Journal of Energy Bioscience 2024, Vol.15, No.4, 243-254
http://bioscipublisher.com/index.php/jeb

Review and Progress **Open Access**

A Comprehensive Review of Palm Oil in Biodiesel Production: From Cultivation to Market

Qi Lin, Wei Zhou ✉
Biotechnology Research Center, Cuixi Academy of Biotechnology, Zhuji, 311800, Zhejiang, China
✉ Corresponding email: wei.zhou@cuixi.org

Journal of Energy Bioscience, 2024, Vol.15, No.4 doi: 10.5376/jeb.2024.15.0023
Received: 03 Jun, 2024
Accepted: 09 Jul., 2024
Published: 21 Jul., 2024

Preferred citation for this article:
Lin Q., and Zhou W., 2024, A comprehensive review of palm oil in biodiesel production: from cultivation to market, Journal of Energy Bioscience, 15(4): 243-254 (doi: 10.5376/jeb.2024.15.0023)

Abstract The study highlights several key findings. Palm oil is an excellent raw material for biodiesel production due to its high oil content and favorable properties that closely resemble petro-diesel. The global market for palm oil biodiesel is significant, with palm biodiesel contributing to 35% of the global biodiesel market and expected to reach a market value of US$92.84 billion by 2021. The use of palm oil by-products and mill effluent for biodiesel production is feasible and can mitigate the food versus fuel debate. The production process of palm biodiesel, including transesterification with methanol and potassium hydroxide, yields biodiesel that meets ASTM standards. The environmental impact of palm biodiesel is favorable, with lower emissions of harmful pollutants and greenhouse gases compared to fossil fuels. The findings suggest that palm oil is a viable and sustainable source for biodiesel production. Utilizing palm oil by-products and mill effluent can further enhance the sustainability of biodiesel production, addressing both economic and environmental concerns. The study underscores the importance of palm oil in the future of renewable energy sources, particularly in regions like Malaysia, Indonesia, and Thailand, which are leading producers of palm oil.

Keywords Palm oil; Biodiesel production; Renewable energy; Sustainability; Transesterification; Environmental impact; Economic analysis; By-products; Mill effluent

1 Introduction

The sustainability of petroleum-based fuel supply has gained broad attention from the global community due to the increase in usage across various sectors, depletion of petroleum resources, and the volatility of crude oil market prices. Additionally, environmental concerns have arisen from the increasing emissions of harmful pollutants and greenhouse gases. As a result, the use of clean energy sources, including biodiesel, has become crucial. Biodiesel is primarily produced from renewable natural resources through a transesterification process, offering several advantages over petro-diesel, such as being non-toxic, biodegradable, and containing fewer air pollutants per net energy produced (Zahan and Kano, 2018; Lam and Lee, 2019). The global push towards renewable energy sources has led to extensive research and development in biodiesel production from various oil-bearing crops, including soybean, rapeseed, sunflower, and notably, palm oil (Lam and Lee, 2019; Mahlia et al., 2019).

Palm oil has emerged as a significant feedstock for biodiesel production due to its high oil yield and favorable properties that closely resemble those of conventional diesel. Palm oil is derived from the fruit of the oil palm tree and is known for its high productivity and positive energy balance, making it a viable alternative to fossil fuels (Mahlia et al., 2019; Fardilah et al., 2023). The use of palm oil in biodiesel production is particularly prominent in countries like Indonesia and Malaysia, which are among the largest producers of palm oil globally (Ishola et al., 2020; Fardilah et al., 2023). The advantages of palm oil biodiesel include its renewable nature, reduced greenhouse gas emissions, and its potential to contribute to energy security and economic development in producing countries (Dey et al., 2020; Zulqarnain et al., 2021). However, the use of palm oil for biodiesel has also sparked debates regarding food versus fuel and the environmental impact of palm oil cultivation, necessitating a comprehensive review of its feasibility and sustainability (Zahan and Kano, 2018; Dey et al., 2020).

This study aims to provide a comprehensive analysis of palm oil in biodiesel production, covering the entire value chain from cultivation to market. It examines the cultivation practices and yield of oil palm trees, highlighting the factors that influence productivity and sustainability. The study also analyzes the various technologies and processes involved in the extraction of palm oil and its conversion to biodiesel, including transesterification and other innovative methods. Additionally, it evaluates the economic, environmental, and social impacts of palm oil biodiesel production, with a focus on life cycle emissions, energy balance, and market dynamics. The challenges and opportunities associated with the use of palm oil as a biodiesel feedstock are discussed, including the potential for utilizing by-products and waste materials to enhance sustainability. The study provides insights into the future prospects of palm oil biodiesel in the context of global energy transitions and policy frameworks. By addressing these objectives, this study aims to offer a holistic understanding of the role of palm oil in biodiesel production and its potential contribution to a sustainable energy future.

2 Palm Oil Cultivation

2.1 Overview of palm oil plant biology

The oil palm (*Elaeis guineensis*) is a tropical plant known for its high oil yield, making it a valuable crop for biodiesel production. The plant thrives in humid tropical climates with well-distributed rainfall and temperatures ranging from 24 °C to 32 °C. Oil palms are typically grown in monoculture plantations, which can lead to reduced biodiversity compared to the forests they replace (Darras et al., 2019; Gómez et al., 2023). The plant's biology includes a robust root system that helps in nutrient uptake and water absorption, essential for its growth and productivity.

2.2 Major regions of palm oil cultivation

Palm oil cultivation is predominantly concentrated in Southeast Asia, particularly in Malaysia and Indonesia, which together account for over 90% of global production (Meijaard et al., 2020; Uning et al., 2020). Other significant regions include Thailand, Nigeria, and parts of Central and South America. In Thailand, for instance, the southern region is most suitable for oil palm cultivation due to its favorable climate and soil conditions (Jaroenkietkajorn and Gheewala, 2021). Nigeria also has a substantial palm oil industry, leveraging its tropical climate to produce biodiesel from palm olein (Ishola et al., 2020) (Figure 1).

