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Review

Biodiesel Sustainability: Review of Progress and Challenges of Biodiesel as Sustainable Biofuel

Ade Suhara [1,*], Karyadi [1], Safarudin Gazali Herawan [2], Andy Tirta [3], Muhammad Idris [4], Muhammad Faizullizam Roslan [5], Nicky Rahmana Putra [6], April Lia Hananto [7] and Ibham Veza [8,*]

[1] Faculty of Engineering, Universitas Buana Perjuangan Karawang, Sukamakmur 41361, Indonesia; karyadi@ubpkarawang.ac.id
[2] Industrial Engineering Department, Faculty of Engineering, Bina Nusantara University, Jakarta 11480, Indonesia; safarudin.gazali@binus.edu
[3] Graduate School of Renewable Energy, Darma Persada University, Jl. Radin Inten 2, Pondok Kelapa, East Jakarta 13450, Indonesia; andy.tirta@pasca.unsada.ac.id
[4] School of Environmental Science, University of Indonesia, Jakarta 10430, Indonesia; muhammad.idris21@ui.ac.id
[5] Automotive Development Center, Institute for Vehicle Systems and Engineering, Universiti Teknologi Malaysia, Johor Bahru 81310, Johor, Malaysia; faizullizam@graduate.utm.my
[6] National Research and Innovation Agency, Bogor 16911, Indonesia; nick003@brin.go.id
[7] Faculty of Computer Science, Universitas Buana Perjuangan Karawang, Sukamakmur 41361, Indonesia; aprilia@ubpkarawang.ac.id
[8] Mechanical Engineering Department, Universiti Teknologi PETRONAS (UTP), Seri Iskandar 32610, Perak, Malaysia
* Correspondence: author: ade.suhara@ubpkarawang.ac.id (A.S.); ibham@vezas.org (I.V.)

Abstract: Biodiesel, an environmentally degradable and renewable biofuel derived from organic matter, has exhibited its capacity as a viable and sustainable substitute for traditional diesel fuel. Numerous comprehensive investigations have been conducted to assess the effects of biodiesel on internal combustion engines (ICEs), with particular emphasis on diesel engine performance metrics, combustion dynamics, and emission profiles. Biodiesel demonstrates a significant decrease in emissions of particulate matter (PM), hydrocarbon (HC), and carbon monoxide (CO) in diesel engines. The addition of biodiesel has shown a minor decrease in power output and a slight increase in fuel consumption and nitrogen oxide (NOx) emissions. Nevertheless, the extensive implementation of biodiesel, despite its potential to effectively reduce detrimental emissions, has encountered obstacles stemming from external influences including restricted availability of feedstock, volatile petroleum oil prices, and inadequate governmental backing. This review presents a concise summary of significant advancements in the global adoption of biodiesel from a sustainability perspective. This review provides valuable insights into the challenges and opportunities associated with the advancement of sustainable biofuel technologies by synthesizing the current state of palm biodiesel and examining global trends in biodiesel implementation. The wider adoption of biodiesel can be facilitated by addressing concerns pertaining to feedstock availability, price stability, and policy support. This would allow for the realization of significant environmental advantages and contribute to a more environmentally friendly and sustainable biofuel.

Keywords: biodiesel production; palm biodiesel; biodiesel blending mandate; biodiesel feedstock; sustainable biofuel

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1. Introduction

Fossil hydrocarbons are a finite and scarce resource, resulting in the high cost of their production. Therefore, the utilization of vegetable oil and biomass for the production of liquid biofuels offers a compelling alternative. Considerable research has been undertaken in the domain of biofuels, with a predominant focus on the mitigation of production

expenses, the curtailment of greenhouse gas emissions, and the optimization of land and water resource utilization. Furthermore, considerable endeavours have been focused on the advancement of biofuels that demonstrate compatibility with the currently available vehicle engines on the market [1].

Due to the fact that it accounts for 75% of the total production cost [2], feedstock is an essential component in the manufacturing of biofuels. Low-cost biodiesel from non-edible sources such as agricultural wastes is a more persuasive alternative [3–5], despite the fact that many people are worried about the high cost of biodiesel generated from edible oils as well as the issue of food vs. fuel that this presents. This category of biofuels is referred to as the "second generation". In addition, the possibility of producing biodiesel from algae has been drawing the attention of people all over the world for the last ten years [6–8]. The third generation of biofuels consists of biodiesel of the sort that is being discussed here. Figure 1 illustrates the three main categories of biofuels as well as the sources of their feedstocks and the results of their production.

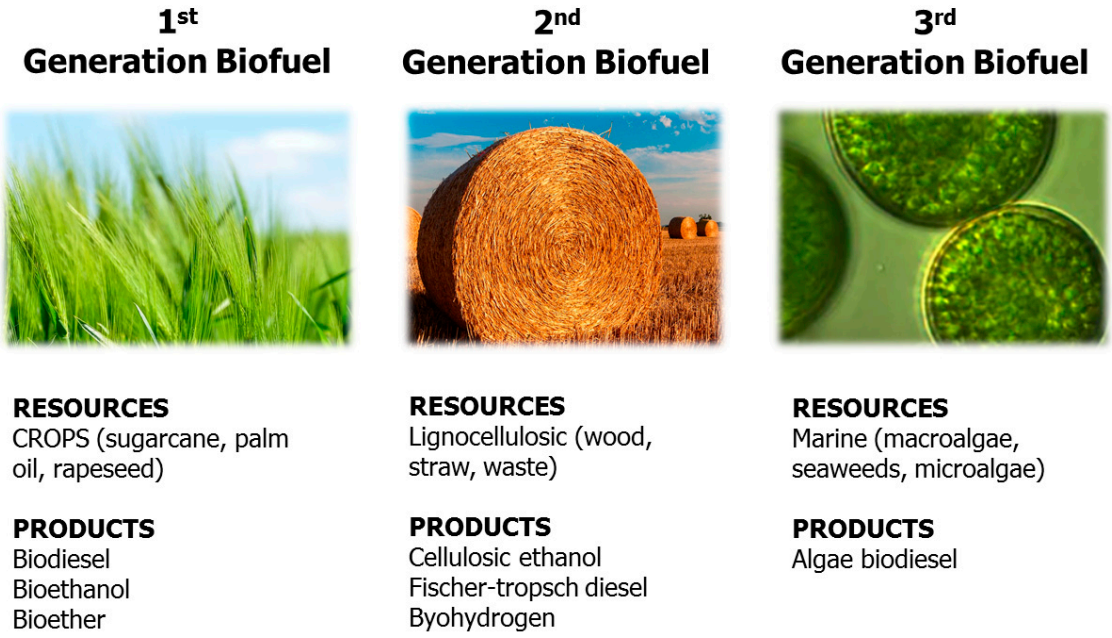


Figure 1. The classification of biofuels based on generation.

Biofuel can be categorized as solid, liquid, or gaseous fuels derived from bio-renewable feedstock. It has the potential to facilitate economic opportunities for communities residing in rural areas, nations reliant on oil imports, and developing countries. Consequently, biofuels have the potential to reduce reliance on imported petroleum oil, mitigate greenhouse gas emissions and pollutants, and stimulate economic growth through the utilization of agricultural resources [9]. Bioethanol and biodiesel are widely recognized as the two primary bio-renewable fuels on a global scale. At present, the predominant source of bioethanol production is derived from agricultural crops with high food values, such as sugarcane in Brazil or corn in the United States [10]. When comparing bioethanol and biodiesel, biodiesel is considered to be more appealing owing to its superior environmental advantages. In addition, it is worth noting that the production of biodiesel through the process of transesterification necessitates a lower energy input compared to the production of ethanol via fermentation [11].

In a theoretical context, biodiesel has the potential to be derived from a range of renewable sources, including palm oil (a type of edible oil), used cooking oil (classified as non-edible), and animal fats. Furthermore, Shan et al. [12] have conducted research indicating that animal bones possess potential as a feedstock in the synthesis of biodiesel. Chakraborty et al. [13] firstly reported the use of fish bones to produce biodiesel in 2011.

