Jurnal Ilmu Pertanian Indonesia (JIPI), April 2025
(Indonesian Journal of Agricultural Sciences)
ISSN 0853-4217 EISSN 2443-3462

Vol. 30 (2): 430‒440
http://journal.ipb.ac.id/index.php/JIPI
DOI: 10.18343/jipi.30.2.430

Potential and Challenges of Biofuels from Keruing *(Dipterocarpus spp.)* to Support Sustainable Fuel Transition in the Transportation Sector

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(Received October 2024/Accepted February 2025)

ABSTRACT

Mobility is an integral part of daily life; however, the transportation sector significantly contributes to greenhouse gas emissions, which trigger global warming. In the context of climate change, a global issue, the Paris Agreement and the Nationally Determined Contribution (NDC) policies of each country encourage the development of environmentally friendly, renewable energy. Keruing (*Dipterocarpus* spp.), a tree found only in tropical forests, has the potential to be a source of biofuel from its non-timber products such as oil and resin. This study aims to analyze the challenges of developing biofuel from keruing for the transportation sector in Indonesia, using a mixed method enhanced by machine learning for data analysis. The results show that keruing oil has potential as a biofuel, but the main challenges lie in infrastructure, knowledge limitations, and processing techniques. Many keruing trees with oily wood are not industrially processed for their oil due to a lack of knowledge and a focus on wood utilization. The conclusion is that the potential for developing environmentally friendly renewable energy in Indonesia is significant, but improving the quality of human resources and capital is necessary to advance the science and technology.

Keywords: biofuel, *Dipterocarpus* spp., energy transition, SDGs, transportation

INTRODUCTION

The continuity of human daily activities is closely linked to mobility. Transportation is a form of mobility that is urgently needed to meet social needs and improve welfare. Transportation mobility is not just the movement of individuals from one place to another, but also the potential involvement of individuals in the global community as an antecedent of well-being through social considerations (Vella-Brodrick and Stanley 2013). With increasing urbanization and global population growth, the need for an efficient and sustainable transportation system is becoming increasingly urgent. The main challenge is how to meet these mobility needs without sacrificing environmental sustainability and social welfare. Overall, the level of emissions sourced from transportation increased more rapidly, at an average annual rate of 1.7% (Jaiprakash *et al*. 2017). In Indonesia, over the last 10 years, the transportation sector has contributed to carbon dioxide emissions at an average of 23% every year (European Commission: Joint Research Centre *et al*. 2024) (Figure 1).

Transportation is closely correlated with the responsibility of using fossil fuels. Inefficient and unfriendly transportation contributes significantly to problems such as traffic congestion, air pollution, and increased greenhouse gas (GHG) emissions. Therefore, the development and implementation of more sustainable transportation systems is important not only to reduce these negative impacts but also to ensure a better quality of life for future generations (Turan *et al*. 2024). Focusing on fuel as the driving force of transportation mobility, reducing emissions is important for realizing climate targets. Climate change is a global environmental problem that has often been discussed. This event is natural, so it must occur over time. However, since the industrial revolution and the adaptation of technology, climate change patterns have occurred uncontrollably (Turan *et al*. 2024). One of the major contributions to climate change is the alarming increase in pollution from human mobility in motorized vehicles (Li *et al*. 2021).

Recognizing the urgency of this problem, the United Nations (UN) established a framework convention on climate change through the United Nations Framework Convention on Climate Change (UNFCCC) and initiated global efforts. One of these is the creation of a universal agreement on climate management called the Paris Agreement. Diesel engines are important for meeting global transportation needs. The main problem related to the environment is that diesel releases harmful emissions that increase global warming, which must be controlled (Muthiya *et al*. 2022). However, the recent phenomenon of diesel scarcity also requires serious attention. The results of processing annual fuel production data from the Directorate General of Oil and Gas of the Ministry of

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Energy and Mineral Resources show that biodiesel (CN 48) tends to decrease. The mobility of the transportation and logistics sector is highly dependent on diesel fuel because many of the vehicles used are equipped with diesel engines (Figure 2). In various regions, there were long queues of vehicles at refueling stations due to running out of diesel stock for days. This scarcity hampers the flow of transportation mobility. The decrease in the number of vehicles disrupts the supply chain of goods distribution, triggering an increase in product prices in the market (Figure 3). The agriculture and fisheries sectors, which rely on diesel for ships and heavy equipment, are also inseparable from this impact, which ultimately reduces productivity. Accelerating the transition of the transportation mobility sector is urgently required (Kii 2020). The climate crisis and ambiguity of fuel depletion have prompted research to explore the potential for improving transportation performance while minimizing the impact on the environment. Alternative fuels have been proposed to offset metric tons of harmful gases and protect the environmental ecosystem. Biofuels are important candidates for renewable energy market products owing to the high interest in energy security, GHG mitigation, and socio-economic harmonization (Han *et al.* 2017).

