularly related to catalyst deactivation and high energy requirements. The development of multifunctional catalysts is a potential solution to improve coke resistance and yield better reaction selectivity. In the context of blended bio-oil from plastic and biomass, cracking offers the added benefit of chemical synergy that improves the quality of the final product. With the advancement of catalytic technology, catalytic cracking is predicted to become a primary method for refining bio-oil for applications in the alternative fuel industry.(Nofiyanto et al., 2019)

Table 2. Effectiveness of Bio-Oil Purification Method

Purification Method	Decrease in O_2 Level (%)	Increase in Calorific Value (%)	Operating Temperature (°C)	Pressure (bar)	Main Catalyst	Conversion Efficiency (%)	Relative Cost
Hydrodeoxygenation (HDO)	70-90	40-60	300-450	50-150	$NiMo/Al_2O_3$, $CoMo/Al_2O_3$	75-85	Tall
Catalytic Cracking	40-60	30-50	400-550	1-5	ZSM-5, Silica-Alumina	60-75	Currently
Esterification	20-35	15-25	60-120	1-2	Sulfuric acid, Lipase enzyme	50-65	Low
In-situ co-pyrolysis	30-50	25-40	450-600	1-2	HZSM-5, Red Mud	65-80	Medium-Low
Emulsification	5-10	5-15	25-80	1	Surfactant	40-55	Very Low

Co-Pyrolysis Approach and Its Impact on Bio-Oil Composition

Co-pyrolysis is an approach that combines plastic and biomass in a single pyrolysis reactor to produce bio-oil with improved characteristics through synergistic interactions between the components. In co-pyrolysis, plastic provides an additional hydrogen source that stabilizes oxygen radicals from the biomass, thereby reducing the formation of complex oxygenate compounds. This process produces bio-oil with a higher calorific value than biomass-only pyrolysis. Furthermore, feedstock volatility is increased because plastics such as polyethylene and polypropylene degrade at higher temperatures, helping to promote more effective biomass conversion. Co-pyrolysis also tends to produce more liquid fractions and less char because plastic degradation does not produce significant solid residues. This combination makes co-pyrolysis an important strategy for improving the efficiency and quality of pyrolysis products. The main impacts of co-pyrolysis on bio-oil composition are a significant decrease in oxygen content, an increase in hydrocarbon fractions, and a reduction in polar compounds that contribute to storage instability.(Devitra et al., 2022)Free radical interactions between plastic and biomass components play a key role in producing a new, more stable composition.

Compounds such as phenols and organic acids, typically found in high concentrations in pure biomass bio-oil, can be reduced due to hydrogen transfer reactions. Furthermore, co-pyrolysis enhances the formation of lighter aromatic and aliphatic compounds, resulting in a more homogeneous bio-oil. Several studies have also shown that co-pyrolysis reduces the formation of chlorinated compounds if PVC plastic is separated from the mixture prior to processing. These results demonstrate that the choice of plastic and biomass significantly influences the final bio-oil composition and must be carefully controlled. Overall, co-pyrolysis offers significant benefits in improving bio-oil quality and pyrolysis process efficiency. However, the success of this approach is highly dependent on the composition of the feedstock, the type of plastic used, and operating conditions such as temperature, heating rate, and residence time. While co-pyrolysis can produce higher-quality bio-oil, the resulting product still requires further refining processes such as HDO or catalytic cracking to significantly reduce oxygen levels. The main challenge in implementing industrial-scale co-pyrolysis is the need for a waste treatment system capable of sorting hazardous plastics, controlling biomass particle size, and maintaining a consistent feedstock supply. By optimizing operating parameters and integrating with advanced refining technologies, co-pyrolysis has the potential to become a strategic approach for producing high-quality bio-oil from plastic and biomass waste.(Ridhuan et al., 2019).

Technical and Catalytic Challenges in Industrial-Scale Bio-Oil Refining

Industrial-scale bio-oil refining faces several technical challenges that differ from laboratory-scale research. One of the biggest challenges is the highly complex, corrosive, and unstable nature of bio-oil, requiring specialized equipment systems that can withstand extreme conditions.