Recent studies utilizing animal bones can be found in the following references [14–16]. In light of the existing infrastructure, biodiesel production predominantly relies on vegetable oil despite the untapped potential of non-edible oil. Palm oil accounted for the highest production volume among global vegetable oils, reaching 62.44 million metric tons in the 2014/2015 period [17]. In the years 2005/2006, palm oil surpassed soybean oil as the predominant vegetable oil in terms of global production. In order to achieve efficient mass production, it is imperative that ample supplies of biodiesel sources are readily accessible, ensuring the ability to meet demand even amidst substantial market fluctuations. In this particular scenario, the presence of palm oil emerges as a promising feedstock option for upholding the long-term viability of biodiesel production.

Therefore, despite the fact that biofuels from the second and third generations are still in the process of being developed into commercial fuels, the usage of biofuels from the first generation, such as those derived from palm oil, continues to be the most practical alternative for use in the current market of contemporary automobiles around the globe. First-generation biofuels continue to be the most viable choice in the current biofuels industry to be mass-produced and commercialized because of the availability of continuous feedstock supplies, numerous development and research supports, no requirements for major engine modifications, and government support in terms of policies and mandates.

In diesel or compression ignition engines, after the initial autoignition of the mixture inside the cylinder, the combustion process continues in two stages [18,19]. Both the premixed and the mixed components are regulated throughout the combustion process. Premixed-controlled combustion takes place in a fuel-rich zone and creates partly oxidized fuel pieces that diffuse outwards, resulting in the mixing-controlled diffusion flame that surrounds the premixed core region. This process takes place in the premixed core region. The first stage, which consists of a heat release and an increase in temperature, happens in a location that contains a lot of premixed fuel. The fuel mixing rate and the amount of oxidizer play the primary roles in determining the total heat release rate (HRR). Figure 2 provides a schematic illustration of a typical instance of direct injection in a diesel engine.

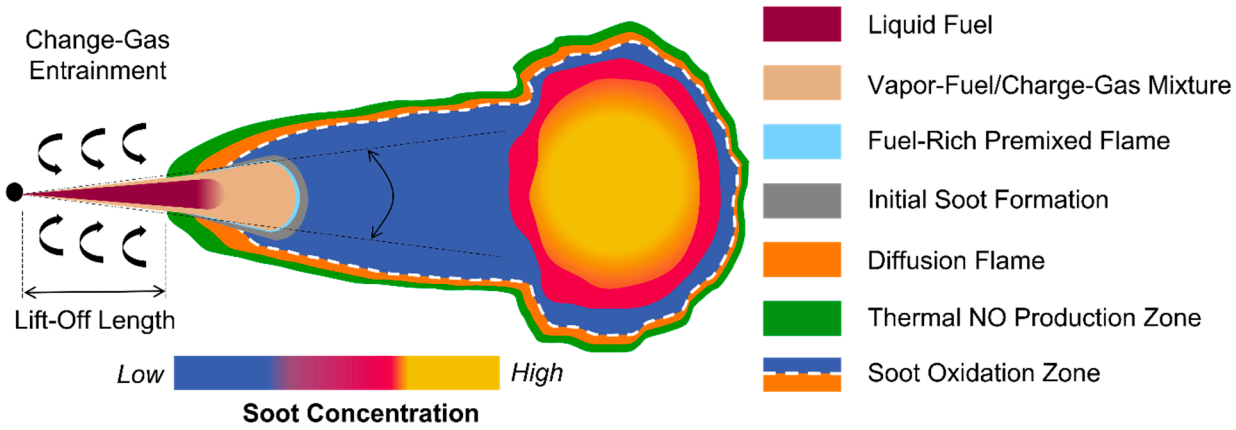


Figure 2. Combustion model of direct injection diesel, reproduced from [20].

The comprehension of the combustion process in diesel engines establishes a foundation for investigating the implications of biodiesel as a substitute fuel. As previously mentioned, diesel engines operate based on the principle of autoignition, wherein the combination of fuel and air occurs within an environment characterized by elevated temperature and pressure. The combustion process at hand is characterized by a complex interplay between premixed and mixed components, which collectively contribute to the overall generation of heat and subsequent rise in temperature. In the section, the significance of biodiesel will be discussed.

Diesel that is produced from fossil fuels may be replaced with biodiesel, which is a fuel that is both environmentally friendly and renewable. In contrast to traditional diesel

fuels, fuels made from biodiesel processes have developed as an alternative that is both renewable and non-toxic.

Biodiesel, which is derived from the transesterification process, exhibits similar properties to conventional diesel fuel. Consequently, this process is deemed advantageous for commercial production from an economic perspective. The transesterification process involves the formation of glycerol and esters as a result of the reaction between a triglyceride and an alcohol. Triglycerides, which are organic fats and oils, consist of a glycerin molecule connected to three fatty acids. Free fatty acids are generated through the process of triglyceride hydrolysis. Following this, the free fatty acids undergo a reaction with alcohol, resulting in the formation of esters, specifically biodiesel in the form of methyl or ethyl fatty acid esters, as well as glycerol. Transesterification, alternatively referred to as alcoholysis, involves the reaction between a free fatty acid and an alcohol. The resulting products of the transesterification process are subsequently separated, with biodiesel exhibiting a tendency to settle at the upper layer due to its lower density, while glycerol, possessing a higher weight, settles at the lower layer. In order to prevent the occurrence of reverse processes, it is imperative that the separation process be conducted with utmost efficiency and speed [21].

Typically, the transesterification process involves the utilization of methanol and ethanol. The transesterification process involving the reaction of methanol with free fatty acids is commonly referred to as methanolysis. During the methanolysis process, thermal energy is utilized to heat a mixture consisting primarily of oil (80–90%) and methanol (10–20%), along with a small amount of catalyst. The solubility of methanol in oil is relatively low, thus emphasizing the importance of thorough mixing. The resulting product of the aforementioned procedure is known as fatty acid methyl ester (FAME) [22]. Methanol exhibits greater reactivity and is more cost-effective relative to other alcohols, thereby rendering it a preferred choice for transesterification processes.

ASTM D6751 (American) and EN 14214 (European) [23,24] are considered to be two of the most important biodiesel standards. Both standards include criteria that are almost exactly the same. The intended criteria for biodiesel should be met by commercially produced biodiesel, while the specific market area requirements might vary. In general, the total sulphur concentration of all feedstocks of biodiesel is less than 0.01% by weight. This number is a significant reduction from both the ASTM D6751 (0.05%wt) and the EN 14214 (0.02%wt) standards. Because the sulphur compounds in diesel fuel may contribute to the creation of acid rain and other forms of air pollution, one of the many advantages of using biodiesel is that it reduces these risks. The higher flashpoint of biodiesel is yet another benefit of using this fuel. Because of this, storing biodiesel is considered to be a comparatively safer option.

In spite of the advantages of having a reduced sulphur content and a higher flash point, biodiesel may cause an increase in the amount of fuel that a vehicle consumes. This is because typically, biodiesel has lower calorific values and higher density when compared to regular diesel fuel. The calorific values of the feedstocks of biodiesel are a little less than what diesel has (43 MJ/kg) [25,26]. This will result in an increase in fuel consumption since a greater quantity of biodiesel is needed to provide the same level of power as diesel fuel. In addition, the US and EU regulations for high viscosity are substantially lower than those of castor oil, which has a viscosity that is significantly greater. However, the increased viscosity of biodiesel may cause a difficulty in the injection system and perhaps make the atomization process less effective [22].

In spite of the fact that the use of various feedstocks may result in slight changes in the qualities of biodiesel, on the whole, this fuel is compliant with the requirements set out by both the United States and the European Union. Because of this, the majority of biodiesel may be used in traditional diesel engines either on its own or in conjunction with traditional diesel fuel. [27,28]. The use of vegetable oils in the production of biodiesel may result in a number of issues; the reasons for the short-term and long-term issues that arise from the use of vegetable oils are presented in Figure 3.

