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Review Article

Recent Progress on the Implementation of Renewable Biodiesel Fuel for Automotive and Power Plants: Raw Materials Perspective

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The issue of energy availability and the impact of global warming has become a specific concern for researchers in various countries in the world. This condition opens up space for potential alternative energy sources that are newer and more sustainable. Biodiesel as a sustainable alternative energy can be applied directly to industrial and automotive fields and even as a fuel source for power plants. This study provides a specific overview of the use and development of biodiesel as a fuel source for renewable power generation based on material sources. An essential part of this study discusses the development of various combinations of biodiesel mixtures and their applications in various types of industries. The physical and chemical characteristics of various types of biodiesel have been studied for their use in various parts of the world. The use of biodiesel has a positive effect on reducing emissions and pollutants, but a particular method is needed to optimize the efficiency and effectiveness, both technically and nontechnically. However, the utilization accompanied by optimizing the characteristics and parameters of biodiesel shows that this alternative energy is feasible and can be applied as a renewable fuel source for automotive industry and power generation in the future.

1. Development of Biodiesel

Before the combustion technology uses fuels as of today, biomass has become an essential primary energy source for human life. Dry wood has long been the primary fuel for cooking as well as heating medium in warm places, while ethanol and vegetable oil are the primary fuels used for lighting [1]. Over time, the energy transition from wood to coal to fossil fuels began to occur. Now, fossil fuels are the primary energy used by humans, with a percentage of up to 80% of energy consumption worldwide [2]. On the other hand, the production and demand for fossil energy have decreased from year to year [3]. In addition, fossil energy contributed to carbon gas emissions of 9,795 Gt in 2014 with 35.9 Gt CO_2 and an increase in emission levels of 0.6% from the previous year [4]. Limited use of fossil energy due to depletion of global reserves, continuous environmental pollution, and market uncertainty has led many researchers to develop alternative energy that is cleaner and more sustainable [5–7].

Biomass as energy is used for all organic materials derived from plants and animals. Biomass resources include wood and its waste, agricultural crops and their waste by-products, solid waste from cities, food waste, aquatic plants, and algae [8]. Meanwhile, according to FAO [9], biodiesel refers specifically to gaseous and liquid fuels derived from biomass. In general, biofuels are divided into two, namely, primary and secondary biofuels. The primary biofuels include firewood, animal waste, landfill gas, wood chips, and pellets typically used in unprocessed forms for cooking, heating, and even electricity production. Meanwhile, secondary biofuel consists of biodiesel and bioethanol, which are usually used as fuel and in various industrial processes [9, 10].

Initially, biodiesel was produced using feedstock in the form of edible vegetable oil such as palm oil, soybean oil, and sunflower oil. This period is known as first-generation biodiesel feedstock [11–14]. The development of the first generation of biodiesel production is a type that has significant growth, where the production process enters a large industrial scale in various countries. Its particular characteristic is that it has a low sulfur content with renewable raw materials. The second generation of biodiesel feedstock includes various types of nonedible vegetable oil, such as *Jatropha*, mahua, jojoba oil, cooking oil, and agricultural and urban waste [15]. This generation has fuel characteristics with performance similar to conventional diesel in terms of chemical structure and performance. In terms of production, this generation is entering the stage of industrialization in several countries. Meanwhile, the third generation includes microalgae, cyanobacteria, and other single-celled oleaginous microorganisms [16]. As for the third-generation biodiesel and after that, the majority are still conducting various studies in many countries, such as Europe and the United States. The two countries are at the forefront of developing this production method, particularly research on catalysts and gasification devices. The fourth generation of biodiesel feedstock began to be developed massively through the use of technology in engineering the required feedstock [17].

In the previous study, Aziz et al. [18] showed that the produced biodiesel feedstock in the form of plants capable of consuming CO_2 more than the atmosphere should be expelled in the form of O_2 during the combustion process. In addition, this fourth generation of biodiesel feedstock also includes the use of pyrolysis, gasification, purification, and genetic manipulation processes in certain organisms to obtain hydrocarbon compounds [19]. Figure 1 shows the biodiesel production process from four generations using different feedstock.

While the increasing development and utilization of biodiesel can be seen above, the development of biodiesel in a country can be described by dividing it into three phases [20].

(a) The first phase is a condition in which the idea of using biodiesel starts to emerge so that research on the use of biodiesel as fuel begins. This phase ends when a country's political decision on the related policies will occur, which is to support biodiesel research and invest on biodiesel as a clean and sustainable energy.

(b) The second phase is marked by a deeper research effort through experimental studies, which are then applied to pilot projects in several regions. This phase also includes the formulation of policies, strategies, and other technical matters that are supported by considerations of the country's economy.

(c) The third phase shows that biodiesel can be applied to support the energy of a country. In this phase, biodiesel has been proven technically, economically, and commercially.

The raw materials for biodiesel are generally animal and vegetable oils, used cooking oils, and microbial oils. However, it is not limited to these sources but is broader and more extensive. However, the problem is that the high production costs considering the efficiency of each raw material are still not able to match the performance of fossil energy both in terms of quality and quantity. On the other hand, optimism about biodiesel in the future is positive considering the development of science and technology and advances in production and cultivation technology, making biodiesel a source of energy in the future. The unlimited number and types of raw materials and the dwindling conventional fossil energy reserves make biodiesel have good prospects in the future and the development of science and technology [21].

2. Biodiesel Mixtures

Recently, there have been many studies on the use of feedstock for both edible and nonedible oils as a mixture in biodiesel. Biodiesel mixtures produced from different feedstocks will yield various compositional values and purities [22]. The choice of raw material as a biodiesel blend is highly dependent on its technical and nontechnical feasibility, such as cost factors and the resulting purity value [23]. On the other hand, the use of a specific feedstock will depend on the conditions and capabilities of a country. Tropical countries, such as Indonesia and Malaysia, produce more biodiesel with a mixture of palm oil, considering the fact that the production of Crude Palm Oil (CPO) is very abundant [24, 25]. European countries, such as France and Italy, mostly use sunflower and rapeseed oils [26], while the United States mainly uses soybean oil [27], and India uses its abundant sal, mahua, neem, and *Pongamia pinnata* oils [28].

Biodiesel mixtures from edible vegetable oils that are often used include soybean oil [29], rapeseed oil, sunflower oil [30], canola oil [31], palm oil [32], coconut oil [33], olive oil [34], peanut oil [35], and mustard oil [36]. Meanwhile, the nonedible vegetable oils that are usually used are *Jatropha* oil [37], malapari or Karanja (*Pongamia pinnata*) oil [38], neem oil [39], linseed oil [40], rubber seed oil [41], castor oil [42], stillingia oil [43], and *Silybum marianum* oil [44]. The other mixtures are microbial oil [45], fish waste oil [46], microalgae [47, 48], pine and cotton oil [49], animal fat [50], broiler chicken waste [51], and used cooking oil [52]. More complete details of the oil content of various types of biodiesel feedstock are shown in Table 1.

Devarajan et al. [36] studied the use of mustard oil and its mixtures on a diesel engine. The sample used was mustard oil methyl ester (M100) and various biodiesel mixtures with *n*-octanol (M90O10, M80O20, and M70O30) to be tested on four-stroke, air-cooled, single-cylinder AVL 5402 diesel engines with a common rail injection system. The experimental study showed that the addition of *n*-octanol had a positive effect on engine performance as well as on emission and combustion characteristics. This result was due to the higher density and oxidation ability of *n*-octanol, which gave a better thermal efficiency effect and optimally reduced CO, HC, and NOx emissions. A study was conducted by Ahmad et al. [35], analyzing physicochemical characteristics, optimal production, and combustion performance of peanut oil biodiesel (POB). The study was conducted using mixtures of diesel oil (High Speed Diesel—HSD) with POB with