The development of this fuel supports environmental sustainability as it is biodegradable. Biofuels derived from biological raw materials have a high viscosity level that allows the oxidation and combustion processes to increase, thereby reducing the pollution rate in diesel engines (Hameed and Muralidharan 2023). Keruing (*Dipterocarpus* spp.) is a timber tree endemic to tropical forest areas and is available in Indonesia. In addition to producing wood, this species also produces non-wood products in the form of resins, which can be in the form of sap and oil (Puthongking *et al.* 2022). Previous research has found

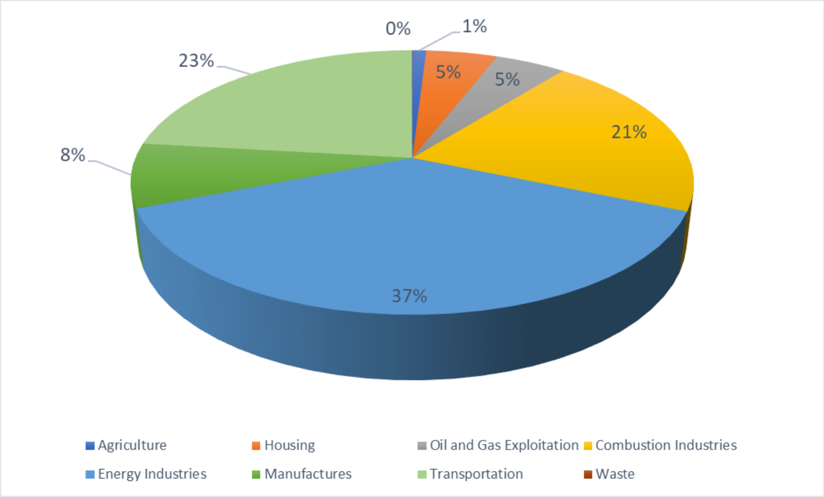

Figure 4 Average annual carbon dioxide (CO2e) emissions in Indonesia during 2014–2023 (EDGAR 2024).

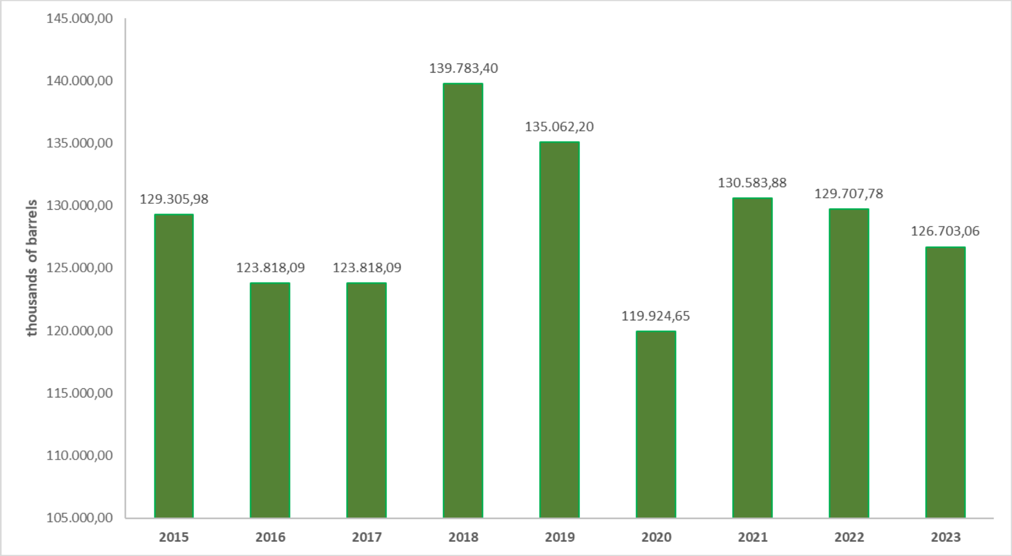

Figure 2 Annual biodiesel production (CN 48) (KESDM 2024).

that the chemical structure and combustion characteristics of keruing oil are equivalent to those of diesel fuel (Khunchalee and Roschat 2020). Through its renewable nature and cleaner energy products, keruing offers solutions to support a sustainable green fuel transition. This study aimed to examine the potential of keruing as an alternative to diesel fuel and its development challenges in Indonesia.