There are many studies focusing on biodiesel production from various feedstocks, challenges and potentials of biodiesel, as well as the applications of biodiesel. Sales et al. [29] performed a bibliometric analysis of primary studies relating to biodiesel production worldwide by identifying the key countries and regions that have shown a strong engagement in biodiesel topics. They concluded that India, China, and Malaysia had shown great interests in this area. However, the sustainability aspects of biodiesel were not included. Besides, Mathew et al. [30] studied the challenges and solutions of biodiesel production but focused more on the mechanisms and chemistries aspects. Furthermore, Anuar and Abdullah [31] made a critical review on the challenges in biodiesel industry with regards to feedstock, environmental, social, and sustainability issues. However, the applications of biodiesel especially in ICE were not mentioned. In this review article, we present a concise summary of significant advancements in the global adoption of biodiesel in sustainability paradigm. Also, we provide valuable insights into the challenges and opportunities associated with the advancement of sustainable biofuel technologies by synthesizing the current state of palm biodiesel and examining global trends in biodiesel implementation.

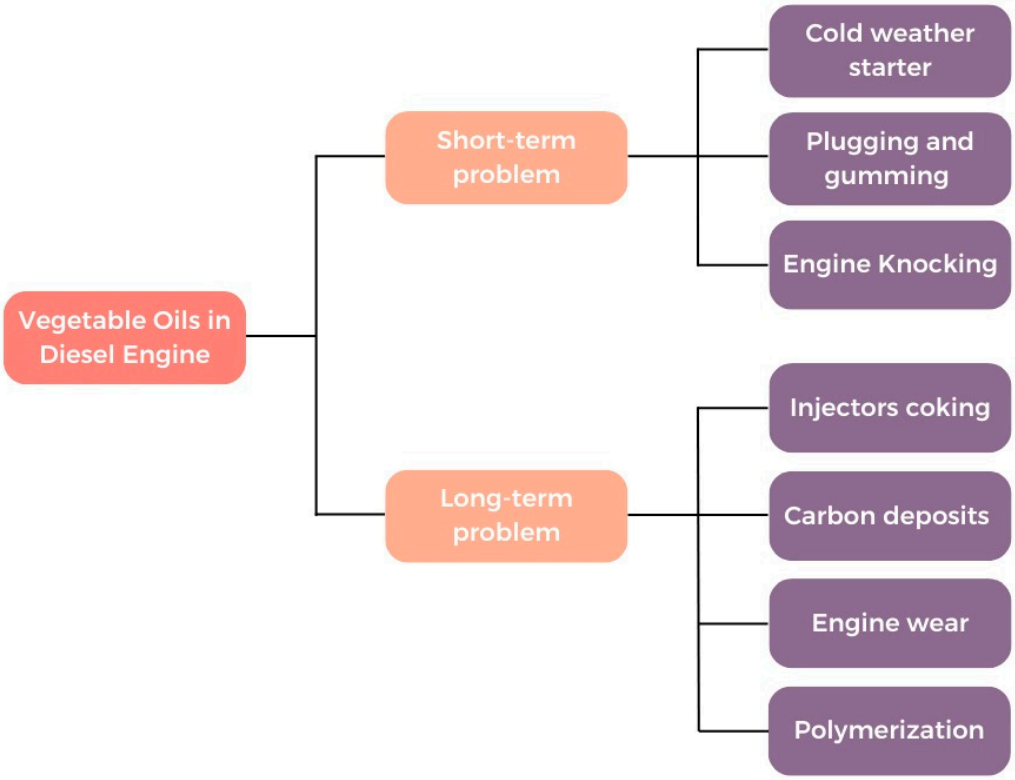


Figure 3. Known problems, probable causes, and potential solutions for using vegetable oils in diesel engines [32].

2. Biodiesel Sustainability

2.1. Sustainability Paradigm

Biodiesel's environmental advantages come from its production process using biomass, such as plant oils or animal fats, which captures carbon dioxide during growth. When burned, biodiesel releases this stored carbon, effectively maintaining a carbon cycle balance. In contrast, fossil fuels emit additional carbon dioxide by releasing carbon previously sequestered underground for millions of years, contributing to increased greenhouse gas (GHG) emissions. Therefore, biodiesel offers a net reduction in GHG emissions compared to fossil fuels, thus making it a more environmentally friendly alternative.

World transformation gradually changes the paradigm of the community towards a technological development. Changing the paradigms from which systems originate is said

to be the most effective change agent [33,34]. Paradigms determine how we see the world, what we think is possible, and how we understand and deal with challenges related to sustainability. It is important for sustainability scholars to understand the paradigms that shape their field and to align their work with the most advanced theories and practices from areas related to sustainability [35]. Recently, sustainability is one of the growing paradigms in resources management [36,37]. Figure 4 illustrates the sustainability paradigm which connects the environmental, social, and economic aspects.

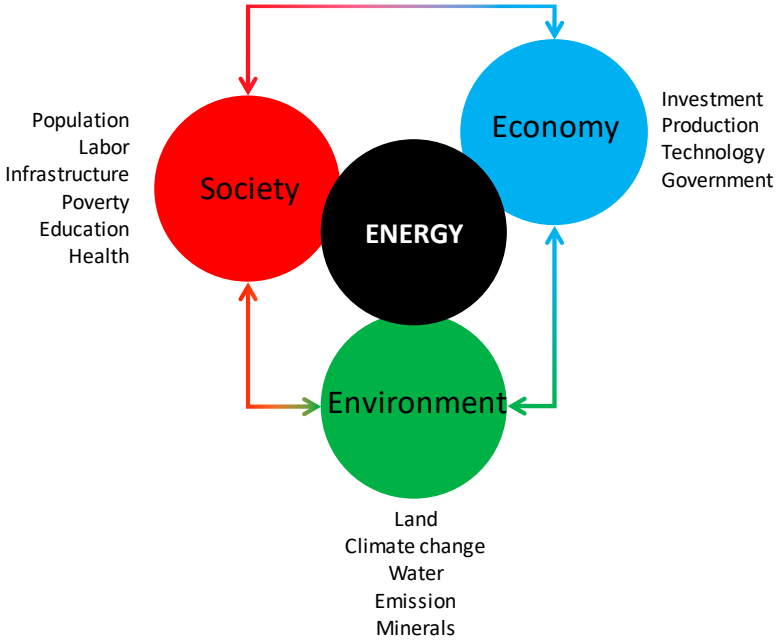


Figure 4. The interdependencies between energy accessibility and sustainability aspects [38].

Biodiesel sustainability refers to the environmental, social, and economic considerations associated with the production and use of biodiesel as a renewable energy source. Sustainable biodiesel production aims to minimize negative impacts on the environment and society while maximizing its potential as a low-carbon alternative to conventional fossil fuels [39]. The importance of the sustainability paradigm in the implementation of biodiesel in a country has a significant positive impact in several key aspects, such as decreased GHG emissions [40], energy sources diversification [41], regional economic development [41], waste management [42], forest protection [42], energy independence [43], and social sustainability [44].

Biodiesel is a fuel based on biomass and can reduce GHG emissions compared to fossil fuels. By adopting a sustainability paradigm in the implementation of biodiesel, countries can reduce the transportation sector's contribution to climate change and achieve GHG emission reduction targets [45]. By relying on biodiesel as an alternative fuel, countries can reduce dependence on imported fossil fuels. Diversification of energy sources increases energy security and reduces the risk of fluctuations in world oil prices.

The sustainability paradigm in biodiesel production can encourage the use of local feedstock, such as palm oil, algae, or food waste. This can provide economic support to local farmers and producers and open up investment opportunities in the bioenergy sector. Biodiesel can be produced from used cooking oil or other organic waste [46]. By optimizing the use of this waste as biodiesel feedstocks, countries can reduce waste problems and promote more sustainable production patterns.

The use of biodiesel from renewable resources can reduce pressure on forests and the environment because it avoids land conversions for biodiesel feedstock farming. This contributes to the preservation of forests and natural habitats. Local biodiesel production can ensure countries are more energy independent and reduce fossil fuel imports [47]. This

can reduce the impact of fluctuations in world oil prices and increase domestic energy stability. The implementation of sustainable biodiesel also considers social aspects, such as ensuring food availability and the welfare of local communities [48]. Involving communities in biodiesel production can create jobs and improve quality of life.