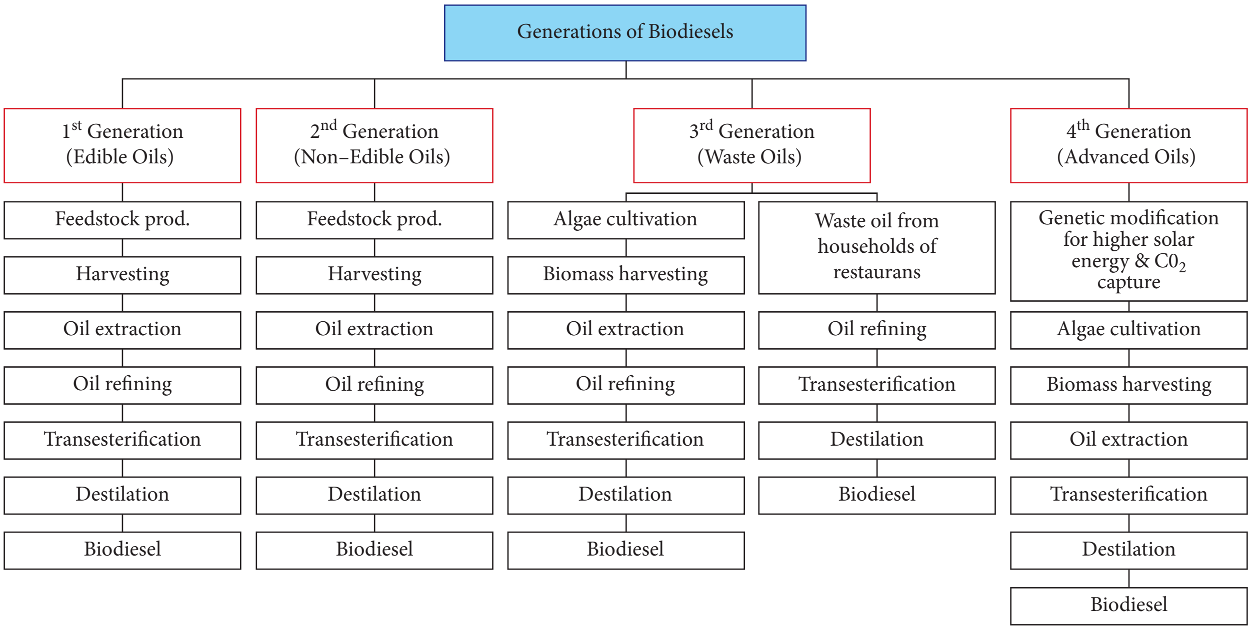

Figure 1: Biodiesel production process of various generations [17].

Table 1: Percentage of oil content in various types of biodiesel feedstock.

Group	Type of material	Oil content (%)
Edible oil	Soybean [29]	15–20%
	Sunflower [30]	25–35
	Rapeseed [53]	38–46
	Palm [32]	30–60
	Linseed [40]	40–44
	Canola [31]	40–45
	Peanut [53]	45–55
	Coconut [34]	63–65
Nonedible oil	Neem [39]	20–30
	Karanja *(Pongamia pinnata)* [38]	27–39
	Jatropha [53, 54]	30–40
	Chinese tallow seed [55]	44.15
	Castor [56]	45–50
	Rubber seed [41]	53.74–68.35
Animal oil and other sources	Algae [57]	25–75
	Boiler chicken waste [58]	
	Microalgae [59]	
	Microbial [45]	
	Pine and kapok [49]	

concentrations of 5%, 10%, 20%, and 100%, and NaOH helps the catalyst that met the requirements of 3.4% by weight. The B5-type mixture (5% POB + 95% HSD) gave the best engine efficiency value, namely, 16.3%, but the largest fuel consumption was 9.8 liters/hour. POB has a low free fatty acid (FFA) value, namely, 2%, and its use affects reducing CO and CO_2 emissions.

One method of biodiesel production is the esterification process, where this method refers to the reaction of carboxylic acids in the form of fatty acids with alcohol to produce esters. The esterification reaction is influenced by several factors, including the amount of methanol reagent and free fatty acids, reaction time, temperature, catalyst conversion, and water content in the oil [60]. The production method is based on the transesterification reaction, a new ester reaction that undergoes an exchange of fatty acid positions [61]. In biodiesel production, the transesterification process works by removing glycerin from oil and reacting its free fatty acids with methanol to form methyl esters [62]. This reaction is also influenced by several factors, such as the water content and free fatty acids, the type of catalyst and its concentration, the molar ratio of alcohol and oil, the temperature and duration of the reaction, the intensity of mixing, and so on. On the other hand, there are developments in biodiesel production technology, namely, in situ transesterification, which is a technology for oil extraction processes and esterification or transesterification reactions that are carried out simultaneously and carried out in one reactor [63]. This production process has the advantage that it can shorten production time, is efficient, saves energy, and produces biodiesel with high quality [64].

Biodiesel as an alternative fuel offers an advantage of a cleaner environment because biodiesel produces fewer pollutant emissions and is biodegradable, nontoxic, and free from sulfur, making biodiesel cleaner than conventional diesel oil [65]. However, this environmental impact has a consequence that biodiesel has high production costs. The use of materials such as nonvegetable oil, cooking oil, and animal oil does not require much money, but the resulting biodiesel is less clean with high levels of impurities [66]. Issariyakul et al. [31] used canola oil (CO) mixture with used cooking oil (UCO) to produce low-cost yet high-quality biodiesel. The transesterification process was carried out with a catalyst of potassium hydroxide (KOH) to produce methyl and ethyl ester in both oils (*canola methyl ester*—CME, *canola ethyl ester*—CEE, *methyl ester*—UME, and *used ethyl ester*—UEE). The test results showed that the methanolysis process produced better characteristics with lower water content, heating value, and viscosity than the ethanolysis process. Conversely, a minimum level of canola oil of 60% was required to achieve high-quality ethyl ester and meet ASTM standards for a UCO: CO ratio of 40 : 60. Residual materials can be utilized as a biodiesel mixture by using reusable low-cost catalysts, such as eggshells, shellfish and crustacean wastes, coconut shell biochar, and kraft lignin [67].

A study by Ewunie et al. [68] showed that *Jatropha* only produced biodiesel products on a minor scale, which is not proportional to the quantity and physicochemical composition, seed production, and oil contained in the plants. Meanwhile, Hariram and Vagesh Shangar [69] used jojoba plants as a component of biodiesel mixture (B20 and B40) with variations in the compression ratio and the load given. From the results, it was found that the effect of smoke, NOx, and CO emissions increased along with the addition of the load on the engine but decreased when the concentration of jojoba was increased. The compression ratio of 18 gave optimal results because it had less brake specific fuel consumption (BSFC) value and less CO emissions compared to the compression ratios of 17.5 and 17. The Karanja material was studied by Pohit and Misra [70] as a biodiesel mixture component by analyzing the most optimal parameters through the calculation of emission levels in a diesel engine at a specific value of compression ratio. By using the gray-based Taguchi method, it was found that the optimal parameter was the Karanja biodiesel B20 mixture with a compression ratio of 17.5. Optimization of diesel engine parameters with fuel in the form of a biodiesel mixture of Karanja oil was carried out using a combination of the Taguchi method and utility theory [71]. Based on the results, it was found that the optimal parameter in the machining process was to use a 10% *Pongamia* mixture, fuel injection timing of 23°bTDC, and injection pressure of 22 MPa with the resulting volume of HC 22 ppm, NOx 761.34 ppm, and 85% smoke emission.

Jacob et al. [72] studied the use of microalgae as a mixture of biodiesel feedstock. This study showed that the closed reactor type is the most suitable medium. Nautiyal et al. [73] used biodiesel blends from *Spirulina platensis* algae on a diesel engine. The properties of the fuel produced from the extraction and transesterification process were able to meet European and American standards. The resulting fuel properties had the effect of reducing the levels of HC and CO emissions, while NOx increased significantly due to the shorter injection time. Meanwhile, Erdoğan et al. [74] used animal fat biodiesel (AFB) from bovine bone marrow, vegetable oil biodiesel (VOB) from safflower oil, and ultra-low-sulfur diesel (ULSD) as fuel in diesel generators. The use of the AFB showed gas pressure in the cylinder and heat release rate (HRR) that are better than ULSD. The AFB mixture reduced emission levels lower than ULSD and VOB with the most significant emission reduction at AFB50 on particulate matter, HC, and CO. On the other hand, the emissions of CO_2 from VOB, AFB, and their mixtures showed an increasing trend compared to ULSD. Aydın [75] used a composition of 10% biodiesel mixture from animal oil, vegetable oil, and microalgae with ULSD, which were applied to diesel engine power generators. The results showed that the B10 biodiesel mixture from each ingredient produced NOx, HC, and O_2 emissions that were slightly higher and able to reduce the thickness of the smoke, CO, and CO_2 emissions compared to ULSD.