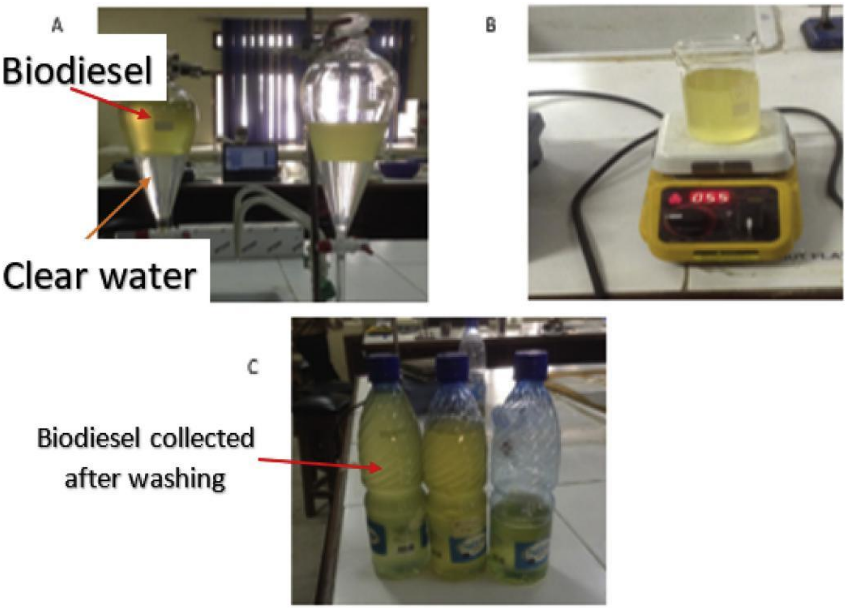

Figure 1 (a) Washing of Crude Biodiesel, (b) Drying of the Biodiesel, (c) Biodiesel obtained (Adopted from Ishola et al., 2020)

2.3 Agricultural practices and sustainability concerns

Effective soil management is crucial for maintaining the productivity of oil palm plantations. Practices such as reduced fertilization and mechanical weed control have been shown to enhance soil quality and biodiversity without compromising yield (Darras et al., 2019). However, excessive use of chemical fertilizers can lead to increased greenhouse gas emissions and soil degradation (Fernández-Coppel et al., 2018; Jaroenkietkajorn and Gheewala, 2021).

Oil palm plantations significantly impact local water cycles. They have higher evapotranspiration rates and lower soil infiltration capacities compared to natural forests, leading to altered water availability and movement (Gómez et al., 2023). Sustainable water management practices are essential to mitigate these impacts and ensure long-term viability.

Pest and disease control in oil palm plantations often involves the use of chemical pesticides, which can have detrimental effects on the environment. Alternative methods, such as integrated pest management (IPM), are being explored to reduce reliance on chemicals and promote ecological balance (Darras et al., 2019).

2.4 Impact of climate change on palm oil cultivation

Climate change poses significant challenges to palm oil cultivation, affecting both the growth conditions and the environmental impact of plantations. Rising temperatures and changing precipitation patterns can alter the suitability of regions for oil palm cultivation, potentially leading to shifts in plantation areas (Uning et al., 2020). Additionally, the conversion of forests to oil palm plantations contributes to CO_2 emissions, exacerbating climate change (Rulli et al., 2019). Sustainable practices and adaptive management strategies are essential to mitigate these impacts and ensure the resilience of the palm oil industry in the face of climate change (Zahan and Kano, 2018; Meijaard et al., 2020).

3 Harvesting and Processing of Palm Oil

3.1 Methods of harvesting palm oil fruits

Harvesting oil palm fruits is a critical step in the production of palm oil, as it directly impacts the yield and quality of the oil. The ideal harvesting cycle involves visiting each palm every eight to twelve days to avoid issues such as loose fruit picking, over-ripeness, or rotten fruit harvesting. Optimizing the harvest cycle can significantly improve yield, as demonstrated in a case study of a 2 000-hectare plantation where reducing the harvest cycle length from 19.6 to 8.3 days showed strong potential for yield improvement (Escallón-Barrios et al., 2020).

3.2 Processing techniques

Traditional methods of palm oil extraction typically involve manual processes that produce lower quality and quantity of oil. For instance, manual vertical presses are commonly used but have been shown to have lower oil extraction ratios (OER) and oil extraction efficiencies (OEE) compared to more modern methods. These traditional methods also result in higher oil extraction losses (OEL) (Kiggundu, 2020).

Modern methods of palm oil processing include the use of motorized extractors and advanced technologies such as microwave treatment and solvent extraction. Motorized palm oil extractors have been shown to produce higher quality oil with better performance efficiencies compared to manual methods. For example, a motorized extractor demonstrated higher OER and OEE, and lower OEL compared to a manual vertical press (Kiggundu, 2020). Additionally, microwave treatment followed by solvent extraction has been optimized to improve the quality of oil extracted from loose fruitlets, which are often more oil-rich than the inner layers of the bunch (Hadi, 2021).

3.3 Quality control in palm oil extraction

Quality control in palm oil extraction is essential to ensure the production of high-quality oil. The latest developments in process technologies aim to improve the sustainability and efficiency of palm oil production while enhancing oil quality. Efforts have been intensified to develop methods that reduce process contaminants such as 3-monochloropropane diol (3-MCPDE) and glycidyl ester (GE), which are found in refined edible oils. These advancements are crucial for producing crude palm oil with improved quality (Chew et al., 2021). Additionally, the quality of oil is assessed through various physio-chemical parameters such as free fatty acids (FFA), iodine value (IV), saponification value (SV), and peroxide value (PV) (Kiggundu, 2020).

3.4 By-products of palm oil processing

Palm oil processing generates several by-products, including palm kernel (PK), mesocarp fiber (MF), and palm kernel shell (PKS). These by-products have significant energy value and can be utilized to improve the overall efficiency of the production process. For example, the energy value of empty fruit bunch (EFB), MF, and PKS can be harnessed to reduce energy losses associated with different processing routes. The industrial route, while having high throughput and producing high-quality crude palm oil (CPO), is associated with higher fruit losses and energy losses compared to small-scale routes (Anyaoha et al., 2018). Proper management and utilization of these by-products can enhance the sustainability of palm oil production.

By integrating advanced harvesting and processing techniques, along with stringent quality control measures and efficient by-product management, the palm oil industry can achieve higher yields, better oil quality, and improved sustainability.