By adopting a sustainability paradigm in biodiesel implementation, countries can achieve long-term environmental, economic, and social benefits [49]. In developing energy policies and strategies, paying attention to the overall and sustainable impact of biodiesel is essential to support the transition to a more sustainable and environmentally friendly future.

Numerous research papers on biodiesel sustainability have emerged to mitigate climate change and energy scarcity. Chong et al. [50] analysed the worldwide impacts of biodiesel on the energy–water–food (EWF) nexus. Their objective was to gain insights into the intricate environmental interrelationships and assess the sustainability of biodiesel. The findings offer valuable insights for governmental entities in formulating environmental policy frameworks for the adoption of biodiesel technology as a more environmentally friendly substitute for conventional diesel fuel.

With a sustainable approach, Brahma et al. [51] reviewed a comprehensive analysis on the manufacture of biodiesel using different mixed oils, also known as hybrid oils. The authors examined the impact of mixed oil on several aspects including the reaction process, physicochemical qualities, fatty acid composition, and fuel quality of the resulting biodiesel products. The research elucidated the efficacy of different catalysts in the mixed oil reaction and assessed its economic viability. This strategy has the potential to increase the production capacity of biodiesel on a large scale and has the potential to stimulate growth in the biorefinery sector, thereby meeting future energy demands, provided that advanced-level research progresses in the desired direction.

2.2. Key Aspects of Sustainability

Many researchers focus more on the performance, characteristics, emission, and economics of biodiesel. Several important keys in sustainability are often overlooked and ignored. Those aspects of biodiesel sustainability include feedstock selection, land use and resource management, deforestation and habitat conservation, waste utilization, and social impact.

The choice of feedstock for biodiesel production is crucial to sustainability. Sustainable biodiesel should be sourced from feedstocks that do not compete with food production, do not contribute to deforestation or land use changes, and have a low impact on biodiversity. In addition, sustainable biodiesel production should not lead to the conversion of natural ecosystems or result in the excessive use of water, fertilizers, or pesticides. It should follow responsible land use practices and promote resource efficiency. Biodiesel feedstocks have been associated with deforestation and habitat destruction. Sustainable biodiesel should avoid contributing to deforestation and should prioritize the protection of critical habitats and biodiversity. Sustainable biodiesel can be produced from waste cooking oil, animal fats, and agricultural residues, which reduces competition with food production and enhances the overall sustainability profile of the fuel. Lastly, sustainable biodiesel production should consider social factors such as respect for land rights, fair labour practices, and community involvement. It should not lead to social displacement or harm to local communities.

As the demand for renewable energy increases, it is essential to prioritize sustainability in biodiesel production to avoid negative environmental and social consequences. Governments, industries, and consumers play critical roles in supporting and promoting sustainable biodiesel practices through policy frameworks, responsible sourcing, and informed choices. To compile aspects beyond technical issues, multi and interdisciplinary sustainability studies need to be developed, especially for the production of biodiesel.

2.3. Sustainability Assessment

The presence of complex global energy challenges highlights the imperative need to shift from fossil fuel to biofuel as a means to effectively pursue sustainable development objectives. Advanced sustainability tools are instrumental in realizing this important objective. The significance of evaluating the sustainability of biodiesel production has grown in prominence as nations seek to develop plans for energy diversification and examine the environmental, social, and economic impact of biofuel production.

The amount of the potential benefits from using biodiesel depends on the sustainability of biomass production. Hence, it is important to employ advanced sustainability assessment tools, such as techno-economic analysis [52,53], socio-economic analysis [54], life cycle assessments (LCAs) [55], system dynamics [56,57], energy analysis [58], exergy analysis [59], and energy–exergy analysis [60,61], to establish the overall sustainability of systems and propose solutions to mitigate the environmental, social, and economic impacts. Moreover, De Ridder et al. [62] provided a comprehensive categorization of seven methodological groups for sustainability analysis, namely assessment frameworks, participative tools, scenario analysis tools, multi-criteria analysis tools, and model tools.

Venturini et al. [63] presented a comprehensive framework for undertaking a multi-dimensional evaluation of various technological configurations, encompassing technical, economic, and environmental aspects. Their study particularly emphasized the integration of several biomass technologies within a sugar and ethanol plant. The evaluation of the performance of the various configurations under consideration was conducted using specific indicators that assessed the relationship between energy consumption, energy production, emissions reduction, and economic factors. The primary metrics utilized in this study to evaluate the sustainability of biofuels were global efficiency, net productivity per hectare, averted carbon dioxide equivalent (CO_2-eq) emissions, net present value (NPV), and levelized cost of energy (LCOE).

Besides their potential environmental advantages compared to conventional fuels, biofuels may also bring other socio-economic benefits. Lechón et al. [64] examined the socio-economic consequences of the biofuels targets implemented in Uruguay. The authors estimate the gross and net effects on the production of products and services, as well as the creation of value-adding jobs. These impacts are further classified into rural and non-rural areas. The significant findings indicate that despite the greater production costs of biofuels compared to fossil fuels, the inclusion of economic factors such as tax revenues and the balancing of payments, along with the previously assessed socio-economic consequences, ultimately result in the total advantages of biofuels outweighing the additional costs. Nevertheless, it is plausible that this scenario could be modified in the forthcoming years due to fluctuations in biofuel production expenses, fiscal regulations, and fluctuations in import and export prices.

Comprehensive life cycle analysis is essential to assess the overall environmental impacts of biodiesel production and use, accounting for factors like energy input, land use changes, and emissions. Gupta et al. [65] applied LCA to investigate the environmental impacts of biodiesel production from rapeseed oil. The study shown that both centralized large-scale and localized small-scale biodiesel production schemes exhibit a yearly global warming potential (GWP) of 2.63 and 2.88 tCO_2-eq/t biodiesel, respectively. Notably, the carbon emissions associated with the rapeseed crop stage accounted for over 65% of the total emissions. The results of the sensitivity analysis indicate a significant correlation between the global warming potential (GWP) and the following three factors: rapeseed yields, glycerol re-utilization techniques, and nitrogen nutrients in the fertilizer. A proposed alternative scenario has been put up for both large- and small-scale systems, which has the potential to achieve a reduction in carbon emissions by 14.1% and 33.6%, respectively.

Regarding the tools for life cycle sustainability analysis, Collotta et al. [66] highlighted key environmental, economic, and social indicators currently being assessed using life cycle sustainability assessments (LCSAs). LCSAs should be further extended to help address

critical aspects of sustainability that are currently dominated by environmental aspects only.

One of the prominent sustainability tools that considers time functions is system dynamics. A system dynamics model was developed and applied to assess sustainability. Bautista et al. [57] proposed a system dynamics model for the evaluation of biodiesel production. The modelling process revealed the presence of system dynamics, wherein the expansion of oil palm farming exhibited a correlation with reduced rates of population displacement, poverty, and emissions of air pollutants such as hydrocarbons (HCs), carbon monoxide (CO), and particulate matter (PM). The findings of the study indicate that the expansion of oil palm agriculture, as projected in the baseline scenario, has the potential to exacerbate disparities in land ownership and contribute to higher greenhouse gas emissions in the palm oil industry. Additionally, this expansion may also have negative implications for food security.

Sandouqa and Al-Hamamre [58] applied energy analysis for jojoba oil by carrying out to account for inputs and outputs of energy and GHG emissions associated with the biodiesel production system. The findings indicate that the net energy balance (NEB) and net energy ratio (NER) values were determined to be 46,724.1 MJ/ha (28.9 MJ/L biodiesel generated) and 2.16, respectively. Simultaneously, it is anticipated that the aggregate quantity of greenhouse gas (GHG) emissions amounts to 2.28 kg-CO_2-eq/L of produced biodiesel, which is equivalent to 66.0 g CO_2-eq/MJ of produced biodiesel.