Biodiesel production can also utilize wastewater from food, food industry, and slaughterhouses that contain high proportions of fat, oil, and grease (FOG) [76]. Biodiesel from FOG derivatives can be processed using the pretreatment method for feedstocks with high FFA, including acid esterification, steam stripping, nanocatalytic technology, biological conversion, glycerolysis, supercritical esterification, and simultaneous in situ conversion. FOG has good characteristics in oxidative stability, flash point, cetane number, and production of total emissions, which meet international standards as well as conventional diesel. FOG has advantages over other feedstocks in terms of decreasing the quantity of feedstock due to excess exploration, rising crude oil prices, environmental damage, and discussions on the use of food or fuel. However, this has a consequence on the cost of producing FOG biodiesel, which has not been able to compete with conventional diesel fuel. Biodiesel properties from various feedstocks or different raw materials are shown in Table 2.

3. Utilization of Biodiesel in Industry

The use of biodiesel in various industrial sectors is inseparable from the type of raw material used in industrial by-products. The increasing number of biodiesel use is practically able to optimize the efficiency of the industry in terms of processing waste and feedstock as well as efficiency in the economic aspect [78]. Figure 2 shows a flow chart of the biodiesel production process, while a comparison of various methods in the conversion process of petroleum to biodiesel is shown in Table 2.

In a simple process, biodiesel is produced by a technology called transesterification reaction, which is carried out on various types of raw materials, including various

Table 2: Biodiesel properties from various raw materials [77].

Properties	Sulfur content, ppm	Kinematic viscosity	Flash point	Cetane number	Cetane index	Iodine value	Lower heating value	Higher heating value
Palm	2	4.61	163	61.9	50.5	54.0	37.3	40.6
Coconut	3	2.75	113	59.3	—	18.5	35.2	38.1
Tallow	7	4.69	124	58.9	59.1	65.9	37.2	39.7
Yellow grease	5	4.80	161	56.9	48.5	88.9	37.6	39.4
Corn	4	4.19	171	55.7	60.9	101.0	39.9	43.1
Jatropha	5	4.75	152	55.7	—	109.5	37.7	40.7
Canola	2	4.38	153	53.7	61.5	108.8	38.9	41.3
Rapeseed	4	4.50	169	53.7	5.7	116.1	37.6	41.1
Soy	2	4.26	159	51.3	52.3	125.5	37.0	39.7
Safflower	—	4.14	174	51.1	—	141.0	—	42.2
Sunflower	2	4.42	175	51.1	55.0	128.7	35.3	40.6
Camelina	2	3.80	136	50.4	—	152.8	—	45.2

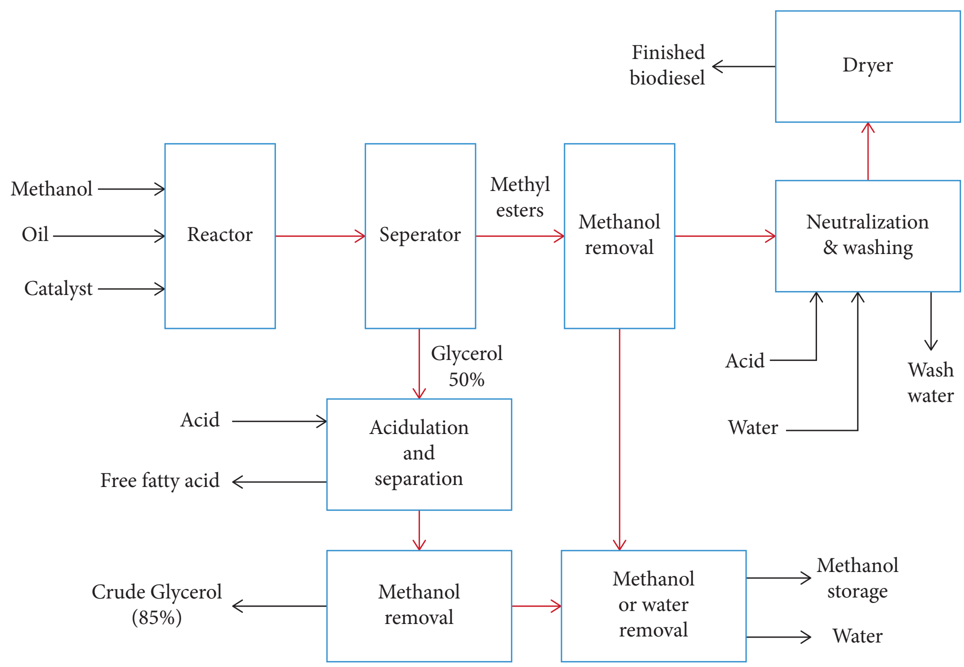

Figure 2: Schematic flow of the biodiesel production process [79].

animal and plant oils or methanol and ethanol, so that this can be used as fuel in internal combustion engines [80]. Currently, the main methods in the biodiesel production process include direct mixing, microemulsion, transesterification, and pyrolysis [81]. This direct mixing method is based on the principle of mixing animal and vegetable oils with traditional diesel oil in specific proportions. However, this method has some drawbacks, such as high viscosity, easy damage, and incomplete combustion. There is also a transesterification process with the principle that triglycerides from vegetable oils react with lower alcohols to produce fatty acid alkyl esters [82].

Vegetable oil has the potential to change this type of fuel, but its high viscosity makes it necessary for unique production methods for this type of feedstock. Chemical and thermal processes can be carried out to make vegetable oil compatible with combustion engines. For example, the pyrolysis process can be carried out to produce biodiesel under heating conditions and a fast reaction. However, it will produce more gasoline compared to considering the fact that the production process uses low-value materials. In addition, other production processes that can be carried out to reduce the viscosity of the resulting fuel are mixtures and microemulsification. Microemulsification is done by mixing animal and vegetable oils and emulsifiers, namely, mixing two types of immiscible liquids and ionic or nonionic molecular into the system to form colloids. However, in practice, this process causes carbon deposition and contamination of lubricating oil. The microemulsion and pyrolysis processes have high production costs even though the optimal biodiesel yield is close to ordinary diesel oil. Therefore, the most effective process to reduce viscosity by minimizing other side effects is a chemical process in the form of transesterification [83]. Comparison of the various methods used in the conversion of refined oil to biodiesel is shown in Table 3.

Table 3: Comparison of the various methods used in the conversion of refined oil to biodiesel.

Method	Advantage	Disadvantage	Reference
Transesterification	(i) High conversion efficiency (ii) Economical (i) The biodiesel produced has almost the same characteristics as petrodiesel (ii) This technology is very suitable for use in industry	(i) Has a side reaction (by-product) (ii) The resulting biodiesel must be neutralized and cleaned of dirt which tends to be a lot (iii) Difficulty in product reaction separation	[21]
Reactive distillation	(i) The process is simple (ii) Product separation available (iii) Able to produce biodiesel from feedstock with high FFA content (iv) Only requires a small amount of methanol in the process	(i) Requires great energy (ii) The oil conversion process is greatly influenced by the efficiency of the catalyst	[17]
Catalytic distillation	(i) Product separation tends to be easy	(i) The use of solvents and the rate of oil conversion depend on catalyst recovery	[17]
Microemulsion	(i) The process is simple and easy	(i) Low volatility (ii) Poor stability	[84]
Microwave technology	(i) Rapid reaction (ii) Not much heat loss	(i) The residue of the postproduction catalyst must be removed (ii) The efficiency of the catalyst significantly affects the biodiesel conversion process	[85]
Pyrolysis	(i) The process is simple and easy (ii) It does not cause emissions	(i) Costly (ii) Requires a very high temperature (iii) Low purity quality	[86]
Superfluid method	(i) No need for a catalyst (ii) Short-lived reaction (ii) High biodiesel conversion efficiency	(i) Costly (ii) Requires large amounts of energy	[87]

Biodiesel production methods have different characteristics and use based on the type and nature of the raw materials to be used [88]. The most common method of extracting fat into oil is transesterification, also known as the alcoholic reaction. However, there are still some modifications in the process according to the characteristics of the raw material used. The various types of characteristics of the transesterification method are described in Table 4. From the previous studies reported by Ramos et al. [89] and Santos et al. [90], it is shown that for the production of biodiesel, several enzymatic catalysts have been used. The catalysts mainly have two types, which are bio-based product and synthetic-based product. In bio-based products, lipase is often used due to economic reasons, reusability, and recycling capability. Lipase-based materials, like other heterogeneous catalytic materials, are inefficient and have mass-transfer limitations. As a result of the environmental concern, lipases are pushed to be immobilized on suitable substrates, giving rise to the concept of heterogeneous biocatalysts. To overcome the limitations outlined above, investigate the use of nanostructures to enable enzyme immobilization, resulting in innovative heterogeneous biocatalysts.