4 Conversion of Palm Oil to Biodiesel

4.1 Chemical composition of palm oil relevant to biodiesel

Palm oil is a highly suitable feedstock for biodiesel production due to its high content of free fatty acids (FFAs) and triglycerides. The primary fatty acids present in palm oil include palmitic acid, oleic acid, linoleic acid, and stearic acid. These components are crucial for the transesterification process, which converts these fatty acids into fatty acid methyl esters (FAMEs), the main constituents of biodiesel (Ding et al., 2018; Phromphithak et al., 2020).

4.2 Transesterification process

The transesterification process is the most common method for converting palm oil into biodiesel. This chemical reaction involves the conversion of triglycerides in palm oil into FAMEs and glycerol by reacting with an alcohol, typically methanol, in the presence of a catalyst. The process can be enhanced using various techniques such as microwave irradiation, which significantly reduces reaction time and increases yield (Ding et al., 2018; Phromphithak et al., 2020). For instance, using microwave irradiation with acidic imidazolium ionic liquids as catalysts has shown to achieve a maximal yield of 98.93% under optimized conditions (Ding et al., 2018).

4.3 Catalysts used in biodiesel production

Several types of catalysts are employed in the transesterification of palm oil, including homogeneous, heterogeneous, and enzymatic catalysts. Homogeneous catalysts like sodium hydroxide (NaOH) are commonly used due to their high efficiency, but they pose challenges in separation and purification of the final product (Chinglenthoiba et al., 2020). Heterogeneous catalysts, such as those derived from natural materials like clinoptilolite doped with Na^+ ions, offer advantages in terms of reusability and environmental impact (Abukhadra et al., 2021). Additionally, novel catalysts like Na^+/K^+ trapped muscovite/phillipsite composites have shown high effectiveness, achieving biodiesel yields up to 97.8% under ultrasonic irradiation (Abukhadra et al., 2019). Enzymatic catalysts, particularly lipases, are also gaining attention due to their specificity and mild reaction conditions, although they are generally more expensive (Moazeni et al., 2019).

4.4 Yield and efficiency of palm oil-based biodiesel

The yield and efficiency of biodiesel production from palm oil can vary significantly based on the catalyst and process conditions used. For example, using a Na^+/Clino nanocatalyst, a biodiesel yield of 96.4% was achieved under optimized conditions (Abukhadra et al., 2021). Similarly, a calcium-modified Zn-Ce/Al_2O_3 catalyst achieved a yield of 99.41% under specific conditions optimized by response surface methodology (Qu et al., 2021). These high yields demonstrate the potential of palm oil as an efficient feedstock for biodiesel production.

4.5 Comparison with other biodiesel feedstocks

Palm oil is often compared with other biodiesel feedstocks such as waste cooking oil, pequi bio-oil, and hybrid feedstocks. Waste cooking oil, for instance, is a cost-effective and sustainable alternative, but it often requires extensive pre-treatment to reduce impurities and FFAs (Milano et al., 2018; Bhatia et al., 2020). Pequi bio-oil has shown promising results with a FAME content of 99.4% under optimized conditions, but its availability is limited to specific regions (Cardoso et al., 2019). Hybrid feedstocks, such as blends of waste cooking oil and beauty leaf oil, have been developed to improve physicochemical properties and yield, demonstrating good potential as biodiesel feedstocks (Milano et al., 2018). However, palm oil remains one of the most efficient and widely available feedstocks for biodiesel production, making it a preferred choice in many regions (Ding et al., 2018; Phromphithak et al., 2020).

By leveraging various catalysts and optimizing process conditions, the conversion of palm oil to biodiesel can achieve high yields and meet international fuel standards, making it a viable and sustainable option for biodiesel production.

5 Environmental and Economic Aspects

5.1 Environmental impact of palm oil biodiesel production

5.1.1 Deforestation and habitat loss

The expansion of palm oil plantations has been a significant driver of deforestation and habitat loss, particularly in countries like Indonesia and Malaysia. Studies have shown that forest cover in concession areas has decreased by 20%, with forest fragmentation increasing by 44% compared to non-concession areas (Rulli et al., 2019). This deforestation not only reduces biodiversity but also impacts carbon storage, as oil palm plantations store significantly less carbon than pristine rainforests (Szulczyk and Khan, 2018; Rulli et al., 2019). Additionally, the conversion of peatlands for palm oil cultivation has led to further environmental degradation, including increased greenhouse gas emissions and loss of unique ecosystems (Meijaard et al., 2020).

5.1.2 Greenhouse gas emissions

Palm oil biodiesel production is associated with significant greenhouse gas (GHG) emissions, primarily due to land-use changes and the release of methane from palm oil mill effluents (POME). For instance, the treatment of POME is crucial as it emits methane, a potent GHG (Szulczyk and Khan, 2018). Moreover, the deforestation associated with palm oil cultivation contributes to CO_2 emissions, exacerbating climate change (Rulli et al., 2019). However, optimizing the production chain and implementing sustainable practices can reduce GHG emissions by up to 55% (Ramirez-Contreras et al., 2020). The use of biodiesel itself can also help reduce emissions compared to fossil fuels, contributing to global emission reduction targets (Zahan and Kano, 2018; Dey et al., 2020).

5.2 Economic viability and market trends

5.2.1 Production costs

The production costs of palm oil biodiesel are influenced by various factors, including the cost of raw materials and the efficiency of the production process. Palm biodiesel has been noted for its relatively low production cost compared to other biodiesel sources, with a price of approximately 660 USD/ton (Dey et al., 2020). However, the high cost of palm oil itself can make biodiesel less competitive with traditional diesel unless subsidized. For example, in Malaysia, government subsidies of RM 1.09 per liter (USD 0.28/liter) are necessary to make palm biodiesel economically viable (Szulczyk and Khan, 2018).

5.2.2 Global market dynamics

The global market for palm oil biodiesel is growing, driven by increasing demand for renewable energy sources and supportive policies in various countries. The market value of palm oil is expected to reach USD 92.84 billion by 2021, highlighting its economic significance (Dey et al., 2020). Major producers like Indonesia and Malaysia dominate the market, with a significant portion of their production destined for export (Rulli et al., 2019). The demand for palm oil biodiesel is also influenced by fluctuations in fossil fuel prices and the implementation of renewable energy policies worldwide (Zahan and Kano, 2018; Dey et al., 2020).