The use of exergy flow analysis encompasses various objectives, including waste accounting, determination of exergetic efficiency, comparison of alternative energy sources, and the establishment of economic and environmental regulations pertaining to resource utilization. Khoobbakht et al. [67] conducted an exergy flow analysis of the process involved in biodiesel manufacturing on the esterification and transesterification of waste canola frying oil. They investigated the potential benefits of this process, including the reduction in material and energy consumption, as well as the improvement of energy and exergy efficiency. The application of thermodynamics analysis was utilized to ascertain the exergy input and output of the system during the experimental runs. The evaluation of several experimental variables, such as the methanol–oil molar ratio, potassium hydroxide concentration, and reaction temperature, was conducted to assess their impacts on the exergy efficiency and exergy loss in the transesterification process.

Overall, Aghbashlo et al. [68] concluded that although these tools provide promising potential, they cannot be considered flawless solutions for addressing all the complexities associated with the implementation of biofuel systems. Integrating these tools can yield more dependable and precise outcomes compared to relying solely on individual approaches.

3. Application of Biodiesel in Different Countries

Biodiesel has a wide range of applications and may be used in a variety of settings, including on-road vehicles (such as passenger cars and heavy-duty trucks), off-road vehicles (such as agricultural machinery, naval engines, and locomotives), and stationary engines (such as those that generate electricity). The applications of biodiesel in a variety of different sectors are outlined in Table 1. Performance parameters such as brake-specific fuel consumption (BSFC) and brake thermal efficiency (BTE), and biodiesel emissions such as PM, nitrogen oxides (NOx), CO, carbon dioxide (CO_2), HC, and smoke are presented in Table 1. In general, it was discovered that biodiesel has the ability to lower harmful emissions such as PM and NOx [21]. Recent research indicated that a greater decrease in PM, NOx, CO, and HC could be obtained when gasoline containing alcohol was mixed with it. This was attributed to the increased latent heat vaporization potential of alcohol.

Utilizing biodiesel might also result in an increase in the combustion efficiency. This is due to the fact that biodiesels include roughly 10% oxygen, which helps to accomplish more thorough combustion, which in turn converts the fuel into CO_2 and water. When utilizing 100% waste cooking oil with 30% exhaust gas recirculation (EGR), Nanthagopal

et al. discovered that there were no significant changes in the cylinder pressure, HRR, or cumulative heat rate [69].

Table 1. Novelty and application of biodiesel fuel.

Engine	Novelty	Main Findings	Ref.
Diesel	Palm oil with additives (TiO_2 nano)	↓ CO, HC, and BSFC	[70]
Diesel	Neat jatropha oil with decanol	↓ CO, HC, and smoke emissions, ↑ NOx and CO_2 emissions	[71]
Diesel	30% EGR on 100% waste cooking oil methyl ester	↓ BTE, NOx, CO, HC, and no changes in combustion characteristics	[69]
Diesel	Electronic steam injection with a canola oil blend	↓ NOx reduction up to 22%	[72]
Diesel	Rice bran biodiesel and octanol blends	↑ BTE, ↓ BSFC, NOx, smoke, HC, and CO	[73]
Gas turbine	Comparison of biodiesel and six other biofuels	↑ H_2O, CO, and CO_2, ↓ N-containing species	[74]
Gas turbine	Bioethanol–biodiesel blends in gas turbine	↑ NOx, better atomization	[75]
Gas turbine	A high volume of soybean oil in the micro-gas turbine	↑ Engine efficiency, EGT, and thrust	[76]
Locomotive	B20 on a passenger train	Comparable results in performance and emissions with diesel fuel	[77]
Locomotive	Soy-based B10, B20, and B40 on train	No changes in NOx, ↓ CO, PM, CO_2, and HC	[78]

It is essential to keep in mind that the use of biodiesel is governed by standards in every sector. The ASTM D6751 and the EN 14214 are the two standards that have been created, as was indicated before. However, in order for biodiesel to be suitable for use in a gas turbine, its qualities must be compliant with the ASTM D2880 standard [79].

3.1. Biodiesel in the USA

Most US biodiesel is produced from vegetable oils and animal fats. In fact, biodiesel is the first leading biofuel produced in the country. Soybean oil is the most important biodiesel feedstock sources in the USA whose share in 2017 was 52% [80]. Corn and canola oil accounted for about 13% each, while the recycled sources (used cooking oil) and animal fats contributed 12% and 10%, respectively.

As the most important biodiesel feedstock in the USA, soybean and corn oils have been investigated in numerous studies. Can et al. [81] used 20% soybean and run it in a direct injection diesel engine under various loads and constant engine speed. The EGR rates were also varied; 5%, 10%, and 15%. By using both soybean and EGR, it was found that the maximum HRR and in-cylinder pressure increased, while the combustion durations were steady with the centre of the HRR moving toward top dead centre (TDC). Engine performance was deteriorated where higher BSFC and lower BTE were reported. However, NOx and PM emissions were successfully suppressed. In another study, Shehata et al. [82] used 20% blending ratio of soybean and corn biodiesel to examine the blends in diesel engine under various injection pressures. They found that improved engine performance (lower BSFC and increased BTE) were observed if higher injection pressure (200 bar) was applied.

Throughout the late 1990s, soybean oil emerged as the predominant oil utilized, since it was the sole oil that adequately met the nation's need. However, the cost of production for this particular edible vegetable oil was found to be too high. Consequently, its utilization was limited to instances characterized by a significant shortage of petroleum diesel fuel. In order to enhance commercial visibility, it is imperative to minimize the expenses associated with the feedstock. One potential strategy for enhancing affordability involves the utilization of feedstocks that are more cost effective. Utilized oils, greases, and animal fats serve as viable and cost-effective feedstocks for the production of biodiesel.

In the USA, a mandate regarding biodiesel blending ratio is not clearly defined. However, by 2022, the US government aims to meet a minimum use of 136 billion litres renewable fuels for its transportation industry [83]. The mandate was legalised through the Renewable Fuel Standard (RFS) that was first introduced in 2005 and reinforced two years afterwards. As a result of this mandate, between 2005 and 2016, biodiesel production in the US surpassed the RFS mandate and profited USD 0.26 per litre from government subsidies. Despite recent termination on the biodiesel subsidy, it was reintroduced in 2015.

The mandate was revised in December 2015, increasing biodiesel production by more than 30% in just four years from 2014 to 2018 [83].

Under the Trump administration, the progress of US biodiesel policies has been uncertain. President Trump postponed the RFS mandates for at least two months. His Special Advisor regarding the President on regulatory reform, Carl Icahn, is known for his anti-biofuel views with a strong interest in petroleum-based fuel [83]. The progress of biodiesel and other renewable biofuels is experiencing a difficult situation in the USA. If the production of petroleum-based fuel increases and the price of diesel fuel decreases, the RFS biodiesel mandate is more likely to be suspended.

The investigation of algae as an alternative biofuel resource has emerged. Ou et al. [84] conducted an assessment of the trade-offs associated with various factors by comparing the production of algae biofuel in two regions. The researchers employed a modelling approach to investigate the effects of high-purity CO_2 on algae biofuel production in open ponds. Specifically, they focused on the Midwest and Gulf Coast regions, which are home to numerous steam methane reforming and ammonia production facilities. This study demonstrated the interconnected relationship among algal productivity, CO_2 delivery, greenhouse gas (GHG) emissions, and water stress in the placement of algae ponds.

In 2018, the U.S. Environmental Protection Agency (EPA) released the report Biofuels and the Environment: The Second Triennial Report to Congress. Then, in 2023, the EPA released the third triennial report to Congress (external review draft) for public comment. This report is a comprehensive assessment of the environmental and resource conservation impacts of biofuels production and use in the USA. It provides an overview of the state of the biofuels industry; evaluates the impacts of biofuels on air quality, water resources, soil health, wildlife, and ecosystems; and assesses the potential for biofuels to help mitigate GHG emissions. The report is intended to provide policymakers with scientific insights into the environmental consequences of biofuel production and to inform the development of sustainable biofuels policies. It is an essential tool for understanding the environmental trade-offs associated with biofuels and guiding decisions that balance energy security, environmental protection, and resource conservation.