3.1. Automotive Industry. Biodiesel in the automotive industry has been widely studied [91–93] and has become a critical concern in its application as a potential alternative fuel source to replace mineral fuel either partially or entirely. Agarwal et al. [91] reviewed the potential and challenges of large-scale biodiesel use in the automotive industry. The global biodiesel production process is dominated by the transesterification method with a catalyst because it can be carried out at low temperatures and pressures, has a high conversion rate, and uses cheap materials in its manufacture. The biodiesel application to the standard compression ratio of diesel engines provides substantial reductions in particulate matter, total hydrocarbons, and carbon monoxide emissions. However, it results in increased BSFC consumption and nitrogen gas emissions compared to mineral diesel. In particular, Lozada et al. [93] analyzed the feasibility of using palm oil biodiesel in a mixture of 5% (B5) and 10% (B10) in the transportation sector in Mexico. Technical and economic analyses were carried out in two alternative scenarios, namely, B5 from 2006 to 2015 and B10 from 2016 to 2031. The particulate matter was reduced by 3.4%, while the CO gas was 3.7%, the total hydrocarbons were 5%, and SO_2 7.6%, but there was an increase in NOx emissions by 0.7%. Cumulatively, the projected reduction in CO_2 emissions during the 25 years reached 148 million tons.

Vegetable oils such as biodiesel can be used as fuel in diesel engines even though they have a slightly lower performance level when compared to the performance of diesel engines with diesel fuel. It is because the fuel derived from vegetable sources has a calorific value slightly lower than the calorific value of diesel fuel. Diesel engines with biodiesel fuel have performances such as power, torque, and thermal efficiency that are slightly lower than diesel engines with diesel fuel. A study was conducted by Harsono and Siregar [94] showed that there was a decrease in power when using biodiesel in a diesel engine, which was 0.9–3.6% for B30 to B100, and a lower torque of 1.7% for B30. In addition, diesel

Table 4: Different types of transesterification method [88].

No.	Transesterification method	Characteristics
1	Homogeneous acid-catalyzed transesterification	(i) Relatively insensitive to the FFA content of the raw material relatively more minor energy-intensive (ii) Requires higher operating temperatures and (iii) The resulting biodiesel usually has a higher amount of free glycerol (lower percentage of purity)
2	Homogeneous base-catalyzed transesterification	(i) Very sensitive to FFA and moisture content (ii) Very selective in the type of raw material (iii) The reaction is fast (iv) The catalyst is relatively inexpensive (v) Usually applied on an industrial scale for biodiesel production
3	Heterogeneous acid-catalyzed transesterification	(i) Avoids product separation problems and purification (ii) Allows the reuse of the catalyst (iii) Requires relatively high alcohol for oil molar ratio and a long reaction time
4	Heterogeneous base-catalyzed transesterification	(i) Reduces process steps and minimizes the waste that harms the environment (ii) Easy separation and reuse of catalyst (iii) The catalyst may be poisoned upon exposure to ambient air (not environmentally friendly)
5	Lipase-catalyzed transesterification	(i) Insensitive to FFA and moisture content (ii) Carried out at low temperature and converting more amount of feedstock into biodiesel (iii) It is expensive because enzymes are expensive and take longer to get good results
6	Nanocatalyzed transesterification	(i) Not sensitive to FFA (ii) Moisture content was carried out relatively at low temperatures and took a short time (iii) Catalysts can be reused many times at a cost (vi) It requires more alcohol for effective results (vii) In some cases, preparation of the suitable catalyst is expensive
7	Ionic liquids-catalyzed transesterification	(i) Allows easy separation of the final product because the biphasic formation (ii) Reduces process costs and being efficient and timesaving (iii) Allows modulation of the desired properties of the catalysts when preparing them (iv) The catalyst has high catalytic activity and excellent stability and can be easily separated and reused many times (v) It requires relatively more alcohol for effective results and is usually expensive to own ionic liquid
8	Supercritical transesterification	(i) Not sensitive to FFA and moisture content of raw materials (ii) Allows to use a broader range of raw materials (iii) Usually takes less time and produces a more significant amount of fuel per mass of feedstock (iv) It requires higher temperature and pressure and consumes more methanol (v) It is not economically profitable because of its high operating costs

engines with diesel fuel also have specific fuel consumption (SFC) higher than diesel engines with diesel fuel. Saputro et al. [95] conducted a comparative study of the performance of diesel engines using B100 and B20 fuels. The results showed that the B100-fueled engine produced lower power, torque, and thermal efficiency, namely, 2.17%, 0.76%, and 1.25%, and produced 14.61% higher SFC than B20-fueled engines. Another study was conducted by Ali and Nugroho [96], which compared the performance characteristics of B30 and HSD fuels in diesel engines. The results showed that the diesel engine with B30 fuel had a higher SFC value because the B100 fuel had a lower heating value than HSD fuel. From the results of this study, it was also found that the SFC value of the mixture of biodiesel fuel with diesel would be higher along with the addition of the proportion of biodiesel in the mixture, which ranged from 3.59% to 6.23% for B10 to B40 [97]. On the other hand, fuels derived from vegetable oil generally have a higher viscosity, even up to ten times higher than diesel fuel, causing problems with the large droplet size that comes out of the diesel engine injectors, disrupting the mixing process between fuel and air, and has the potential to interfere with the perfection of combustion in diesel engine cylinders. Although the viscosity of the fuel can be lowered by mixing the biodiesel fuel with diesel fuel by up to 40%, the performance of a diesel engine with blended fuel still cannot match the performance of a diesel engine with 100% diesel fuel.

Another method for reducing viscosity is using the transesterification reaction via methyl and ethyl esters and consider the cetane number [98]. Meanwhile, Sun et al. [99] used a biodiesel mixture of dimethyl esters (DME) on a turbocharged common rail, a six-cylinder engine. In this case, a torrefaction reaction using a heterogeneous acid catalyst was used to process low-value feedstock into the oil with high FFA levels [100]. Therefore, considering the facts above, the research challenges related to biodiesel are to make this alternative and renewable energy product have the same or higher performance and lower SFC than diesel-fueled engines.

3.2. Generating Industry. Biodiesel in the power industry has been widely studied [101–103]. Indrawan et al. [101] studied the use and projection of palm oil biodiesel for the power generation sector in the Jamali region (Java, Madura, and Bali), Indonesia. During the analysis process, it was found that the use of biodiesel instead of diesel oil resulted in a cumulative emission reduction of 12.1% (3.2 Mton), 2.2% particulate matter (186.3 thousand tons), 0.6% carbon monoxide, 0.2% Volatile Organic Compound (VOC), and 0.1% nitrogen oxide, yet causing a 0.8% increase in carbon dioxide. The calculation also showed that the use of biodiesel in this sector could reduce the burden of externalities by up to 32.5 billion USD. Meanwhile, Somorin and Kolios [102] conducted a performance analysis of *Jatropha* biodiesel-fueled power plants and made comparisons with natural gas and diesel power plants. The use of *Jatropha* biodiesel could be applied to the gas turbine industry by replacing natural gas and could reduce engine power by 2% and plant efficiency by 3%, but it required more energy input. Tan et al. [103] specifically analyzed the impact of biodiesel from the *nyamplung* plant (*Calophyllum inophyllum*) on fuel savings and reduction of carbon dioxide emissions applied to motor combustion and gas turbines for the power generation industry. The biodiesel mixture used was 10% *nyamplung* oil and 90% diesel, resulting in a reduction in CO_2 emissions of the combustion motor as much as 972 kton and 1067 kton for the generator sector. More details related to feedstock, technical analysis, and economic calculations of biodiesel applications at various power plants are shown in Table 5.