5.3 Regulatory frameworks and policies

5.3.1 National and international regulations

Regulatory frameworks at both national and international levels play a crucial role in shaping the palm oil biodiesel industry. Countries like Malaysia have implemented regulations to enhance the GHG efficiency of their agricultural sector, including mandates for POME treatment and deforestation prevention (Szulczyk and Khan, 2018). Internationally, agreements such as the Paris Agreement drive countries to adopt policies that reduce GHG emissions, indirectly promoting the use of biodiesel (Szulczyk and Khan, 2018; Ramirez-Contreras et al., 2020). Additionally, the European Union and the United States have renewable energy policies that significantly impact global palm oil production and trade (Rulli et al., 2019).

5.3.2 Incentives and subsidies

Incentives and subsidies are essential for the economic viability of palm oil biodiesel. Governments in major producing countries provide financial support to offset the high production costs and encourage the adoption of biodiesel. For instance, Malaysia's subsidy of RM 1.09 per liter for biodiesel production is a critical measure to make it competitive with traditional diesel (Szulczyk and Khan, 2018). Such incentives not only support the biodiesel industry but also help achieve environmental goals by reducing reliance on fossil fuels and lowering GHG emissions (Szulczyk and Khan, 2018; Ramirez-Contreras et al., 2020).

6 Case Studies

6.1 Successful implementations of palm oil biodiesel

Malaysia has been a leading example in the successful implementation of palm oil biodiesel. The country has developed a robust palm oil sector, which is a significant contributor to its economy, accounting for more than 5% of its GDP. The Malaysian government has successfully implemented the B5 and B7 biodiesel programs and is now focusing on the B10 blend (10% biodiesel, 90% petroleum diesel). These programs have increased the use of renewable energy sources and are expected to further boost the productivity of palm oil and biodiesel implementation in the country (Zulqarnain et al., 2020). Additionally, Malaysia's collaboration with Colombia in the biodiesel sector highlights the potential for international cooperation to enhance biodiesel policies and strategies (usoff et al., 2020).

Indonesia has also made significant strides in palm oil biodiesel production. The country implemented the B30 program in early 2020 to reduce its dependency on fossil fuels and protect its palm oil market. This initiative has shown positive results, with an average energy return on investment (EROI) of 3.92 for palm oil-based biofuel, indicating a positive energy return (Prananta and Kubiszewski, 2021). Furthermore, the integration of biomass residues in biodiesel production has improved the cost competitiveness of the industry, reducing dependency on government subsidies and enhancing resource efficiency (Harahap et al., 2019). Indonesia's efforts in palm oil biodiesel production have also been supported by life cycle assessments to ensure environmental sustainability (Wahyono et al., 2020) (Figure 2).

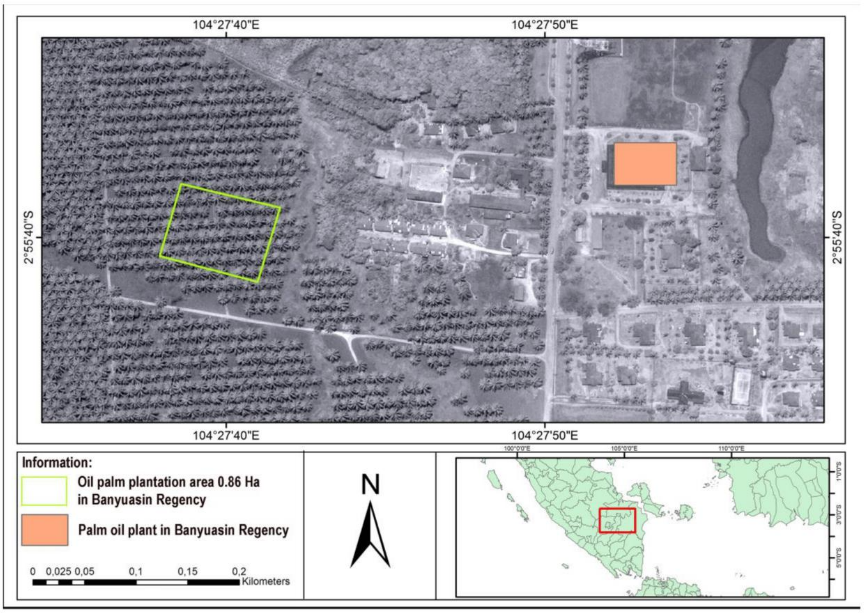

Figure 2 Map of the oil palm plantation in the Banyuasin Regency (Adopted from Wahyono et al., 2020)

6.2 Lessons learned from failures or challenges

Despite the successful implementation of the B5 and B7 programs, Malaysia faces several challenges in its biodiesel sector. The fluctuation in crude palm oil prices, low domestic usage of palm oil, and vehicle warranty issues have hindered the full-scale implementation of the B10 program. These challenges highlight the need for targeted efforts to improve palm oil productivity and promote biodiesel through specific agencies (Zulqarnain et al., 2020). Additionally, the environmental impact of palm oil cultivation, such as deforestation and habitat loss, has raised concerns that need to be addressed to ensure sustainable biodiesel production (Dey et al., 2020).

Indonesia's palm oil biodiesel program, while successful in some aspects, has faced criticism due to its environmental externalities, particularly during land preparation and restoration. The EROI of 3.92, although positive, has been categorized as "not feasible for development" compared to other renewable energy sources, indicating the need for significant improvements in the biofuel program (Prananta and Kubiszewski, 2021). The environmental performance of palm oil biodiesel production in Indonesia has also been a concern, with the oil palm plantation processing unit being the primary contributor to the carbon footprint, human health damage, and ecosystem diversity damage (Wahyono et al., 2020) (Table 1). These challenges underscore the importance of implementing more stringent environmental policies and improving the sustainability of palm oil biodiesel production.

Other Asian countries, such as Thailand, have also faced challenges in biodiesel production. High feedstock costs, insufficient feedstocks, high viscosity of biodiesel, and high nitrogen oxide (NOx) emissions have limited the widespread use of biodiesel compared to petrodiesel. These issues suggest the need for exploring alternative resources and improving the economic performance and yield production rate of biodiesel (Syafiuddin et al., 2020). The debate on the usage of palm oil as food versus fuel further complicates the situation, necessitating extensive studies to utilize by-products and mill effluent as raw materials for biodiesel production (Zahan and Kano, 2018).