3.2. Biodiesel in the European Union (EU)

Similar to the US with its RFS mandate, the EU introduced a biofuel target in 2003, reinforced five years later under the name of Renewable Energy Directive (RED). No detailed blending rate for biodiesel was specified, but the RED required that by 2020, 10% of the transportation sector should come from renewable sources [83]. A year after the introduction of RED, biodiesel (B5) accounted for 70% of the renewable vehicle fuels in the EU, while the remaining 30% were from ethanol.

Biodiesel production nearly tripled in merely a decade between 2005 and 2015. Production capacity skyrocketed by more than five times, benefitting from inexpensive feedstock imports. Rapeseed oil is the major biodiesel sources in the EU, especially in Germany and France. Other feedstocks such as palm oil, sunflower, and soy are also imported and used in some EU countries. Several studies have reported the use of rapeseed oil as a biodiesel. A comprehensive review of the use of rapeseed oil has been recently written by Aldhaidhawi et al. [85]. Generally, it was found that rapeseed biodiesel lowers the heat release rate, has a shorter ignition delay, and decreases BSFC and BTE. These results are understood to be caused by the fact that rapeseed has a lower volatility, heating value, and energy density, thus deteriorating engine performance. As for the emissions, lower CO and PM, and higher CO_2 and NOx were observed compared to conventional diesel fuel. Reduced ignition delay and early fuel injection resulted from the use of rapeseed oil may be the reasons for the changes in the emissions behaviour.

To protect its rapeseed and biodiesel industry, the EU introduced a 3.5% and 6.5% import duty for B0-B30 and B30-B100, respectively. Furthermore, anti-dumping tariffs were also imposed on biodiesel from the USA, Canada, Argentina, and Indonesia. Despite the fact that the anti-dumping tariffs were cancelled for Argentina and Indonesia in September

2016, a revised version of the RED proposed in 2016 further restricted the sustainability issue regarding the conversion of food crops into biodiesel. It is expected that future EU mandates will contain stricter environmental criteria and social metrics.

The most recent version, RED II, was adopted in 2018 and sets a binding target for the EU to achieve at least 32% renewable energy consumption in the overall energy mix by 2030. Biodiesel is one of the biofuels covered by this directive. The EU has established sustainability criteria to ensure that biofuels, including biodiesel, used within the EU meet certain environmental and social standards. These criteria aim to prevent negative impacts on land use, biodiversity, and food production, among other factors. The EU has addressed the issue of indirect land use changes in biofuel production through the Indirect Land Use Change (ILUC) directive. It aims to account for the GHG emissions associated with land use changes caused by biofuel production. The EU has set specific targets for the use of renewable energy and biofuels in the transport sector. For instance, RED II mandates a target for at least 14% of energy consumption in the transport sector to come from renewable sources by 2030. The EU is also promoting the development and use of advanced biofuels, which offer higher sustainability and lower GHG emissions than conventional biofuels. Biodiesel derived from waste oils and residues falls under this category.

3.3. Biodiesel in Asia

3.3.1. China

In China, waste oil is the major biodiesel feedstock [86]. Recently, the production of waste oil has increased significantly to meet the biodiesel mandate, but its utilization is only 30–50% due to poor market demand. This is because the implementation of the B5 mandate is not strictly applied throughout the country, although the biodiesel blending standard (B5) has been introduced since 2010 (GBT 25199).

Recently, low-cost sources such as used oils from restaurants have been widely used as edible feedstocks. Nevertheless, producing fuel-grade biodiesel from these low-cost oils is far more difficult, as they encompass a high level of free fatty acids. However, various studies have indicated that the use of waste cooking oil methyl ester (WCOME) in diesel engines could reduce a considerable amount of PM, CO, and total HC emissions with no efficiency loss in several types of the diesel engines in comparison to conventional diesel fuel. Some studies have also shown that NOx emissions may increase slightly. Attia and Hassaneen [87] reported that 10% gave the best fuel economy with in-cylinder pressure being partially affected by the blending ratio. Between 30% and 50% WCOME provided the best emission behaviours. Regarding the unregulated emissions, Wei et al. [88] examined the effect of waste cooking oil (WCO) with a ratio of B20, B50, and B75. Despite reducing most of the unregulated emissions, it was found that a substantial decrease in the weighted total number concentration (TNC) was merely seen for higher biodiesel blend, i.e., B75.

The ignition delay reduction in edible waste oil (WEO) biodiesel is primarily caused by its higher cetane number concerning the petroleum-based diesel fuel. Fuels that have higher cetane numbers easily initiate auto-ignition, so the ignition delay is consequently shortened. The oleic and linoleic fatty acid methyl esters may tear apart into smaller compounds when entering the combustion chamber, allowing higher spray angles. As a result, ignition occurred earlier. Ignition reduction is also attributed to the smaller number of aromatic compounds found in WEO biodiesel. Therefore, the fuel that contains more aromatic compounds would delay the ignition.

Despite being illegal, it is common in China to reuse cooking oil to benefit the food industry because of its low prices. More than 50% of waste oil is recycled to be used as cooking oil. With such huge demand from the food industry, it is difficult to meet the demand for biodiesel production, relying merely on waste oil. Imposing stricter regulations on the use of waste oil is expected to help increase the supply for biodiesel production. In addition to that, the utilization of vegetable oils has also been initiated in three plants using Jatropha. These projects are supported by Chinese oil corporations such as the China

National Petroleum Corporation (CNPC), the China Petroleum & Chemical Corporation (Sinopec), and the China National Offshore Oil Corporation (CNOOC) [86].

3.3.2. India

The National Biodiesel Mission (NBM) was introduced in India after the country recognised Jatropha curcas as a potential biodiesel feedstock [89]. The Indian government provide generous financial incentives to encourage the plantation of Jatropha, aiming to achieve 11.2–13.4 million hectares of Jatropha plantations between 2011 and 2012 [89]. Recent interests have been shifted towards non-edible feedstock since the cultivation cost of J. curcas was found to be expensive and has low productivity. J. curcas has a very high acid value/FFA content. As a result, two-step acid-based transesterification is required [22].

In 2015, the Indian government launched the B5. Two years later, the country aimed to increase the mandate by using B20 through the National Policy on Biofuels [89]. However, similar to China, India has not firmly implemented the mandate. As a result, only 0.08% of the blending rate was achieved in 2015 [90].

The policy that was implemented in 2018 was quite likely to lower the cost of production, which in turn would increase the affordability for users [91]. By the year 2030, the suggested policy aims to achieve a 20% blending of ethanol in petrol (E20) and a 5% blending of biodiesel (B5). However, India has only achieved a blending of ethanol and biodiesel of 2% (E2) and less than 0.1% (B0.1), respectively (National Policy on Biofuels, 2018). Hence, the inquiry persists regarding the method by which the nation would attain a formidable objective by the year 2030. The scope of the policy is restricted to specific types of biofuels, including bioethanol, biodiesel, advanced biofuels derived from lignocellulosic feedstocks, and drop-in fuels made from agri-residues, plastic waste, industrial waste, and municipal solid wastes (Clause 2 of the Biofuel Policy, 2018).

Regarding biodiesel sustainability research, Mookherjee [92] conducted a concise evaluation of India's existing biofuel pathway, considering its lifecycle implications. The study identified deficiencies in the current policy and put forth a comprehensive and enduring sustainable solution.

3.4. Biodiesel in ASEAN

3.4.1. Indonesia

To raise its domestic palm oil production and consumption, Indonesia promoted the use of the B20 blend in September 2018 [93]. The country provides subsidies to the biodiesel industry, resulting in competitive biodiesel prices compared to conventional diesels on the market. Like Malaysia, Indonesia has gradually raised the blend of biodiesel. In 2009, the country began with its B1 policy. The blend was increased to B2.5 between 2010 and 2012. Indonesia then significantly increased its blend mandate to B10, B15, and B20 in 2014, 2015, and 2016, respectively [94]. However, the B20 was fully implemented nationwide starting from 1 September 2018 [93]. In 2020, the country planned to increase the blend to B30 from palm oil for all sectors, with the preparation being accelerated in 2019 [94].