3.2.1. Boiler. Park et al. [106] conducted an experimental testing of the torrefaction process on Empty Fruit Bunch (EFB) to increase biodiesel's energy density. This study was conducted by reducing the water and oxygen content of the EFB to increase the Heat Heating Value (HHV). The results showed that a decrease in water content caused a significant increase in the EFB torrefaction results. In particular, the torrefaction process resulted in an increase in the energy yield and HHV from 52.2% to 99.3% and 18.2–19.2 MJ/kg. This study shows that experimentally and in modeling, EFB has the potential to replace Palm Kernel Shell (PKS) on a palm oil mill biomass boiler. Changing the EFB through a torrefaction process can simultaneously address waste and disposal problems. Its use in boilers as a substitute for PKS can provide a cleaner combustion effect and additional economic value. Scott [107] studied the impact of biodiesel growth on the palm oil industry. The increasing demand for palm oil production as a raw material for biodiesel has made a sustainable exploration through plantation practices and improvements in planting materials. By modeling cases in Malaysia's palm oil industry, it was found that when the price of crude oil is below 38 USD/barrel, biodiesel is considered unprofitable even with a low CPO price of 200 USD/ton.

The combustion performance and emission of a mixture of petrodiesel and biodiesel from grape seed, corn, sunflower, soybean oil, olive oil, and rice husk have been studied and compared in semi-industrial boiler applications [108]. At high pressure, the six types of vegetable-based methyl esters had lower carbon gas emissions than petrodiesel, with complete combustion occurring at 19.305 bar where CO emissions reached zero. Meanwhile, at low pressure, biodiesel produced higher emissions due to its viscosity effect, which hindered fuel distribution to the combustion chamber. Meanwhile, Ghorbani et al. [109] conducted a comparative study of the use of petrodiesel and biodiesel in boilers based on the value of fuel efficiency and exhaust gas produced (CO, CO_2, NOx, and SO_2). The test results showed that mixtures other than B10 (B5, B20, B50, B80, and B100) produced less CO, SO_2, and CO_2 than petrodiesel, where B10 emitted lower CO_2 and NOx but higher SO_2 than petrodiesel. The test also showed that at higher energy levels (249 kJ/hour), the combustion efficiency of petrodiesel was slightly higher than biodiesel. In comparison, at lower energy levels (219 kJ/hour), it showed that biodiesel efficiency was better than petrodiesel.

Gonza [110] analyzed the utilization of biodiesel from sunflower oil as fuel on 26.7 kW liquid fuel heating boiler. From the test results, it was found that the biodiesel from this material had an ester content of 92% so that it did not meet the feasibility standards for its use in an internal combustion engine (ICE). However, biodiesel's addition to diesel fuel could reduce CO_2 and SO_2 and produce higher CO when the biodiesel content was increased. The proportion of this fuel mixture must be adjusted to specific parameters to produce optimum combustion, including reducing the airflow rate because biodiesel has a higher oxygen content than diesel. The comparative study of total NO emissions in boiler applications has been studied [111] by looking at the prompt and thermal NO concentration in exhaust emissions. Combustion was carried out with six types of methyl esters and petrodiesel, which were then tested with various combustion operating points, including variable combustion pressures, equivalence ratio, fuel spray pattern, and swirl angle. The test results showed that all types of methyl esters produced more NO than petrodiesel. In contrast, palm oil methyl ester (POME) emitted the least amount of NO compared to the other five methyl esters (SOME, rapeseed oil methyl esters (ROPE), olive oil methyl ester (OOME), grape seed oil methyl ester (GOME), and corn oil methyl ester (COME)). Specifically, the boiler scheme in industry is shown in Figure 3.

Bazooyar et al. [112] studied the economic aspects of petrodiesel use and common alternatives to biodiesel from soybean oil (SBO), soybean oil methyl ester (SOME), and a mixture of 5% (B5) and 20% (B20) of SOME in petrodiesel. Cost-based calculations were carried out on experimental boilers from 2000 to 2015 with one-year performance and four-day tests in different seasons. This study focuses on calculating fuel prices, exhaust emissions (CO, CO_2, NOx, and SO_2), and particulate matter, as well as the total accumulative costs of the boiler. The optimal equivalence ratio of fuels for SBO, SOME, B5, and B20 was 0.77, 0.72, 0.73, 0.75, and 0.76, respectively. Based on the analysis results, pure biodiesel and vegetable oils were not economically feasible, while the use of B5 and B20 provided annual cost savings of up to 1,155 USD and 752 USD, making these fuels

Table 5: Application of various biodiesel mixtures in the power industry.

Case study	Biodiesel feedstock	Technical analysis	Economic calculation
Jamali (Java, Madura, and Bali) power plants in Indonesia [101]	Palm oil	(i) Able to reduce cumulative emissions by 12.1% SO121 (3.2 Mton), 2.2% particulate matter (186.3 thousand tons), 0.6% CO (8.6 thousand tons), 0.2% (839 tons) volatile organic compounds, 0.1% NO222 (19 thousand tons), but there was an increase in CO32 0.8% (49.6 million)	(i) Save up to 32.5 billion USD on externality costs (ii) Biodiesel production costs from waste oil are 0.42 USD/liter, while palm oil is 0.85 USD/liter
National Integrated Power Project (NIPP), Nigeria [102]	Jatropha	(i) Increased fuel consumption with less power loss (2%), generating efficiency (1%)	(i) Produce levelized cost of electricity (LCOE) 0.279/kWh and 0.203 USD/kWh (ii) The minimum PBI parameters are 0.082 USD/kWh for a 7-year Jatropha-FOP and 0.052 USD/kWh for a 9-year Jatropha-FCP
Power plant in Malaysia [103]	*Nyamplung* (*Calophyllum inophyllum*)	(i) B20 produces optimal reduction with 972 kton/year for transportation applications and 1,057 kton/year for power generation.	—
Chicken-waste biodiesel-based power generation potential in Bangladesh [104]	Chicken fat waste	(i) With the simulation from the HOMER software, 492,695 liters of biodiesel can be produced annually from chicken skin and converted into electricity of 883 MWh/year. (ii) There was a reduction of 70.3% in greenhouse gases in the region.	(i) The operating cost is 188,062 USD/year, and the energy production cost is 0.214 USD/kWh.
The potential for biodiesel-based power generation in Brazil [105]	Soybean oil, palm oil, used cooking oil	(i) The increase in the specific fuel consumption is proportional to the increase in the concentration of biodiesel (ii) The addition of 50% biodiesel mixture made the specific consumption value 4.9–8.7% higher than B4 and 2.7–4.3% higher than B20.	—

feasible for application in boilers. On the other hand, although the prices of B5 and B20 were higher than petrodiesel, both were able to reduce the external costs of a bigger boiler so that their use could generate more profit. Furthermore, a study on a similar case was carried out by Ghorbani and Bazooyar [113] by optimizing the combustion of SOME B5, B10, B20, and petrodiesel in semi-industrial boilers. In this case, B5 fuel showed the best performance and was most suitable for boiler applications. Although there were minor differences between B5 and petrodiesel in terms of combustion performance, B5 had a lower total cost, and its raw material was locally available, renewable, and supported energy security.