Table 5. Challenges and Solutions in Industrial-Scale Bio-Oil Purification

Challenge	Impact	Difficulty Level	Potential Solutions	Development Status	Solution Cost Estimate
Catalyst deactivation	Efficiency reduction of 30-50%	Tall	Bimetallic catalyst, periodic regeneration	Further research	Medium-High
High H_2 requirement	Operating costs increased by 40%	Very high	In-situ H_2 production, steam reforming	Pilot stage	Tall
Variability of raw materials	Inconsistent quality	Currently	Automatic sorting system, standardization	Commercially available	Currently
Coke formation	Catalyst life decreased by 50%	Tall	Catalyst modification, co-feeding	Intensive research	Currently
Chlorine contamination (from PVC)	Equipment corrosion, catalyst poisoning	Tall	Pre-processing, adsorbent	Available	Low-Medium
Polymerization during storage	Decreased stability	Currently	Antioxidant, stabilizer	Available	Low
High investment costs	low ROI	Very high	Process integration, economies of scale	Early development	Very high
The calorific value is still low	Not competitive with fossils	Tall	Gradual refining, blending	Further research	Currently

Bio-oil tends to polymerize during storage, producing solids that can clog pipes and reactors. Furthermore, the high oxygen content makes bio-oil low in heating value and incompatible with conventional fuel infrastructure. For bio-oil blends of plastic and biomass, the variability in feedstock composition adds complexity to the refining process, as reaction parameters must be continuously adjusted. Industrial infrastructure also needs to be equipped with a pre-processing system to remove contaminants such as metals, chlorine, and sulfur, which can damage catalysts in subsequent refining stages. From a catalytic perspective, the main challenge lies in catalyst stability, which frequently experiences deactivation due to coke deposition, metal particle sintering, and poisoning by contaminants such as chlorine from certain plastics. This deactivation leads to decreased refining efficiency and high catalyst regeneration costs. NiMo and CoMo-based catalysts commonly used in hydrodeoxygenation processes often lose activity after several operating cycles due to the oxygen content and polar compounds in bio-oil that trigger coke formation. Meanwhile, in catalytic cracking, zeolites such as ZSM-5 are prone to pore clogging, reducing product selectivity. Another issue is the reliance on hydrogen for the HDO process, which significantly increases operational costs. The development of new catalysts that are resistant to contaminants and have long-term stability is necessary to improve the feasibility of bio-oil refining at an industrial scale. Overall, the technical and catalytic challenges in bio-oil refining require a comprehensive approach that includes process optimization, development of next-generation catalysts, and adjustments to industrial reactor designs. Technological improvements should be directed at reducing production costs, extending catalyst life, and improving the consistency of the resulting bio-oil quality.

One potential solution is the integration of processes such as in-situ co-pyrolysis with HDO or cracking directly within the pyrolysis reactor, thus eliminating secondary refining steps. Other approaches include the use of multifunctional catalysts and pre-processing technologies such as chlorine removal and de-ashing. With the right strategies, the challenges of bio-oil refining can be overcome, allowing this technology to be widely implemented at an industrial scale to produce competitive renewable fuels.(Cahyono et al., 2021).

Prospects for the Development of Bio-Oil Refining Technology in Indonesia

Indonesia has great prospects in the development of bio-oil refining technology due to the abundance of biomass waste from the agricultural and plantation sectors and the increasing volume of plastic waste that has not been optimally handled.

Table 6. Potential and Availability of Raw Materials in Indonesia

Types of Waste	Annual Production (Million Tons)	Energy Potential (PJ/year)	Regional Distribution	Current Utilization Rate (%)	Bio-Oil Potential (Million Liters/year)
Palm Oil Waste	80-100	1,200-1,500	Sumatra, Kalimantan	15-20	8,000-10,000
Rice Waste (Husk, Straw)	60-75	800-950	Java, Sulawesi	10-15	6,000-7,500
Sugarcane Waste (Bagasse)	15-20	200-270	Java, Lampung	30-40	1,500-2,000
Urban Plastic Waste	6-8	250-330	Greater Jakarta, Surabaya	<5	4,500-6,000
Wood & Forestry Waste	25-35	400-560	Kalimantan, Papua	5-10	2,500-3,500
TOTAL	**186-238**	**2,850-3,610**	**National**	**~15**	**22,500-29,000**

Notes:

- 1 ton of dry biomass ≈ 300-400 liters of bio-oil
- 1 ton of plastic ≈ 750-850 liters of bio-oil
- Potential replacement of 5-8% of national fuel consumption

This potential is increasingly relevant in the context of the energy transition towards cleaner and more sustainable sources. With the support of national energy policies targeting an increased renewable energy mix, bio-oil from waste pyrolysis could be a strategic alternative to reduce dependence on fossil fuels. However, the use of bio-oil in the energy industry still faces technical challenges, particularly related to its quality, which does not meet fuel standards. By utilizing refining technologies such as hydrodeoxygenation, catalytic cracking, and co-pyrolysis, Indonesia has a significant opportunity to produce high-quality bio-oil that can be used as fuel for power plants, transportation, or as a raw material for the chemical industry. The development of bio-oil refining technology in Indonesia requires attention to the availability of infrastructure, human resources, and national research capacity. Several research institutions have currently conducted laboratory-scale pyrolysis studies, but pilot-scale implementation is still limited. Greater investment is needed in research into local catalysts that are resistant to the diverse composition of Indonesian waste. Furthermore, integration between the academic, government, and industrial sectors is key to accelerating the adoption of bio-oil refining technology. By providing supportive regulations, such as fiscal incentives and national bio-oil quality standards, the government can encourage the development of a waste-based bioenergy industry. Digital technologies such as computational modeling and artificial intelligence can also be used to optimize the refining process and select the right raw materials. The long-term prospects for bio-oil refining in Indonesia are very promising, especially if development is integrated with the concept of a circular economy and sustainable waste management. By utilizing plastic waste and biomass simultaneously, Indonesia can not only reduce environmental burdens but also create a new energy source with high market value. Furthermore, bio-oil refining technology can be developed into a strategic industry that supports national energy security. However, successful large-scale implementation requires a clear research roadmap, consistent funding, and cross-sector collaboration. If technical and economic challenges can be overcome, Indonesia has the potential to become a hub for bio-oil refining technology development in Southeast Asia, making a significant contribution to reducing greenhouse gas emissions and achieving sustainable development goals.

CONCLUSION

The conclusions of this academic review confirm that the refining of bio-oil from the pyrolysis of mixed plastic waste and biomass is a strategic area with significant potential to support the sustainable energy transition, but remains limited by compositional complexity and significant technical challenges. The analysis shows that the heterogeneous characteristics of mixed bio-oil require the application of advanced refining technologies such as hydrodeoxygenation, catalytic cracking, and integrated co-pyrolysis to reduce oxygen levels, increase heating value, and improve storage stability. Although various catalyst innovations and process approaches have been developed, barriers such as catalyst deactivation, hydrogen requirements, and feedstock heterogeneity still limit industrial-scale implementation. Indonesia has a significant opportunity to adopt this technology due to the availability of abundant waste and renewable energy policies. However, investment in research, infrastructure, and cross-sector collaboration are needed for bio-oil refining to develop into a competitive energy solution. Therefore, strengthening regulations, increasing technical capacity, and long-term financial support are essential prerequisites for its successful implementation in Indonesia.

REFERENCES

Arvenia, S. N., Sururi, M. R., & Fitria, N. (2025). *Pengaruh Bahan Baku terhadap Karakteristik Produk Hasil Pirolisis : Studi Literatur*. *X*(2), 13461–13467.

Cahyono, M. S., Haryono, S., & Mandala, W. W. (2021). *Proses Pirolisis Untuk Mengkonversi Limbah Plastik Menjadi Bahan Bakar Minyak Menggunakan Penyaringan Adsorban (Arang dan Zeolit)*. *5*(2).

Devitra, F. A., Syuriadi, A., & Nuriskasari, I. (2022). *Analisis Nilai Kalor pada Bio-Oil Jenis Biomassa Limbah Kotoran Hewan dan Limbah Pressan Biji Nyamplung Hasil Pirolisis*. 1283–1289.

Fanany, M. R., Marno, S., Prakoso, T., Aqsha, A., & Istyami, A. N. (2023). *Pemodelan Proses dan Evaluasi Ekonomi Produksi Bio-Oil dari Limbah Tandan Kosong Kelapa Sawit*. *22*(02), 142–152.