METHODS

This study explored the potential use of keruing non-wood products as diesel fuel to realize a sustainable energy transition. The data used in this study were a combination of primary and secondary data. Primary data were obtained from the results of direct observation of field problems related to the research objectives. Secondary data were obtained from the Directorate General of Oil and Gas of the Ministry of Energy and Mineral Resources and the *Emission Database for Global Atmospheric Research* (EDGAR) (Figure 4).

iNaturalist

This platform was developed from the results of a collaboration between the California Academy of Sciences and National Geographic to produce data from various regions (Munzi *et al.* 2023). iNaturalist integrates artificial intelligence in computer imaging of nature through citizen science (Aristeidou *et al.* 2021). The observation data produced by iNaturalist are in the form of taxonomic species information in a place, complete with the time of collection supported by images. In this study, the limitation in data collection at iNaturalist with the keyword "Dipterocarpus" was in the location of Indonesia. As a result, 73 observations were recorded from September 2012 to October 2024 (Table 1). This citizen science contribution is effective in helping to trace unknown species, details of their location, and distribution areas without having to conduct direct research on site by involving institutions to avoid wasting funds during the data collection process (Wangyal *et al.* 2022).

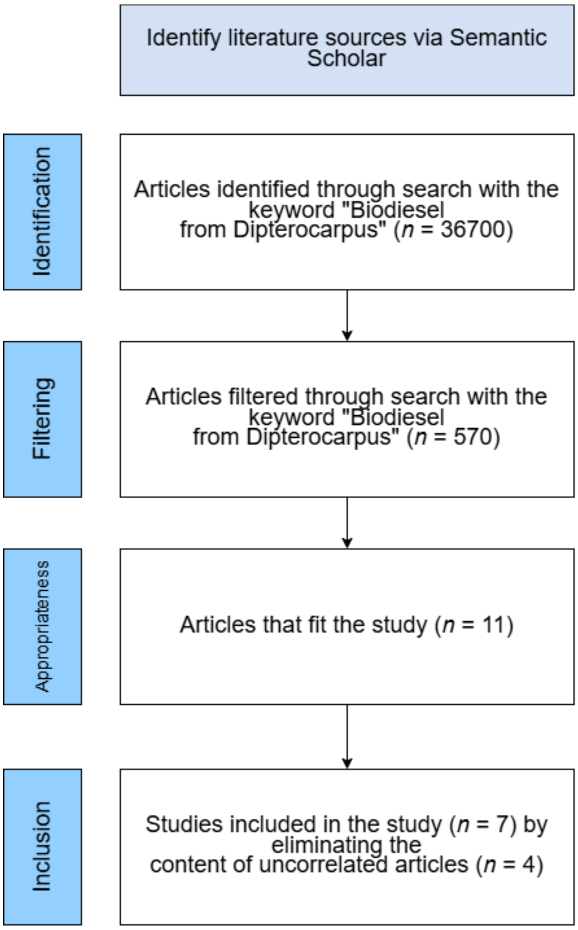

Figure 5 PRISMA diagram on research.

Figure 3 Biodiesel scarcity at one of the petrol stations in Bondowoso Regency, East Java.

Table 11 Distribution of keruing species (Dipterocarpus spp.) in Indonesia during 2012−2024

Species	Number	Location (Island)
Dipterocarpus confertus	2	Kalimantan
Dipterocarpus cornutus	1	Kalimantan
Dipterocarpus costatus	1	Kalimantan
Dipterocarpus costulatus	1	Sumatra
Dipterocarpus crinitus	2	Kalimantan
Dipterocarpus elongatus	2	Kalimantan, Java
Dipterocarpus gracilis	1	Kalimantan
Dipterocarpus grandiflorus	3	Sumatra, Kalimantan
Dipterocarpus hasseltii	7	Sumatra, Bali, Jawa
Dipterocarpus humeratus	2	Sumatra
Dipterocarpus littoralis	1	Java
Dipterocarpus oblongifolius	1	Kalimantan
Dipterocarpus retusus	9	West Nusa Tenggara, Bali, Java
Dipterocarpus sp.	39	Sumatra, Kalimantan, Java, Bali, Papua
Dipterocarpus sublamellatus	1	Kalimantan