In conclusion, while Malaysia and Indonesia have demonstrated successful implementations of palm oil biodiesel, they also face significant challenges that need to be addressed to ensure the sustainability and scalability of biodiesel production. Lessons learned from these challenges can guide future efforts in improving biodiesel policies, strategies, and environmental performance.

7 Challenges and Opportunities

7.1 Technical challenges in biodiesel production

One of the primary technical challenges in biodiesel production is feedstock variability. The quality and characteristics of feedstocks such as palm oil can vary significantly, affecting the efficiency and consistency of the biodiesel production process. For instance, the high viscosity of biodiesel derived from palm oil can pose challenges in its use and processing (Syafiuddin et al., 2020). Additionally, the presence of impurities in the feedstock can lead to issues in the transesterification process, which is crucial for biodiesel production (Ishola et al., 2020).

Process optimization is another significant technical challenge. The transesterification process, which involves converting oils into biodiesel, requires precise control of various parameters such as temperature, pressure, and catalyst concentration to achieve high yields and quality (Lam and Lee, 2019). Innovations in processing technologies, such as the use of supercritical and microwave-assisted transesterification methods, have been suggested to improve efficiency and reduce costs (Zulqarnain et al., 2021). However, these technologies need further development and scaling to be viable for large-scale production.

7.2 Socio-economic challenges

The socio-economic challenges associated with biodiesel production from palm oil are multifaceted. Land use conflicts are a major concern, as the expansion of palm oil plantations often leads to deforestation and displacement of local communities. This not only affects biodiversity but also raises ethical and social issues (Dey et al., 2020). The competition for land between food and fuel production exacerbates these conflicts, as the same land resources are needed for both purposes (Souza et al., 2018).

Table 1 Characterization of the impact assessment of biodiesel production (Adopted from Wahyono et al., 2020)

Impact category	Unit	Total	Biodiesel—Biodiesel Production	Methanol	Sodium Hydroxide	Water, Ultrapure	CPO-Palm Oil Production	Electricity, Low Voltage
Climate change—human Health	DALY	0.00432	0	0.000 422	4.54×10^{-5}	7.78×10^{-5}	0.003 537	0.000 236
Ozone depletion	DALY	5.44×10^{-7}	0	2.35×10^{-7}	5.95×10^{-8}	2.35×10^{-8}	2.04×10^{-7}	2.17×10^{-8}
Human toxicity	DALY	0.000 368	1.59×10^{-6}	8.66×10^{-5}	1.26×10^{-5}	1.17×10^{-5}	0.00021	4.64×10^{-5}
Photochemical oxidant formation	DALY	1.54×10^{-7}	0	5.1×10^{-8}	3.75×10^{-9}	1.54×10^{-8}	6.68×10^{-8}	1.67×10^{-8}
Particulate matter formation	DALY	0.000 936	0	0.000213	2.69×10^{-5}	4.13×10^{-5}	0.000 512	0.000 143
Ionizing radiation	DALY	1.74×10^{-6}	0	2.18×10^{-7}	7.57×10^{-8}	8 × 10−8	9.59×10^{-7}	4.07×10^{-7}
Climate change—ecosystems	species·yr	2.44×10^{-5}	0	2.39×10^{-6}	2.57×10^{-7}	4.41×10^{-7}	2 × 10−5	1.34×10^{-6}
Terrestrial acidification	species·yr	4.98×10^{-8}	0	1.67×10^{-8}	9.56×10^{-10}	1.72×10^{-9}	2.58×10^{-8}	4.65×10^{-9}
Freshwater eutrophication	species·yr	2.52×10^{-8}	0	3.28×10^{-9}	8.24×10^{-10}	2.06×10^{-9}	1.49×10^{-8}	4.15×10^{-9}
Terrestrial ecotoxicity	species·yr	2.44×10^{-7}	9.49×10^{-10}	8.12×10^{-9}	4.56×10^{-10}	2.74×10^{-9}	2.31×10^{-7}	1.36×10^{-9}
Freshwater ecotoxicity	species·yr	1.39×10^{-8}	8.01×10^{-10}	4.09×10^{-9}	3.95×10^{-10}	2.66×10^{-10}	6.47×10^{-9}	1.84×10^{-9}
Marine ecotoxicity	species·yr	2.24×10^{-9}	1.71×10^{-12}	4.84×10^{-10}	7.76×10^{-11}	7.04×10^{-11}	1.26×10^{-9}	3.48×10^{-10}
Agricultural land occupation	species·yr	9.13×10^{-7}	0	4.29×10^{-8}	2.5×10^{-8}	1.59×10^{-8}	7.25×10^{-7}	1.05×10^{-10}
Urban land occupation	species·yr	5.15×10^{-7}	0	5.32×10^{-8}	7.29×10^{-9}	7.06×10^{-8}	3.63×10^{-7}	2.11×10^{-8}
Natural land transformation	species·yr	7.18×10^{-7}	0	2.9×10^{-7}	8.35×10^{-9}	3.54×10^{-8}	3.48×10^{-7}	3.67×10^{-8}
Metal depletion	$	5.180 802	0	1.221	0.131	0.253	3.345	0.230
Fossil depletion	$	107.626 8	0	61.422	1.364	3.056	34.780	7.005

Labor conditions in palm oil plantations are another critical socio-economic challenge. Reports of poor working conditions, low wages, and exploitation of labor in some regions highlight the need for better labor practices and regulations (Fardilah et al., 2023). Ensuring fair labor conditions and sustainable practices in palm oil cultivation is essential for the long-term viability of biodiesel production.

7.3 Opportunities for improvement

Despite the challenges, there are significant opportunities for improvement in biodiesel production from palm oil. Innovations in cultivation practices, such as the development of high-yield and disease-resistant palm varieties, can enhance productivity and sustainability (Zahan and Kano, 2018). Additionally, the use of by-products and mill effluents from palm oil processing as feedstocks for biodiesel production can reduce waste and improve overall efficiency (Zahan and Kano, 2018).

Advances in processing technology also present opportunities for improvement. The adoption of more efficient and cost-effective transesterification methods, such as enzymatic and non-catalytic supercritical alcohol processes, can enhance biodiesel yields and reduce production costs (Lam and Lee, 2019). Furthermore, the integration of biodiesel production with other renewable energy sources and technologies can create synergies and improve the overall sustainability of the energy system (Kamil and Almarashda, 2023).