As one of the popular biodiesel's feedstock, palm oils have been examined in diesel engines. Palm oil methyl ester (PME) has higher ignitability and lower exhaust emissions compared to conventional diesel fuel and other biodiesels such as rapeseed oil methyl ester and soybean oil methyl ester. Other advantages of using palm oil as a biodiesel are high productivity and low production costs. However, like other vegetable oils, palm biodiesel has a higher kinematic viscosity and boiling point than diesel fuel. Such properties are less favourable, but they can be improved by blending biodiesel with alcohol fuel. When biodiesel is blended with butanol, for instance, the oxygen content in the fuel will increase, resulting in lower smoke emissions compared to that of pure biodiesel.

Otaka et al. [95] found that by adding 1-butanol to PME, the smoke emissions of PME decreased with the increase in 1-butanol content. However, the 1-butanol was used only up to 30%, thus not achieving the maximum 1-butanol mixing ratio that can be used in diesel engines. Following this study, the author further investigated the research by increasing

the 1-butanol in the blend up to 60%. The experiments were tested in a DI diesel engine with a jerk-type fuel injection pump, and the comparisons were conducted with JIS No. 2 diesel fuel (gas oil). No problems were reported on the starting ability and stability of the engine when 60% 1-butanol was used. The results showed that the 1-butanol/PME blend had a longer ignition delay than PME due to 1-butanol's low cetane number. As the percentage of 1-butanol increased, the smoke emissions of 1-butanol/PME decreased, but the HC and CO emissions increase resulted from a longer ignition delay. Taking into account the ignitability, brake thermal efficiency, and the exhaust emissions, the author concluded that the maximum 1-butanol addition to PME is 50%. Lastly, adding 1% of 2-Ethylhexyl nitrate (2EHN) to 1-butanol/PME blend could improve the ignitability of the blends, thus reducing HC and CO emissions.

Combustion characteristics are normally defined using ignition delay, rate of pressure rise, peak pressure, and HRR. Most of the biodiesel used in the diesel engine will reduce ignition delays. An ignition delay is described as the time interval between the start of injection (SOI) timing and the start of the combustion timing of the fuel, being presented by the degree of crankshaft rotation. As for the SOI timing, properties of palm biodiesel such as density viscosity and compressibility correlate with the earlier SOI timing. The SOI timing has an essential effect on in-cylinder pressure, combustion efficiency, and exhaust gas emissions. The SOI timing is determined from the fuel injection line pressure. Biodiesel-derived diesel fuel and petroleum-based diesel fuel have a similar pattern, yet their injection line pressures are different. The higher viscosity of biodiesel tends to deteriorate the injection process.

3.4.2. Thailand

Despite being the third largest palm oil producer, after Indonesia and Malaysia, and contributing 4% to the global biodiesel production, Thailand has not yet shown a strong commitment to the use of biodiesel until the increased price in fossil fuel and drop of palm oil prices occurred in 2012. The government introduced the Renewable and Alternative Energy Development Plan by implementing the B7 mandate, with palm oil being the major biodiesel feedstock [83]. However, the mandate was not stringently imposed as a result of a palm oil shortage. Thus, the country only achieved an average blending of B5.8 in 2015. Currently, Thailand has recently introduced the B10 mandate starting in April 2019 due to a steady increase in crude palm oil (CPO) production in the past three years [96].

One aspect that hinders the development of biodiesel in Thailand is its food price dilemma. The development of palm oil has reduced the planted areas for Thai's important export resources: rice and coffee [97]. Another issue that discourages the use of biodiesel in Thailand is its low CPO yields due to its smallholder model [87]. Thai national agricultural policy always prefers a model in which large-scale utilization of planted areas is problematic. As a result, most farmers work self-sufficiently with poor quality fruits, thus leading to a low CPO yield. Therefore, considering these two limitations in Thailand (the food prices stability and the smallholder model), the Thai government seems to be cautious about increasing its biodiesel mandate.

3.4.3. Malaysia

The interest to commercialised biodiesel in Malaysia began in the early 1980s due to its strategic position as the number one palm oil producer and exporter in the world. The government then realised the country's potential to become the initiator of the biodiesel industry [98]. Laboratory research sponsored by the palm oil industry was initiated in 1982 by the Palm Oil Research Institute (PORIM). PORIM was later taken over, through a merger with Palm Oil Registration and Licensing Authority (PORLA), to become the Malaysian Palm Oil Board (MPOB) [99]. In 1984, a preliminary plant was built in partnership with Petronas (Petroliam Nasional Bhd). A year later, the plant successfully produced 3000 tonnes of palm oil methyl ester annually. Winter grade biodiesel was also successfully developed in 1992 by MPOB, allowing it to be used at low temperatures.

Despite a massive breakthrough during the 1980s and 1990s, the progress of biodiesel in Malaysia had been stagnant until the Fifth Fuel Diversification policy was executed under the Eighth Malaysia Plan (2001–2005) [100]. The use of palm biodiesel was further emphasised in the Ninth Malaysia Plan (2006–2010) to reduce the country's fossil fuel dependency. When the National Biofuel Policy was introduced in 2006 to increase the use of biodiesel, the government committed to reserving approximately 6 million tonnes of CPO for biodiesel production. Furthermore, the first Malaysian commercialised biodiesel plant started to run in August of the same year in Pasir Gudang, Johor. From August to December 2006, Malaysia could only produce 55,000 tonnes of biodiesel, but within merely three years, the figure increased dramatically to 130,000, 180,000, and 230,000 tonnes in 2007, 2008, and 2009, respectively.

The implementation of B5 was planned to come into force on 1 January 2010. However, the mandate was delayed to the following year due to the rise in palm oil prices, leading to higher government subsidies for biodiesel production. Therefore, the Malaysian authority considered reducing the blend to a B3. Nevertheless, this plan was opposed by the biodiesel producers throughout the country since the use of B3 was considered too insignificant and not economically feasible. As a result, the B5 policy was re-enacted, but the mandate was delayed until 2011 and limited to several regions only. In November 2014, the blend was increased to B7. Figure 5 displays the milestone of the biodiesel industry in Malaysia from the 1980s to the present day.

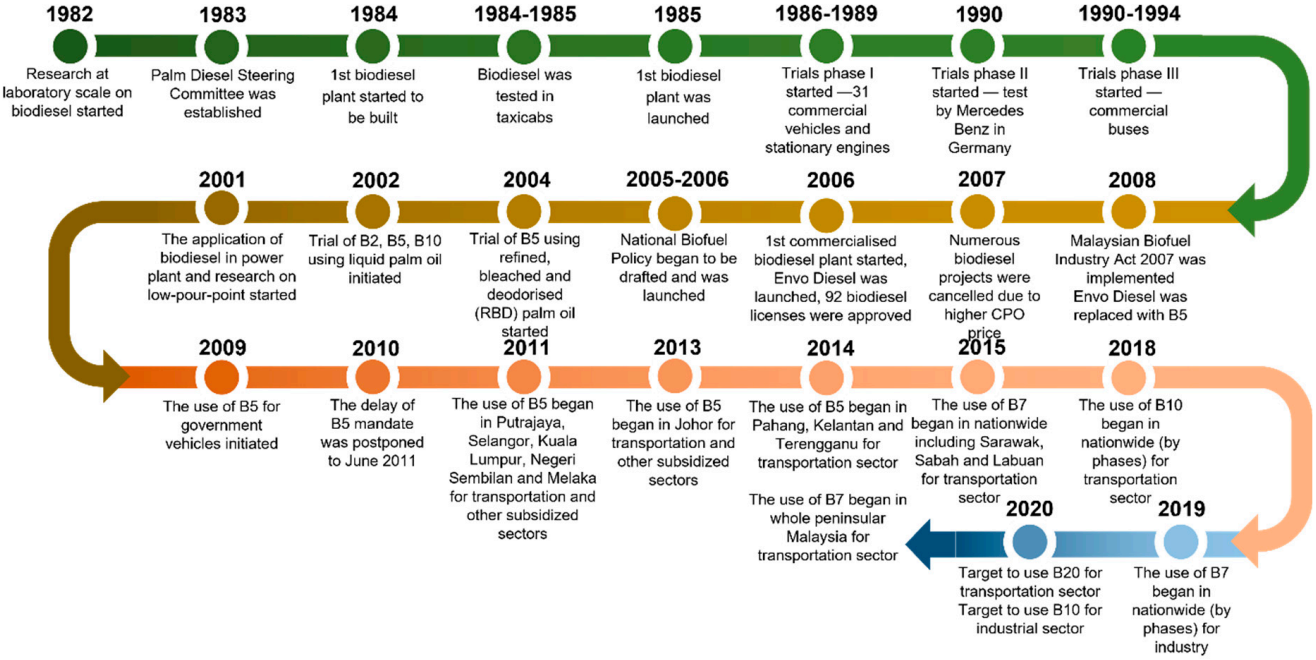


Figure 5. Progress of Malaysian biodiesel industry and policy [98,100–102].