Source: iNaturalist

Semantic Scholar

Semantic Scholar applies machine learning in natural language processing to understand the context and content of scientific papers to present more relevant search results. The machine learning algorithms on this platform can group similar articles, identify citations, and recommend related articles based on research data patterns relevant to the topic under review. Data were obtained from this database using the systematic literature review (SLR) method by identifying and collecting more specific study results (Carrera-Rivera *et al.* 2022). Literature sources were used to obtain theoretical foundations, perspectives, and previous research results relevant to the problem being researched (Sugiyono 2019). The results obtained from the literature were further analyzed to obtain the theoretical foundation and previous research results that support this research.

RESULTS AND DISCUSSION

The threat of the fuel energy crisis that is being faced has encouraged research on alternative fuels from plants. Biomass is a promising renewable energy candidate as an energy source that can replace conventional fuels (Gupta and Agarwal 2021). The threat of depletion of fossil fuels, increasing energy demand, superiority of fuels with lower pollutants, and the efficient performance of suitable engines (Chanthawong *et al.* 2016) in the long term encourage the development of biofuels. As a tropical region overgrown with various species of flora, Indonesia could achieve national energy independence by developing biomass, bioethanol, biodiesel, and biogas. One of the plants endemics to the tropics, whose distribution is quite high in Indonesian forests, is keruing (*Dipterocarpus* spp.). The keruing tree has a cylindrical straight trunk height of up to 40–50 m with a grayish-brown bark color (Sudarmonowati *et al.* 2021). Trees that are in great demand because of the commercialization of their wood products can also produce non-wood products called resin in the form of oil and sap (Saengavut and Jirasatthumb 2021). On average, one large keruing tree can release between 22.5 and 31.1 L of oil and can even reach 32.5 L through tapping by injuring the trunk, which is then given steam from the fire to drain the oil (Srichat *et al.* 2021). The development of the keruing tapping technique to minimize stress on plants involves using an electric drill to pierce the tree trunk to half the diameter and allowing the oil to flow in a hose without heat treatment in the hole (Suiuay *et al.* 2019) to reduce injuries to the stem organs (Table 2).

Long before the advent of technology, the use of keruing trees as an energy source has been practiced. Southeast Asians use keruing oil to make torches. The results of the study of physicochemical structure reported that the composition of keruing oil is suitable (Leesing *et al.* 2022) to produce plant-based fuels (biofuels). Biofuels for diesel engines can be produced by transesterification of vegetable and animal oils, thermal distillation of vegetable oils with other similar fuel mixtures, and it has even been found that biofuel production can be done through the rapid pyrolysis method (Rashed *et al.* 2016). Broadly speaking, the suitability of keruing oil for biodiesel was reviewed based on its characteristics, including composition and engine performance, such as torque, power, thermal engine efficiency, and exhaust gases.

The main component of refined keruing oil is a sesquiterpene group of hydrocarbon compounds. Hydrocarbon compounds like fossil diesel oil allow keruing oil to produce more energy than biodiesel. Based on the results of gas chromatography tests with mass spectrometers (Yongram *et al.* 2019), the oil consists of compounds α–gurjunene (30.31%), isoledene (13.69%), β-caryophyllene (3.14%), γ-gurjunene (3.14%), alloaromadendrene (3.28%), and spathulenol (1.11%) (Artchayasawat *et al.* 2021). Its higher calorific value compared to biodiesel (Khunchalee and Roschat 2020) provides better combustion efficiency with engine performance close

Table 12 Research development on the potential of keruing oil (Dipterocarpus spp.) for biodiesel fuel