In conclusion, while there are significant technical and socio-economic challenges in biodiesel production from palm oil, there are also numerous opportunities for improvement. By addressing these challenges through innovation and sustainable practices, the potential of palm oil as a viable feedstock for biodiesel can be fully realized.

8 Future Prospects

8.1 Emerging technologies in palm oil biodiesel production

Emerging technologies in palm oil biodiesel production are pivotal for enhancing efficiency and sustainability. Recent advancements include the use of homogeneous, heterogeneous, enzymatic, noncatalytic supercritical alcohol, and ultrasound transesterification methods. These technologies aim to optimize the conversion process, reduce costs, and minimize environmental impacts (Lam and Lee, 2019). Additionally, innovative oil extraction technologies such as supercritical and microwave-assisted transesterification are recommended for their cost-effectiveness and efficiency (Zulqarnain et al., 2021). The integration of these advanced methods can significantly improve the overall yield and quality of palm oil biodiesel.

8.2 Potential for integrating palm oil biodiesel with other renewable energies

The integration of palm oil biodiesel with other renewable energy sources presents a promising avenue for enhancing energy security and sustainability. For instance, biorefineries can be designed to co-produce biodiesel and bio-jet fuel, leveraging the residual biomass from palm oil extraction (Julio et al., 2021). This integrated approach not only maximizes the utilization of palm oil but also diversifies the energy output, making the process more economically viable and environmentally friendly. Furthermore, the development of advanced biofuels and platform chemicals from oil palm biomass can enhance the sustainability of the palm oil industry (Ahmad et al., 2019).

8.3 Research and development priorities

Research and development (R&D) priorities in palm oil biodiesel production should focus on several key areas. Firstly, there is a need to explore the use of third-generation feedstocks, such as waste oils and microalgae, which offer higher oil content and lower environmental impact (Ortiz-Martínez et al., 2019; Zulqarnain et al., 2021). Secondly, advancements in genetic engineering and process technologies should be pursued to increase the commercial-scale production of biodiesel (Ambaye et al., 2021). Additionally, the development of novel, cost-effective technologies for biomass conversion and biodiesel production is essential to meet future energy demands (Callegari et al., 2020; Ambaye et al., 2021).

8.4 Long-term sustainability and ethical considerations

Long-term sustainability and ethical considerations are critical in the palm oil biodiesel industry. The use of palm oil for biodiesel production raises concerns about deforestation, loss of biodiversity, and social impacts on local communities. Therefore, it is essential to adopt sustainable practices, such as utilizing by-products and mill effluent for biodiesel production, to mitigate these issues (Zahan and Kano, 2018). Moreover, the development of integrated biorefineries that convert oil palm biomass into high-value products can enhance the economic and environmental sustainability of the industry (Ahmad et al., 2019). Ethical considerations should also include fair labor practices and the equitable distribution of benefits to local communities involved in palm oil cultivation and processing (Ramos et al., 2019; Dey et al., 2020).

9 Concluding Remarks

The review of palm oil in biodiesel production has highlighted several critical aspects. Palm oil is a highly suitable feedstock for biodiesel due to its high oil content and favorable properties that closely resemble conventional diesel. The transesterification process is the most commonly adopted method for converting palm oil into biodiesel, offering high yields and cost-effectiveness. Additionally, the use of palm oil by-products and mill effluent has been extensively studied, providing a sustainable approach to biodiesel production and addressing the food versus fuel debate. The environmental benefits of palm biodiesel, such as reduced greenhouse gas emissions and lower pollutant levels, further underscore its potential as a renewable energy source.

For policymakers, it is crucial to support research and development in biodiesel production technologies, particularly those that enhance the efficiency and sustainability of using palm oil and its by-products. Incentives for adopting advanced transesterification methods and integrating biorefineries can significantly improve production yields and reduce costs. For industry stakeholders, investing in innovative extraction and conversion technologies, such as supercritical and microwave-assisted transesterification, can optimize the production process and make it more environmentally friendly. Additionally, collaboration with agricultural sectors to ensure sustainable palm oil cultivation practices will be essential to maintain the balance between food supply and biofuel production.

The future of palm oil in biodiesel production appears promising, given its high yield, cost-effectiveness, and environmental benefits. However, the industry must address challenges such as the environmental impact of palm oil cultivation and the need for sustainable practices. Advancements in technology and supportive policies will play a pivotal role in overcoming these challenges and ensuring that palm biodiesel can contribute significantly to the global renewable energy landscape. Continued research and innovation will be key to optimizing production processes and making palm biodiesel a viable and sustainable alternative to fossil fuels.

Acknowledgments

We appreciate the feedback from two anonymous peer reviewers on the manuscript of this study, whose careful evaluation and constructive suggestions have contributed to the improvement of the manuscript.

Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Abukhadra M., Basyouny M., El-Sherbeeny A., El-Meligy M., and Luqman M., 2021, Insights into the green doping of clinoptilolite with Na^+ ions (Na^+/Clino) as a nanocatalyst in the conversion of palm oil into biodiesel; optimization and mechanism, Nanotechnology, 32(15): 155702. https://doi.org/10.1088/1361-6528/abd7b0

Abukhadra M., Salam M., and Ibrahim S., 2019, Insight into the catalytic conversion of palm oil into biodiesel using Na^+/K^+ trapped muscovite/phillipsite composite as a novel catalyst: Effect of ultrasonic irradiation and mechanism, Renewable and Sustainable Energy Reviews, 115: 109346. https://doi.org/10.1016/j.rser.2019.109346

Ahmad F., Zhang Z., Doherty W., and O'Hara I., 2019, The outlook of the production of advanced fuels and chemicals from integrated oil palm biomass biorefinery, Renewable and Sustainable Energy Reviews, 109: 386-411. https://doi.org/10.1016/J.RSER.2019.04.009

Ambaye T., Vaccari M., Bonilla-Petriciolet A., Prasad S., Hullebusch E., and Rtimi S., 2021, Emerging technologies for biofuel production: a critical review on recent progress, challenges and perspectives, Journal of Environmental Management, 290: 112627. https://doi.org/10.1016/j.jenvman.2021.112627