Dias et al. [114] studied the use of four different types of pellets in a small-scale domestic boiler with a capacity of 13 kW. The study results showed the same thermal performance with boiler efficiency of up to 77%. Meanwhile, Sungur and Topaloğlu [115] conducted experimental studies on the combustion performance of biodiesel pellets in boilers and compared them with pellet materials. The absorption effect of biodiesel on pellets provides an increased thermal power input to 37.5%, from 15.2 kW to 20.9 kW, where the thermal efficiency also increased from 91.7% to 93%. The exhaust gas temperature reached 89.6 C with a higher CO concentration and lower NOx. Kilic et al. [116] analyzed the effect of combustion of a mixture of biodiesel, diesel, and butanol on boiler performance and their emissions of reversal flame tube boiler. Diesel fuel could be mixed homogeneously with butanol at a mixture ratio of up to 40%. The increased butanol ratio had implications for meeting oxygen demand so that it was able to carry out complete and efficient combustion. In addition, this mixture was able to reduce CO emissions drastically from 281 ppm to 4.5 ppm. Another study conducted by Macor and Pavanello [117] demonstrated significantly reduced CO and particulate matter emissions when using biodiesel. The use of biodiesel has polycyclic aromatic hydrocarbons (PAH) in a particulate matter is 13 times less toxic than oil. It indicates that biodiesel is considered cleaner, both for home heating and boiler use in industrial processes. The inorganic fraction provided more than 50% of the total condensable particulate matter (CPM) for boilers with solid fuel (coal-fired boilers—CFB and wood-fired boilers—WFB) and gas (natural gas-fired boilers—NGFB). On the other hand, the organic fraction in CPM was mainly contained in liquid fuel boilers (heavy oil-fired boilers—HOFB and diesel-fired boilers—DFB) [118].

García-Contreras et al. [119] tested mix of 50/50% (volume) tire pyrolysis liquid (TPL) and diesel in a residential boiler with a power of 29.1 kW then applied it as an alternative household heating oil. This mixture provided slightly higher thermal efficiency than pure diesel and resulted in lower CO and THC concentrations. However, it had a higher concentration of particulate matter compared

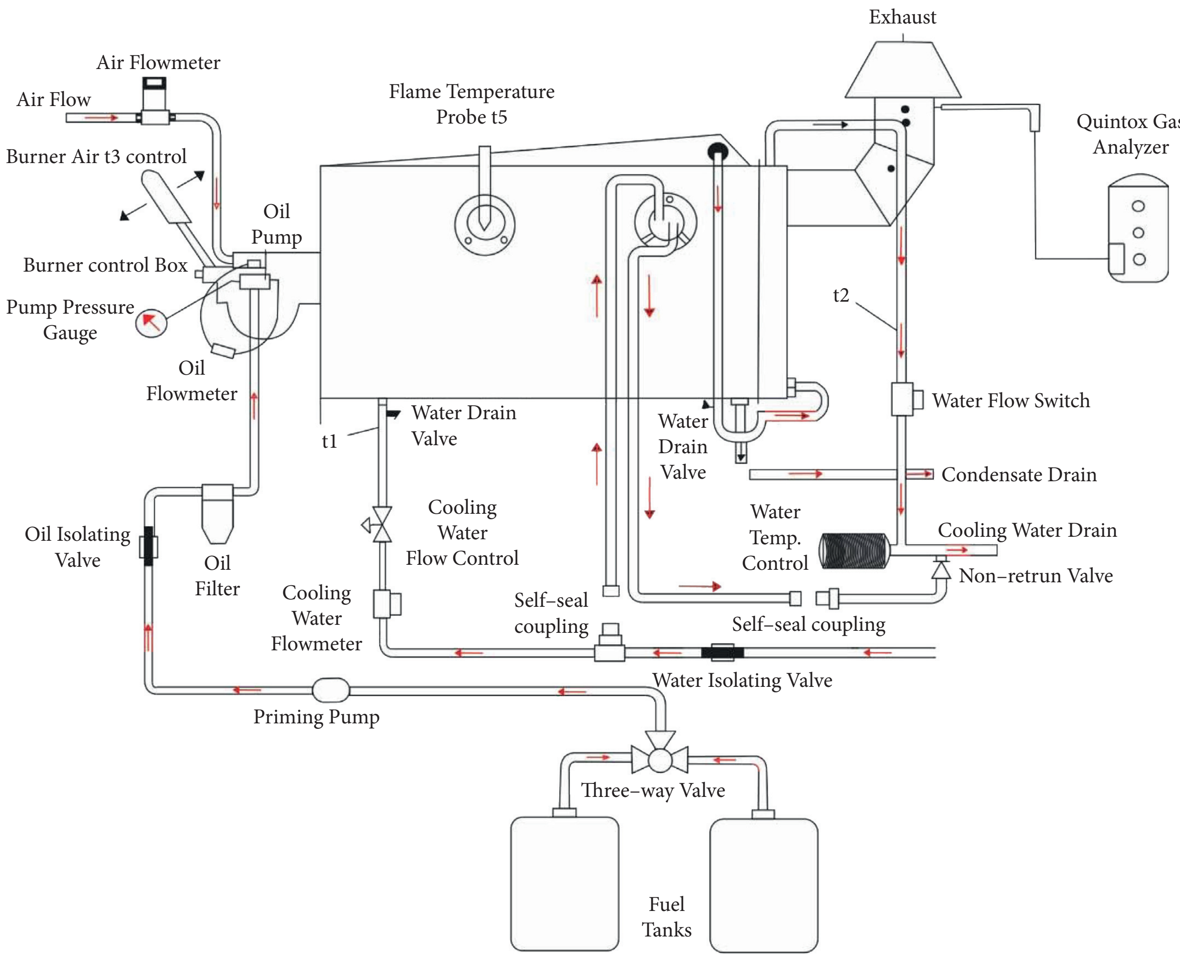

Figure 3: Boiler scheme [106].

to conventional fuels. Chong et al. [120] studied the use of bottom ash on palm oil mill boiler (POMB) and flocculants as a method for minimize boron in the ceramic industry. Coarse POMB bottom ash with a particle size of more than 2 mm is an absorbent material suitable for removing up to 80% boron under optimal conditions with a pH of 2.5, 40 g bottom ash/300 ml of wastewater, and a residence time of one hour. In oil palm ash (OPA), the combustion products of boilers were not classified as toxic waste because the levels of heavy metals in the form of copper, cadmium, lead, and nickel were still below the applicable safe limits. OPA contains a great amount of potassium and has silica that can be reused as a coarse fertilizer or a cement substitute [121].

Song et al. [122] used microalgae oil to optimize the biodiesel production process through the waste heat recovery approach and the integration process. Exergy analysis was performed on each heat exchanger and generated an efficient heat coupling value between hot and cold flows to minimize the total exergy destruction. Meanwhile, Intang [123] studied the use of biodiesel-diesel mixture to determine the optimum parameters and the value of heat transformation changes in boiler installations. In this study, an analysis was carried out on the components of the energy conversion process, especially in the combustion chamber and heat exchanger. The test results showed that the exergy destruction in the combustion chamber was still above 30% (B0: 66.29%; B20: 54.38%, and B50: 56.13%), thus allowing an increase in the combustion efficiency of the boiler and preventing severe exergy destruction. The exergy destruction in the heat exchanger was 30% (B0: 29.17%; B20: B50 and 24.78%: 24.12%) with the lowest boiler exergy destruction rate occurring at B20 (65.1977 kJ/s), but it has a higher exergy efficiency. This exergy destruction was influenced by the increase in the temperature of the combustion chamber with optimal results at B20 so that it strengthened the statement that the quality of diesel as a fuel can be increased by adding biodiesel in a certain ratio and size.

3.2.2. Biodiesel Blends in Generation. Ho et al. [124] presented analysis of 203 samples of bioliquids (BLs) used in oil-fired power plants in Korea, as well as an additional analysis of three types of bioliquids from one HFO obtained from a power plant with a capacity of 75–100 MW. The power plant used was fueled with HFO with an analysis of 18 parameters, including heating value and elemental composition. The test results showed that the calorific value of bioliquids was about 88% of HFO, with excellent combustion reactivity and fewer N and S components. It also confirms that bioliquids are an environmentally friendly fuel for power generation and are quite feasible to replace heavy oil. The demonstration test was carried out using an oil-fired power plant with a capacity of 75, 80, and 100 MW, which indicates that the usage of bioliquids can still operate the power plant at full load without experiencing operational, combustion, or environmental problems. Nejad and Zahedi [125] studied optimization of the transesterification reaction to produce biodiesel to optimally convert oil into methyl esters but still at a minimum cost. This study showed that the best conditions for producing biodiesel were with oil: methanol's constant molar ratio of 1 : 6, a temperature of 60 C, NaOH concentration of 0.3% wt/wt, and a reaction time of 60 minutes. At this optimum condition, the methyl ester yield and biodiesel production cost per liter were 78.6% and 0.706 USD, respectively.