Researcher	Objective	Result
Khunchalee and Roschat 2020	Studying the physico-chemical structure of keruing oil as a potential liquid biofuel material in Thailand.	The FTIR test shows that keruing oil is a hydrocarbon compound with composition, heat, and fuel properties that meet the biodiesel qualification.
Senawong *et al.* 2020	Comparing the performance and emissions of diesel engines that use keruing oil fuel with conventional diesel fuel	Keruing's oil-fueled diesel engine has experienced an average increase in torque, braking power, and thermal efficiency with a decrease in fuel consumption. However, emissions from CO, CO_2, and NO_X increased slightly.
Khangwichian *et al.* 2021	Investigating the effect of chemical agent type on the pore properties of activated carbon generated from the solid waste of Dipterocarpus alatus leaves hydrolyzed by oleaginous yeast and chemically activated	*Dipterocarpus alatus* leaves can be used as a biodiesel production material. The waste in the form of pulp still has the potential to be processed into activated carbon.
Katekaew *et al.* 2021	Optimizing the performance and exhaust emissions of single-cylinder diesel engines by mixing diesel-like fuel (DLF) from pyrolytic oil with biodiesel from used cooking oil (WCOB) as well as engine speed variations	A DLF-WCOB mixture of about 20% at an optimal engine speed of 1700 rpm can improve engine performance, reduce exhaust emissions, and can be used as an alternative fuel for diesel engines.
Puthongking *et al.* 2022	Identifying the chemical components of oleoresin.	Keruing produces oleoresin, which can be in the form of oil or rubber. Distillation to make it a biofuel extracts dipterocarpol oleoresin.
Sakkampang *et al.* 2023	Testing the performance and emissions of diesel engines with a biodiesel blend from keruing oil to be compared with standard diesel fuel	Biofuel that works according to diesel standards for engines is a mixture of keruing oil and diesel with a ratio of 70:30 and 80:20.
Roschat *et al.* 2024	Searching for efficient and cost-effective liquid biofuels for agricultural diesel engines through the mixing of three fuels from used cooking oil biodiesel, distilled keruing oil, and conventional diesel oil	The mixture of the three types of biofuels with a ratio of 50:30:20 and 50:25:25 is equivalent to B10 diesel.

to that of conventional diesel. Compared to diesel, diesel engines that use keruing fuel oil have an increase in torque of 5.22%, brake power of 5.38%, and thermal efficiency of 4.27%. The oil consumption was 6.27% lower than the diesel expenditure (Senawong *et al.* 2020).

The combustion in the engine and pollution from imperfect combustion residues are important for evaluating fuel performance. Focusing on the thermal decomposition of the oil, the thermogravimetry technique showed that the refined keruing oil underwent faster and cleaner decomposition, with a combustion temperature below 80°C. The characteristics of this distillate are comparable to those of diesel fuel, showing the same combustion temperature in the range of 200–300°C (Khunchalee and Roschat 2020), allowing its use in diesel engines, especially for heavy equipment in agricultural transportation (Figure 5).

The cloud point, oxidation stability, flash point, moisture content, and corrosion to copper in keruing oil were in accordance with the American Standard Testing and Material (ASTM) bio-automotive fuel standard. However, the density of keruing oil is still above the ASTM standards (Khunchalee and Roschat 2020); therefore, it must be mixed with conventional diesel or other biodiesels to meet liquid fuel standards. Fuel densities that are higher or lower than the standard cause evaporation to occur in a narrow temperature range. As a result, combustion occurs rapidly, increasing the pressure in the combustion chamber, which can damage the engine performance. Therefore, research to optimize the combustion of biofuels from keruing and its impact on exhaust emissions continues to be developed. Commonly used techniques to improve the structure of fuels include mixing other fuels or adding additives such as diesel-biodiesel, diesel-bioethanol, biodiesel-*n*-butanol, diesel-butanol, biodiesel-gasoline-kerosene, and the addition of nano-additives in the diesel-biodiesel mixture (Figure 6).

Quadratic method modeling or Rotatable Central Composite Design (RCCD) using statistical analysis (ANOVA) Response Surface Methodology (RSM) was applied to a mixture of keruing biofuel and used cooking oil by varying the proportion of used cooking oil and engine speed. Tests were carried out to find out how to optimize the performance and exhaust gases of single-cylinder diesel engines. The higher the mixture of used cooking oil, the more optimal the engine performance during combustion. Meanwhile, exhaust gas emissions also increased with an increase in the percentage of used cooking oil (Katekaew *et al.* 2021).

Biofuel-Based Fuel Transition: Opportunities and Challenges

Tropical forest areas are home to an incredible wealth of flora, with many types of plants that have great potential as a source of biofuels. Trees such as castor trees, coconuts, and keruing are known to produce oils as renewable fuel candidates. The use of these natural resources is a great opportunity for the transition to sustainable fuels, especially to reduce dependence on fossil fuels, which are increasingly depleted. In addition, biofuels from tropical forests can help reduce carbon emissions and support the achievement of net-zero emissions targets in the future (Shakya *et al.* 2023).