Anyaoha K., Sakrabani R., Patchigolla K., and Mouazen A., 2018, Evaluating oil palm fresh fruit bunch processing in Nigeria, Waste Management & Research, 36: 236-246. https://doi.org/10.1177/0734242X17751848

Bhatia S., Gurav R., Choi T., Kim H., Yang S., Song H., Park J., Park Y., Han Y., Choi Y., Kim S., Yoon J., and Yang Y., 2020, Conversion of waste cooking oil into biodiesel using heterogenous catalyst derived from cork biochar, Bioresource Technology, 302: 122872. https://doi.org/10.1016/j.biortech.2020.122872

Callegari A., Bolognesi S., Cecconet D., and Capodaglio A., 2020, Production technologies, current role, and future prospects of biofuels feedstocks: a state-of-the-art review, Critical Reviews in Environmental Science and Technology, 50: 384-436. https://doi.org/10.1080/10643389.2019.1629801

Cardoso C., Zavarize D., and Vieira G., 2019, Transesterification of pequi (*Caryocar brasiliensis* Camb.) bio-oil via heterogeneous acid catalysis: catalyst preparation, process optimization and kinetics, Industrial Crops and Products, 139: 111485. https://doi.org/10.1016/J.INDCROP.2019.111485

Chew C., Low L., Chia W., Chew K., Liew Z., Chan E., Chan Y., Kong P., and Show P., 2021, Prospects of palm fruit extraction technology: palm oil recovery processes and quality enhancement, Food Reviews International, 38: 893-920.
https://doi.org/10.1080/87559129.2021.1890117

Chinglenthoiba C., Das A., and Vandana S., 2020, Enhanced biodiesel production from waste cooking palm oil, with NaOH-loaded Calcined fish bones as the catalyst, Environmental Science and Pollution Research, 27: 15925-15930.
https://doi.org/10.1007/s11356-020-08249-7

Darras K., Corre M., Formaglio G., Tjoa A., Potapov A., Brambach F., Sibhatu K., Grass I., Rubiano A., Buchori D., Drescher J., Fardiansah R., Hölscher D., Irawan B., Kneib T., Krashevska V., Krause A., Kreft H., Li K., Maraun M., Polle A., Ryadin A., Rembold K., Stiegler C., Scheu S., Tarigan S., Valdés-Uribe A., Yadi S., Tscharntke T., and Veldkamp E., 2019, Reducing fertilizer and avoiding herbicides in oil palm plantations—ecological and economic valuations, Frontiers in Forests and Global Change, 2: 65.
https://doi.org/10.3389/ffgc.2019.00065

Dey S., Reang N., Das P., and Deb M., 2020, A comprehensive study on prospects of economy, environment, and efficiency of palm oil biodiesel as a renewable fuel, Journal of Cleaner Production, 286: 124981.
https://doi.org/10.1016/j.jclepro.2020.124981

Ding H., Ye W., Wang Y., Wang X., Li L., Liu D., Gui J., Song C., and Ji N., 2018, Process intensification of transesterification for biodiesel production from palm oil: microwave irradiation on transesterification reaction catalyzed by acidic imidazolium ionic liquids, Energy, 144: 957-967.
https://doi.org/10.1016/J.ENERGY.2017.12.072

Escallón-Barrios M., Castillo-Gomez D., Leal J., Montenegro C., and Medaglia A., 2020, Improving harvesting operations in an oil palm plantation, Annals of Operations Research, 314: 411-449.
https://doi.org/10.1007/s10479-020-03686-6

Fardilah V., Pusparizkita Y., Tauviqirrahman M., and Bayuseno A., 2023, An overview of biodiesel, a fuel blend made from palm oil, IOP Conference Series: Earth and Environmental Science, 1268(1): 012057.
https://doi.org/10.1088/1755-1315/1268/1/012057

Fernández-Coppel I., Barbosa-Evaristo A., Correa-Guimarães A., Martín-Gil J., Navas-Gracia L., and Martín-Ramos P., 2018, Life cycle analysis of macauba palm cultivation: a promising crop for biofuel production, Industrial Crops and Products, 125: 556-566.
https://doi.org/10.1016/J.INDCROP.2018.09.036

Gómez A., Parra A., Pavelsky T., Wise E., Villegas J., and Meijide A., 2023, Ecohydrological impacts of oil palm expansion: a systematic review, Environmental Research Letters, 18: 033005.
https://doi.org/10.1088/1748-9326/acbc38

Hadi N., 2021, The effect of microwave treatment and delayed harvesting on oil palm fruitlets (*Elaeis guineensis*) oil quality, Journal of Oil Palm Research, 33(4): 678-688.
https://doi.org/10.21894/JOPR.2021.0015

Harahap F., Silveira S., and Khatiwada D., 2019, Cost competitiveness of palm oil biodiesel production in Indonesia, Energy, 170: 62-72.
https://doi.org/10.1016/J.ENERGY.2018.12.115

Ishola F., Adelekan D., Mamudu A., Abodunrin T., Aworinde A., Olatunji O., and Akinlabi S., 2020, Biodiesel production from palm olein: a sustainable bioresource for Nigeria, Heliyon, 6: e03725.
https://doi.org/10.1016/j.heliyon.2020.e03725

Jaroenkietkajorn U., and Gheewala S., 2021, Understanding the impacts on land use through GHG-water-land-biodiversity nexus: the case of oil palm plantations in Thailand, The Science of the Total Environment, 800: 149425.
https://doi.org/10.1016/j.scitotenv.2021.149425

Julio A., Batlle E., Trindade A., Nebra S., Reyes A., and Palácio J., 2021, Energy, exergy, exergoeconomic, and environmental assessment of different technologies in the production of bio-jet fuel by palm oil biorefineries, Energy Conversion and Management, 243: 114393.
https://doi.org/10.1016/J.ENCONMAN.2021.114393

Kamil M., and Almarashda F., 2023, Economic viability and engine performance evaluation of biodiesel derived from desert palm date seeds, Energies, 16(3): 1513.
https://doi.org/10.3390/en16031513

Kiggundu N., 2020, Performance evaluation of a motorised palm oil extractor with quality assessment of the palm oil extracted in comparison with a manual vertical press, Journal of Oil Palm Research, 33(1): 64-73
https://doi.org/10.21894/jopr.2020.0096