Biodiesel from the waste products of the fish canning industry has been studied by Costa et al. [126]. In order to improve fuel quality, the mixture used was 80% olive oil and 20% fish oil waste. Using this mixture, it was observed that the purity of biodiesel increased by about 15% approaching the standard prerequisite, namely, 96.5% wt, while the oxidation stability was following the standard value of biodiesel quality. Keskin et al. [127] undertook an experimental study of leather industry waste fat (LWFB) utilization as biodiesel. LWFB was blended with diesel fuel at a ratio of 10% and 30% (LWFB10 and LWFB30) and tested on a four-stepped direct injection diesel engine. The BSFC value of the LWFB mixture was higher than that of diesel with engine speed, brake thermal efficiency (BTE), and LWFB, insignificantly reducing smoke emission from NOx.

The processing of biodiesel through industrial by-products has been widely studied [128–130]. Rodriguez et al. [130] analyzed the characteristics of biodiesel obtained from three by-products that were rarely used in the oil refining industry, namely, soap stock, acid oil, and fatty acid distillate, which were then tested on the motor combustion. Based on the study, it was shown that soap stock obtained an FFA value that tends to be lower than other by-products. The use of soap stock is highly dependent on oil processing technology, refining process, and other characteristics of raw material mixtures. The biodiesel production process produces various by-products and materials that can be used as a mixture for the manufacture of an object. Martínez-Martínez et al. [131] then used glycerin derived from oil transesterification and mainly consisted of glycerol, which is used as the raw material of clay bricks. The cement industry produces large amounts of gaseous pollutants, which are challenging to regulate efficiently and economically. Microalgae are used as raw material for biodiesel production and can be used for the biotreatment of cement industry exhaust gas [132].

Wang et al. [133] studied the use of recycled catalysts in biodiesel production by transesterification of soybean oil with methanol. Biodiesel produced through a transesterification reaction between triglycerides and light alcohol requires a different catalyst. Meanwhile, Al-Sakkari et al. [134] studied the methanolysis kinetics of soybeans using cement kiln powder as a heterogeneous catalyst. This catalyst made the separation and purification process shorter and produced glycerol with a high level of purity. Sukiran et al. [135] developed new heterogeneous catalysts in palm oil mills and tested their feasibility if used to synthesize biodiesel from crude palm oil (CPO) under mild transesterification conditions. The study results showed that the type of ash support, catalyst loading, and $CaCO_3$ calcination affected the catalytic activity of the developed catalyst. The optimum condition for catalyst preparation was 15% wt $CaCO_3$ which was calcined at 800 C loaded with fly ash, which resulted in 94.48% conversion of CPO through the transesterification process.

4. Production and Use of Biodiesel in Developing Countries

As an agrarian country with large agricultural area, Indonesia has the potential to be used as biodiesel-producing plant land. This is inseparable from the fact that biodiesel production in this country has increased from 8.59 kiloliters in 2020, which is a significant increase compared to 2017, which was at 3.4 million kiloliters [136]. Biodiesel production shows advanced trend and continues to grow every year, especially when viewed from the palm oil. It has significant implications for increasing the potential for large-scale use of biodiesel in the automotive and power generation sectors. In this case, two primary raw materials make up the majority as raw materials for biodiesel production, namely, palm oil and *Jatropha curcas*. For biodiesel production, *Jatropha* can be chosen because it does not compete with food-producing crops, is not eaten by animals because it is toxic, has the potential to become a new business for the community, and its production activities can be more decentralized. This plant is also easy to adapt to various soil textures, whether high in mineral content, sandy soil, or clay with sure drainage [137]. The availability of land for the development of *Jatropha* in Indonesia, which is very suitable, reaches 14.2 million hectares with the current availability of about 5 million hectares. In order to support the provision of superior seeds for the development of *Jatropha curcas* covering an area of 2.4 million ha by 2025, superior plants have been obtained from the collected accessions. *Jatropha* cultivation is relatively new, and its cultivation technology continues to be developed, such as components of pest and disease control technology, cropping patterns, fertilization, and processing technology. Currently, the total production of *Jatropha* seeds throughout Indonesia is still deficient at only 7,852 tons in 2007 from an area of 68,200 ha, increased to 7,925 tons in 2008 from an area of 69,221 ha and in 2009 to 8,013 from an area of 69,315 ha [138].

In terms of daily production per 2019, Indonesia was ranked first, followed by the United States, Brazil, and Germany, as shown in the list of countries with daily biodiesel production in Table 6 below.

Palm oil is the primary type of vegetable oil used as raw material for biodiesel and other types of vegetable oil such as cottonseed, sunflower, rapeseed, soybean, and so on. In this case, the total area of the world's vegetable oil producers for 290 hectares is 221 million tons of vegetable oil in 2019. Oil palm is widely chosen because it is the most efficient crop in

Table 6: List of countries with the highest biodiesel production in the world [139].

Rank	Country	Production (thousand barrels/day)
1	Indonesia	137.86
2	United States	112.49
3	Brazil	99.95
4	Germany	62.29
5	Argentina	43.08
6	France	40.02
7	Spain	36.61
8	Netherlands	35.08
9	Thailand	30.24
10	Malaysia	29.12

Table 7: List of countries with the highest palm oil production in the world [141, 142].

Rank	Country	Palm oil production (metric tons)
1	Indonesia	42,500
2	Malaysia	19,255
3	Thailand	2,800
4	Colombia	1,529
5	Nigeria	1,220
6	Guatemala	862
7	Honduras	580
8	Papua New Guinea	555
9	Brazil	540
10	Côte d'Ivoire	515

land use, which is only 7% but still has good production effectiveness [140]. There were differences in palm oil production at the same year, with Indonesia and Malaysia ranked first and second, respectively, as shown in Table 7.

Developing countries, such as Malaysia, are in the third phase of biodiesel development with production levels reaching 642,417 tons in 2008 [143]. It happens considering that Malaysia is the country with the second largest CPO production globally with a percentage of 40% of the total demand for CPO in the world [144]. In contrast to Malaysia, which produces biodiesel with abundant CPO as raw material, India uses a mixture of nonedible oil because CPO production is limited and prioritized for domestic needs [145]. The potential for biomass energy in India reaches 24,600 MW [146] by utilizing plants such as *Jatropha*, Karanja (*Pongamia pinnata)*, mahua, and neem [147] planted on marginal land or abandoned land [148]. On the other hand, most countries in the African continent are still in the first phase of biodiesel development. South Africa and Zimbabwe are already at the forefront of biodiesel development compared to other African countries. However, South Africa's biodiesel production and market are still on a small and medium scale. At the same time, Zimbabwe has started production through the first commercial biodiesel plant in this country and on the African continent [149]. Meanwhile, Latin American countries such as Brazil have achieved the distribution of B5 biodiesel use since 2008, focusing on the automotive sector. Besides, the biodiesel from sunflower oil is gradually being used for machinery in agricultural processes in several regions of the country [150].

Indonesia, as a country with abundant palm oil potential, makes biodiesel from palm oil widely used and projects to replace diesel fuel with biodiesel in power plants [101]. Gradually, the use of biodiesel in Indonesia is intended to achieve the national energy mix target. On the other hand, there was an imbalance in the realization of biodiesel in Indonesia, especially in the public service obligation (PSO) sector against other sectors in 2016 [151]. The majority of national biofuel (Bahan Bakar Nabati—BBN) production was absorbed by Pertamina's PSO with its solute product, B20 (dexlite). However, it only contributed little to the industrial and commercial sectors due to the insufficient supply caused by not fully operational biodiesel refineries and uneven distribution to each sector. On the other hand, Malaysia uses and implements palm oil B7 biodiesel in the road transportation sector as well as projections for the implementation of B15 for 2020 and the following years [152].

Biodiesel production has increased in various countries in the world with various mandatory programs that are different in each country. By calculation, for the case in Indonesia, if this country wants to completely replace oil consumption from fossil energy, which currently reaches one million barrels per day, then 15 million hectares of new oil palm plantations are needed. The program is intended to reduce Indonesia's dependence on imports of crude oil and switch to so-called biofuels, which are a cleaner alternative to conventional fossil-fueled diesel.