Figure 6 Keruing oil visible on the log.

Figure 7 Soaking keruing logs in a room temperature pool.

The transition to sustainable fuels is not only an option to address the impacts of climate change but also an urgent need due to limited fossil fuel reserves. However, in practice, it is not easy because it is closely related to the policy and availability of the state as an object (Kamali-Saraji and Streimikiene 2023). The field reality shows that many challenges are faced in energy transition efforts. In this study, the challenges of implementing a sustainable fuel transition are classified into four scopes (Figure 7).

- **Infrastructure**

The transition of the energy system requires fundamental changes in infrastructure, politics (Muinzer and Ellis 2017), and consumer behavior. For example, the transition from gasoline-fueled vehicles to electric vehicles requires automotive technology innovation and new infrastructure equipped with electric-charging points. The uncertain demand for renewable energy is also a challenge to the stability of the energy grid (Hunt *et al.* 2023), which means that innovative energy infrastructure is essential. However, infrastructure privatization reduces a country's capacity to manage climate change mitigation efforts. Some facilities, especially transportation, which are old and less flexible to apply innovation, also hinder the penetration of renewable energy. Consequently, decisions related to the focus of infrastructure development can result in regional economic inequality that risks energy poverty (Bachner *et al.* 2020).

- **Science and Social**

Public acceptance and involvement in fuel transitions are often hampered by a lack of understanding of new technologies (Smith and Stirling 2007). On the one hand, education and public awareness are still low on the benefits of biofuels in reducing carbon emissions. There is no theoretical basis for applying the potential utilization of resin from cut-down keruing wood. To date, keruing has only been used for the purpose of commercializing its timber. Behavioral changes and resistance are also obstacles because people tend to maintain old habits and doubt the effectiveness of renewable energy. In addition, energy justice is a major concern because the impact of this transition may be uneven. Workforce transition also poses a challenge (Meadowcroft 2016) as the fossil-based energy sector must shift to a workforce skilled in biofuel technology. Finally, energy security remains a critical issue, where dependence on biofuels requires supply stability and adequate infrastructure to meet the growing demand for energy (Novikau 2021).

- **Economy**

The economy is a driving force of life and a challenge that hinders the transition to environmentally friendly energy. This is due to the imbalance between the funds needed to support low-carbon technologies and the availability of such funds. The need for climate change mitigation and adaptation incurs considerable costs. The main challenge in the development of low-carbon energy is the lack of international cooperation and private investment (Shem *et al.* 2019). Many non-profit investors or individuals do not have sufficient incentives to participate in renewable energy, and sometimes their participation in renewable energy is even hampered. The government needs to provide commercial incentives to reduce investment risk, especially in terms of public financing. Most low-carbon energy projects are expected to be financed by private funds; therefore, a major shift in private investment