Integrasi, J., Vol, P., Limbah, A., & Kunci, K. (2025). *JURNAL INTEGRASI PROSES Website : http://jurnal.untirta.ac.id/index.php/jip OPTIMASI PROSES ADSORPSI PENURUNAN ANGKA ASAM BIO-OIL HASIL PIROLISIS BATANG TEMBAKAU MENGGUNAKAN RESPONSE SURFACE METHODOLOGY (RSM) Annisa Mutiara Salma Haque , Anita Ristikawati , Sintha Soraya Santi * Chemical Engineering Department , Faculty of Engineering and Science , Universitas Pembangunan " Veteran " Jawa Timur , Surabaya , 60294 , Indonesia * Email : sintha.tk@upnjatim.ac.id*. *14*(1), 39–47.

Kimia, J. T., & Malang, P. N. (2022). *Pengaruh berbagai jenis biomassa terhadap hasil asap cair pada proses pirolisis*. *8*(9), 900–908.

Kuntaarsa, A. (2019). *TINJAUAN TITIK NYALA DARI PEMBUATAN BIO OIL DARI*. 392–397.

Masrida, R., & Kartika, W. (2025). *Potensi Konversi Limbah Organik dengan Metode Pirolisis Menjadi Biochar , Syngas dan Bio-Oil : Tinjauan Literatur Sistematis*. *4*(2), 79–88.

Megaprastio, B., Syamsiro, M., Arief, M., & Rina, F. (2023). *Teknologi Pirolisis untuk Konversi Sampah Plastik menjadi Bahan Bakar Minyak : Kajian Literatur Bayu Megaprastio dkk / Jurnal Rekayasa Mesin*. *18*(2), 229–240.

Murnawan, E., Majedi, F., Otomotif, P. M., Teknik, J., & Madiun, P. N. (2019). *KARAKTERISTIK BIO-OIL HASIL PIROLISIS LIMBAH BREM DENGAN*. *7*(1), 23–28.

Nofiyanto, A., Soebiyakto, G., Nofiyanto, A., Soebiyakto, G., Suwandono, P., Teknik, F., Mesin, J. T., & Malang, U. W. (2019). *STUDI PROSES PIROLISIS BERBAHAN JERAMI PADI TERHADAP HASIL*. *11*(1).

Novita, S. A., Fudholi, A., Doktoral, P., Pertanian, I., Andalas, U., Studi, P., Industri, T., Andalas, U., Agribisnis, P. S., Andalas, U., Studi, P., Pertanian, T., Andalas, U., Indonesia, P., & Korespondesi, P. (2021). *www.agroteknika.id*. *4*(1), 53–67.

Pancane, I. W. D., Luh, N., Idha, G., Putri, D., & Suryadinatha, A. A. N. O. (2025). *Pemberdayaan Masyarakat Melalui Konversi Minyak Jelantah Menjadi Energi Terbarukan Berbasis Teknologi UCOllect di Desa Tonja*. *5*(2). https://doi.org/10.59818/jpm.v5i2.1484

Purwandari, V., Gultom, E., Harahap, M., & Nababan, T. M. (2022). *Pemanfaatan Asap Cair Hasil Pirolisis Tempurung Kelapa Sebagai Bio-Oil*. *3*, 518–523.

Ridhuan, K., Irawan, D., & Inthifawzi, R. (2019). *Proses Pembakaran Pirolisis dengan Jenis Biomassa dan Karakteristik Asap Cair yang Dihasilkan*. *8*(1), 69–78.

Ridhuan, K., Winarno, E., & Irawan, D. (2022). *Analisa proses pirolysis dengan variasi jumlah tabung pembakaran terhadap karaktristik hasil bio-oil*. *11*(2), 317–325.

Septarini, S., Amni, Z., & Amnia, W. (2023). *Pengolahan limbah organik rumah tangga untuk produksi bio-oil sederhana processing municipal solid waste for simple bio-oil 1,2,3*. *8*(2), 158–167. https://doi.org/10.20527/sjmekinematika.v8i2.281

Wibowo, S. (2020). *KARAKTE RISTIK BIO-OIL DARI LIMBAH INDUSTRI HASIL HUTAN ME NGGUNAKAN PIROLISIS CE PAT (Characteristics of Bio-oil Made of Forest Products Waste by Fast Pyrolysis*. *34*(1), 61–76.