Malaysia and Indonesia are currently the two major palm oil producers in the world, as shown in Table 2. Malaysia used to be the largest producer of palm oil for several decades before the position was taken by Indonesia in 2006 [103]. Despite producing a high volume of palm oils, both countries are struggling to commercialise their palm biodiesel due to several technical and non-technical issues. However, the government in both countries took a decisive step in 2018 when a mandate for B10 and B20 came into force in Malaysia and Indonesia, respectively. This section will focus on the current scenario of biodiesel in Malaysia, while the next section will discuss the progress in Indonesia and other countries.

Table 2. Palm oil production by country in 2023/2024.

Country	Production (1000 MT)
Indonesia	47,000
Malaysia	19,000
Thailand	3280
Colombia	1900
Nigeria	1500
Guatemala	920
Papua New Guinea	820
Cote d'Ivoire	600
Honduras	595
Brazil	585

Source: Foreign Agricultural Service, U.S. Department of Agriculture Database.

As can be seen in Figure 5 in the previous section, in 2018, the Malaysian government set to increase palm oil production and encourage its use by raising the blend mandate to B10. The B10 was implemented for the transportation sector starting from December 2018, while B7 was intended for the industrial sector and was realised from February 2019 [102]. By 2020, the country aims to increase its biodiesel mandate to B20 for the transportation sector and B10 for the industrial sector [100]. The government will allocate 117 million ringgits for the agricultural sector [101]. Most of the funds will be assigned for research and development to increase the productivity of the seeds. The bold policy from the government has indicated the importance of using biodiesel in Malaysia.

The use of biodiesel will bring numerous benefits to Malaysia. Figure 6 summarises the advantages of biodiesel for Malaysia in terms of economic, social, and environmental aspects. Furthermore, the introduction of B10 in 2018 has a major impact on the CPO production throughout Peninsular Malaysia as well as in Sabah and Sarawak. There has been a 9% increase in Malaysian total CPO production between January and May 2019 in comparison with the previous year in the same period. All states have been experiencing steady growth. Johor, Pahang, and Perak are the top three prolific producers with total production reaching 1,327,131, 1,307,529, and 809,062 tonnes, respectively. Note that despite being the largest CPO in Malaysia, Johor has reached 91% maturity of its palm oil planted area, while Pahang and Perak were only at 86.4 and 88.1% maturity, respectively. More abundant opportunities lie in Sabah and Sarawak.

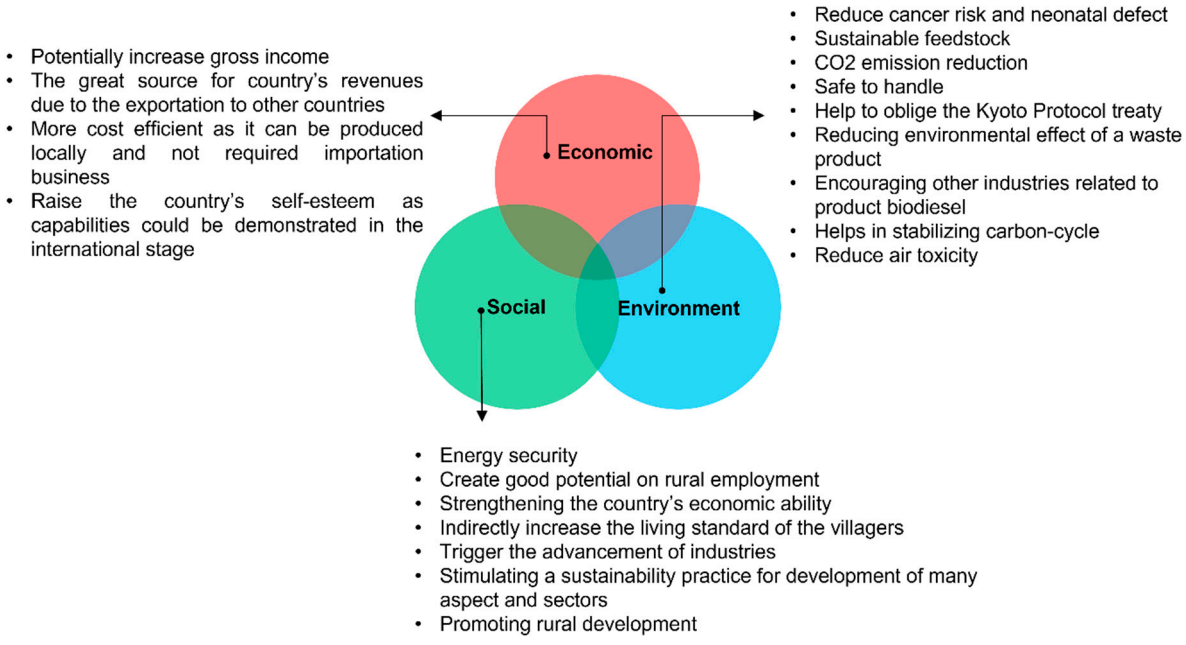


Figure 6. Advantages of using biodiesel for Malaysia [31,98,104–107].

4. Conclusions

There is a growing emphasis on promoting the utilization of biodiesel as a substitute for diesel fuel derived from petroleum sources. Numerous nations have enacted biodiesel mandates as a means to diminish their reliance on imported diesel and promote the utilization of domestically manufactured biodiesel. The countries that have implemented biofuel blending mandates are Indonesia (B20), Malaysia (B10), Thailand (B10), and India (B5). With the exception of Indonesia, Malaysia, and Thailand, no other countries globally have implemented a requirement for a biodiesel blend at or above B10. These three countries are able to sustain their biodiesel supply owing to their advantageous position as the leading palm oil producers globally. Malaysia has set an ambitious goal to implement a B20 mandate for its transportation sector by the year 2020.

The advancement of biodiesel in other regions of the world has not exhibited a comparable level of significance when compared to the progress observed in Indonesia and Malaysia. Another nation, similar to Brazil, is expected to give higher importance to its bioethanol sector as a result of its well-established infrastructure and abundant sugarcane resources. Moreover, it is worth noting that countries such as the United States, India, and China have lagged significantly in the advancement of biodiesel utilization. This can be attributed to the inadequate level of commitment demonstrated by their respective governments, as evidenced by the lax enforcement of regulations. Consequently, the industry has suffered from a lack of market demand in these nations.

Despite encountering various obstacles during its development, biodiesel continues to be regarded as a highly promising biofuel on a global scale. Due to the volatile nature of petroleum oil prices and the potential for domestic production of biodiesel, it is highly likely that there will be a gradual and consistent rise in the global demand for biodiesel and its associated blending requirements in the foreseeable future. In order to mitigate the expenses associated with feedstock in the production of biodiesel, future research endeavours may focus on exploring the potential of second and third generation biodiesel derived from non-edible sources, such as agricultural waste and microalgae. Nevertheless, it is crucial to acknowledge that, in conjunction with the recent advancements and studies in biodiesel, the sustained dedication of governmental entities plays a fundamental role in the global adoption and execution of biodiesel initiatives.

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