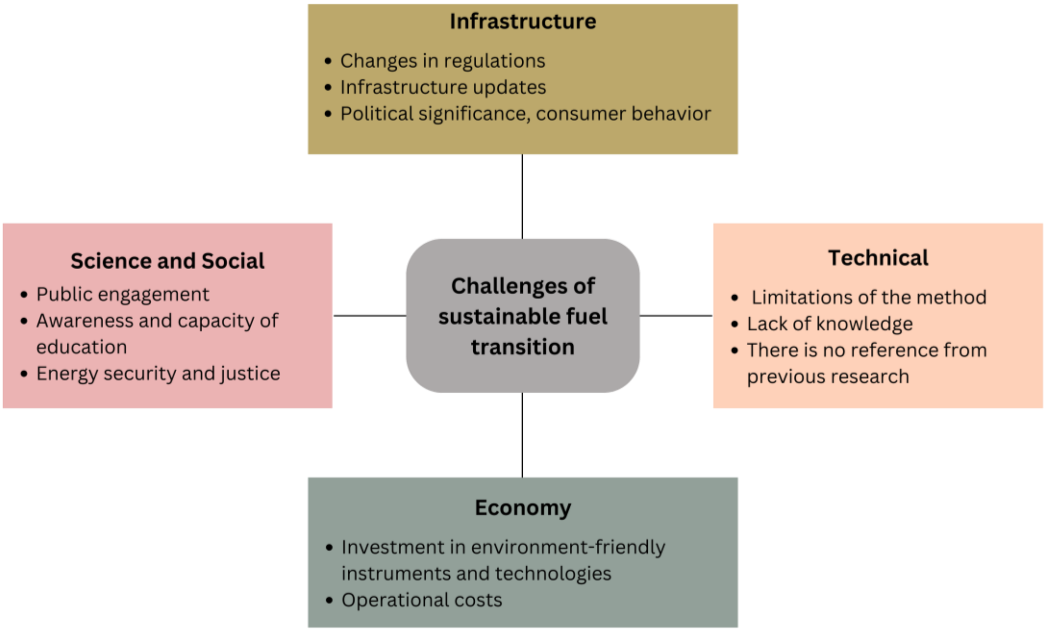

Figure 8 Sustainable fuel transition challenge framework.

from existing energy systems to low-carbon systems will be required. Policies such as subsidies for fossil fuels also have a negative impact due to the actions of irresponsible individuals (Monasterolo and Raberto 2019). Subsidies that are not on target encourage the use of excess fuel that is hoarded, which hinders the adoption of renewable energy. Subsidy reform is needed to balance the economic sustainability and market costs of various energy sectors.

- **Technical**

The low-carbon transition is a complex long-term process driven by many factors (Wu et al. 2020). The low-carbon energy transition requires the adoption of new technologies (Rosenbloom et al. 2018), policies, and regulations. This complex process requires a considerable amount of time for implementation. Current regulations are inadequate to support the application of new technologies, such as distributed energy, renewable energy, and information technology, in the energy industry. In addition, decisions and regulations that do not include all potential pollutants can allow waste production that remains legal to keep going. Keruing wood is favored by the manufacturing industry as the main raw material for processing. One of these tropical forest wood products was chosen as the main raw material for making veneers. Veneer is a very thin sheet of wood with a thickness of approximately 0.3 mm. This group I-II commercial hardwood has several features, including flexibility, color, and regular straight-grain patterns. Veneer is usually used as a raw material for plywood or as a surface finish for cabinets to enhance their appearance. One aspect that determines the feasibility of veneers for sale in the international market is that they do not contain oil and rubber.

As forest trees that produce non-timber products, certain species contain oils and sap that degrade the quality of the wood, which remains an unresolved problem. The distribution of keruing wood faces several significant problems in the manufacturing industry, mainly due to its oily and gummy nature. No effective separation technique has been found for separating keruing sap and oil. Consequently, wood with these characteristics cannot be treated optimally and has the potential to become wasteful. The high oil and sap content reduces the quality of wood so that it does not reach the international standard American Standard Testing and Material (ASTM), one of which is the in fact, wood with oily and rubbery properties is more appropriate for biofuel production than just harvested wood. This problem is exacerbated by the raw material procurement system regulated by local forestry services. As a forest product, keruing is managed in the timber forest product primary industry business license (IUIPHHK), where logging is carried out, considering physical aspects. Consequently, the industry lacks the flexibility to select wood raw materials that meet the required specifications, including avoiding wood with high oil and sap content.

To date, no technique has been proven successful in extracting oil and sap from felled keruing trunks (logs). The solution to the oil and sap problem applied by industry through immersion in warm water at 40°C or cold water at room temperature is not able to remove the sap effectively. Although the oil content appears to be partially empty, there is no guarantee that the structure of the wood fiber is free from oil content. This shows that the use of keruing wood is not on target. Problematic timber that has great potential for processing into biofuels has reached the industry. Further research is needed to trace how the technique of separating oil and sap from keruing stems is performed. Therefore, oily keruing, which is a raw material in the manufacturing industry, is not just taken from wood.

CONCLUSION

Based on the results of this study, it can be concluded that the development of biofuel from keruing oil *(Dipterocarpus* spp.*)* has great potential for supporting a sustainable fuel transition in Indonesia's transportation sector. The physicochemical structure of the oil, which is equivalent to the standard composition of diesel fuel, supports the production process of biofuels from keruing, which can be an important alternative for reducing dependence on fossil fuels. In addition, the potential for the development of biofuels contributes to the environment in the context of climate change mitigation. However, given the complexity of the sustainable energy transition, there are many challenges that must be faced to achieve it. Limitations in methods and technologies, as well as economic, social, and infrastructure factors, are the main obstacles to the widespread implementation of biofuels. Overall, despite the complex challenges, with the synergy between technology, policy, and sustainability commitments, keruing oil can be an important part of green energy solutions in Indonesia's transportation sector.

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