Lam M., and Lee K., 2019, Production of biodiesel using palm oil, Biofuel, 2019: 539-574.
https://doi.org/10.1016/B978-0-12-385099-7.00016-4

Mahlia T., Ismail N., Hossain N., Silitonga A., and Shamsuddin A., 2019, Palm oil and its wastes as bioenergy sources: a comprehensive review, Environmental Science and Pollution Research, 26: 14849-14866.
https://doi.org/10.1007/s11356-019-04563-x

Meijaard E., Brooks T., Carlson K., Slade E., García-Ulloa J., Gaveau D., Lee J., Santika T., Juffe-Bignoli D., Struebig M., Wich S., Ancrenaz M., Koh L., Zamira N., Abrams J., Prins H., Sendashonga C., Murdiyarso D., Furumo P., Macfarlane N., Hoffmann R., Persio M., Descals A., Szantoi Z., and Sheil D., 2020, The environmental impacts of palm oil in context, Nature Plants, 6: 1418-1426.
https://doi.org/10.1038/s41477-020-00813-w

Milano J., Ong H., Masjuki H., Silitonga A., Kusumo F., Dharma S., Sebayang A., Cheah M., and Wang C., 2018, Physicochemical property enhancement of biodiesel synthesis from hybrid feedstocks of waste cooking vegetable oil and beauty leaf oil through optimized alkaline-catalysed transesterification, Waste Management, 80: 435-449.
https://doi.org/10.1016/j.wasman.2018.09.005

Moazeni F., Chen Y., and Zhang G., 2019, Enzymatic transesterification for biodiesel production from used cooking oil, a review, Journal of Cleaner Production, 216: 117-128.
https://doi.org/10.1016/J.JCLEPRO.2019.01.181

Ortiz-Martínez V., Andreo-Martínez P., García-Martínez N., Ríos A., Hernández-Fernández F., and Quesada-Medina J., 2019, Approach to biodiesel production from microalgae under supercritical conditions by the PRISMA method, Fuel Processing Technology, 191: 211-222.
https://doi.org/10.1016/J.FUPROC.2019.03.031

Phromphithak S., Meepowpan P., Shimpalee S., and Tippayawong N., 2020, Transesterification of palm oil into biodiesel using ChOH ionic liquid in a microwave heated continuous flow reactor, Renewable Energy, 154: 925-936.
https://doi.org/10.1016/j.renene.2020.03.080

Prananta W., and Kubiszewski I., 2021, Assessment of Indonesia's future renewable energy plan: a meta-analysis of biofuel energy return on investment (EROI), Energies, 14: 2803.
https://doi.org/10.3390/EN14102803

Qu T., Niu S., Zhang X., Han K., and Lu C., 2021, Preparation of calcium modified Zn-Ce/Al_2O_3 heterogeneous catalyst for biodiesel production through transesterification of palm oil with methanol optimized by response surface methodology, Fuel, 284: 118986.
https://doi.org/10.1016/j.fuel.2020.118986

Ramirez-Contreras N., Munar-Florez D., García-Núñez J., Mosquera-Montoya M., and Faaij A., 2020, The GHG emissions and economic performance of the Colombian palm oil sector; current status and long-term perspectives, Journal of Cleaner Production, 258: 120757.
https://doi.org/10.1016/j.jclepro.2020.120757

Ramos M., Dias A., Puna J., Gomes J., and Bordado J., 2019, Biodiesel production processes and sustainable raw materials, Energies, 12: 1-30.
https://doi.org/10.3390/en12234408

Rulli M., Casirati S., Dell'Angelo J., Davis K., Passera C., and D'Odorico P., 2019, Interdependencies and telecoupling of oil palm expansion at the expense of Indonesian rainforest, Renewable and Sustainable Energy Reviews, 105: 499-512.
https://doi.org/10.1016/J.RSER.2018.12.050

Souza S., Seabra J., and Nogueira L., 2018, Feedstocks for biodiesel production: Brazilian and global perspectives, Biofuels, 9: 455-478.
https://doi.org/10.1080/17597269.2017.1278931

Syafiuddin A., Chong J., Yuniarto A., and Hadibarata T., 2020, The current scenario and challenges of biodiesel production in Asian countries: a review, Bioresource Technology Reports, 12: 100608.
https://doi.org/10.1016/j.biteb.2020.100608

Szulczyk, K., & Khan, A., 2018. The potential and environmental ramifications of palm biodiesel: Evidence from Malaysia, Journal of Cleaner Production, 203: 260-272.
https://doi.org/10.1016/J.JCLEPRO.2018.08.241

Uning R., Latif M., Othman M., Juneng L., Hanif N., Nadzir M., Maulud K., Jaafar W., Said N., Ahamad F., and Takriff, M., 2020, A review of southeast Asian oil palm and its CO_2 fluxes, Sustainability, 12(12): 5077.
https://doi.org/10.3390/su12125077

Wahyono Y., Hadiyanto H., Budihardjo M., and Adiansyah J., 2020, Assessing the environmental performance of palm oil biodiesel production in Indonesia: a life cycle assessment approach, Energies, 13(12): 3248.
https://doi.org/10.3390/en13123248

Yusoff M., Zulkifli N., Sukiman N., Chyuan O., Hassan M., Hasnul M., Zulkifli M., Abbas M., and Zakaria M., 2020, Sustainability of palm biodiesel in transportation: a review on biofuel standard, policy and international collaboration between Malaysia and Colombia, Bioenergy Research, 14: 43-60.
https://doi.org/10.1007/s12155-020-10165-0

Zahan K., and Kano M., 2018, Biodiesel production from palm oil, its by-products, and mill effluent: a review, Energies, 11(8): 2132.
https://doi.org/10.3390/EN11082132

Zulqarnain, Ayoub M., Yusoff M., Nazir M., Zahid I., Ameen M., Sher F., Floresyona D., and Nursanto E., 2021, A comprehensive review on oil extraction and biodiesel production technologies, Sustainability, 13(2): 788.
https://doi.org/10.3390/SU13020788

Zulqarnain, Yusoff M., Ayoub M., Jusoh N., and Abdullah A., 2020, The challenges of a biodiesel implementation program in Malaysia, Processes, 8(10): 1244.
https://doi.org/10.3390/PR8101244