The government is launching this program in stages by mixing biodiesel derived from palm oil with increasingly higher concentrations into conventional diesel. The program is currently at stage B30, which means that the diesel sold at the gas station contains a 30% biodiesel blend derived from palm oil. It is expected to reach stage B50, 50 : 50 mix, by 2025. However, to do that, the total area planted with oil palm must be at least 22.7 million hectares [153]. If the government maintains the program at B30 until 2025, or even lowers the mix to B20, the need for new oil palm plantations will not be as large as around 338,880 to 5.25 million hectares but will still require a large amount of deforestation. This program is still far from the facts on the ground, whereas from January to October 2019, only 68,427 hectares (169,086 hectares) were deforested, which only reached 38% of the target. This year, the government could only replant 67,018 hectares (165,605 hectares), or 37% of its target [140].

5. Production and Use of Biodiesel in Developed Countries

In general, the market conditions and biodiesel production in several countries in the world from 2010 along with data extrapolation up to 2027 can be visualized as shown in Figure 4 below.

Biodiesel in developed countries receives more attention as they focus on worsening environmental issues so that a transition to cleaner and more sustainable energy is needed. The European Union (EU), the leading biodiesel producer globally, has a production rate of up to 65% of the total

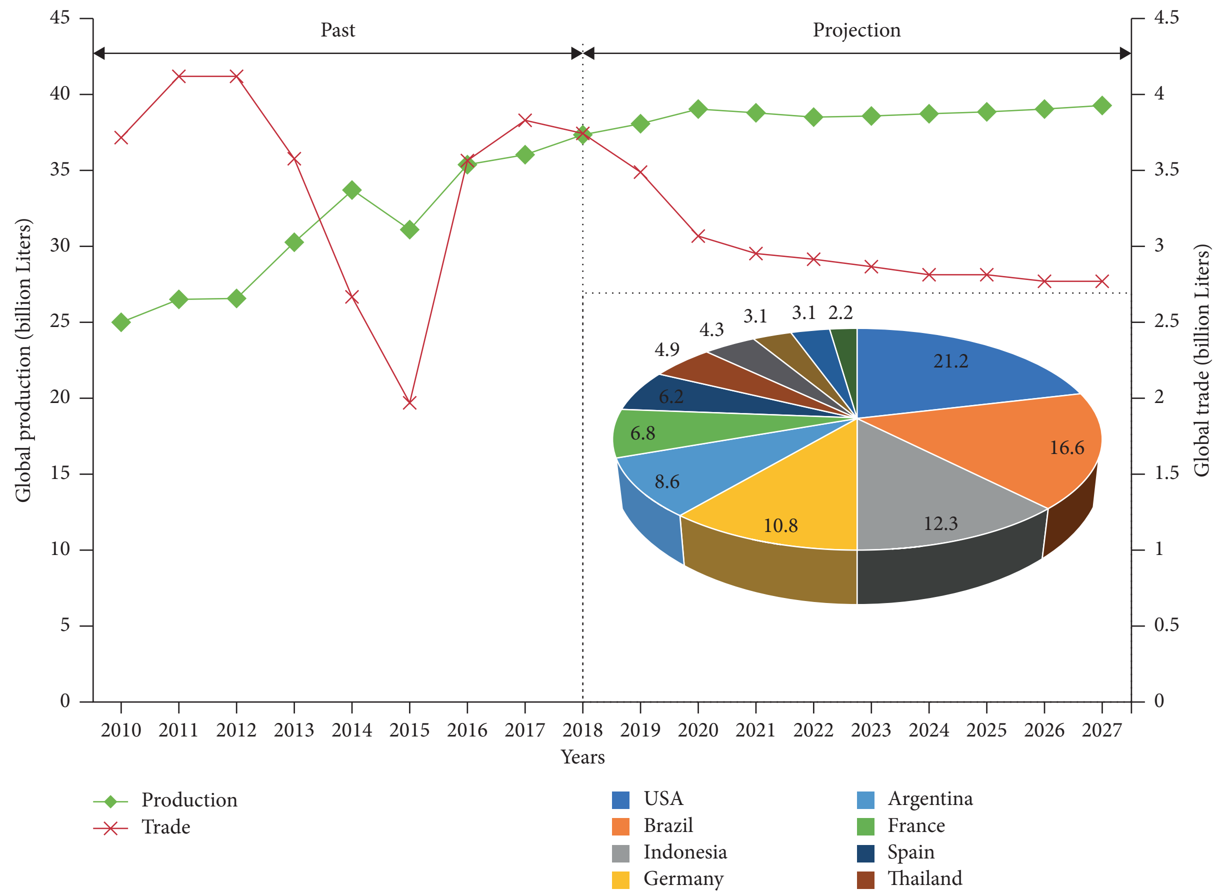

Figure 4: Market conditions and biodiesel production in several countries [76].

biodiesel production worldwide in 2008 [154]. In this case, Germany and France were the main suppliers with production for nearly 50% of the total EU production or around 4280 ktoe in 2009 [155]. The biodiesel in France is exclusively sold and used as fuel in motor fuel with a composition ranging from 5 to 30% added to diesel oil [156]. In Germany, however, only B100 was used by some car, truck, and bus users before the tax exemption to a lower the mixed level. Now, blends up to B5 are starting to be widely used as commercial fuel for transportation in the country. Meanwhile, Australia has produced biodiesel with a quantity of consistently above 100 million liters since 2015 [157]. However, the import level reached more than 350 million liters in 2014, and domestic consumption reached 500 million liters in the same year.

Biodiesel in the People's Republic of China is produced on a minor scale when compared to ethanol production in the country [158]. The production of ethanol has gone through a trial period in several areas using corn as the primary source (80%) and wheat. Meanwhile, the production of biodiesel is around 300 thousand metric tons, with the primary sources of animal fat and vegetable waste oils. The use of biodiesel in the transportation sector in this country is used explicitly for diesel engines both through a 5% mixture ratio mechanism and pure biodiesel as engine fuel [159]. Its use in boilers is only about 6% of the total production, and this is far less than its application in the transportation sector in the country. However, its use is projected at the proportion of 63% biodiesel in the power generation industry, 26% in the service industry, and 11% in public facilities.

6. Conclusion

An overview of the development of biodiesel as an alternative and renewable fuel for the automotive and power generation sectors has been presented in the previous sections. The use of biodiesel in the automotive industry and power generation has many positive implications from technological to economic aspects. Biodiesel as a potential alternative energy provides many feedstock choices that can be explored and applied to automotive and power plants. The following section summarizes various literature studies on the development of biodiesel as a renewable fuel for automotive and power generation.

(a) Biodiesel production shows a relatively advanced trend and continues to grow every year, especially when viewed from palm oil. It has significant implications for increasing the potential for large-scale use of biodiesel in the automotive and power generation sectors.

(b) Various types of mixtures of feedstock of biodiesel from the first to fourth generations ranging from edible oil, nonedible oil to oleaginous microorganisms, as well as the use of catalysts and the latest technology, have a great potential to be developed and utilized as future alternative fuels, especially in power generation applications.

(c) The use of biodiesel in automotive and power plants has a good impact in reducing carbon gas emissions and pollutants but still has challenges because it produces more NOx emissions, low-performance efficiency, and potential maintenance costs. It also still experiences obstacles when applied on a large and massive scale.

(d) Biodiesel production has increased in various countries in the world with various mandatory programs that are different in each country. Currently, biodiesel is primarily projected for automotive needs, but other implementations have been studied extensively for various industries, especially in electricity generation.

The descriptions above are facts that indicate that the study of developing biodiesel as a renewable fuel for automotive and power generation can continue to be studied in depth and thoroughly. Since the economic analysis of biodiesel's use has not been able to completely shift the current use of fossil energy, strengthening the technical aspects in terms of massive implementation and economic aspects to save production costs needs to be studied further.

Data Availability

No data were used in this study.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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References

[1] F. Ishola, D. Adelekan, A. Mamudu et al., "Biodiesel production from palm olein: a sustainable bioresource for Nigeria," *Heliyon*, vol. 6, p. e03725, 2020, https://doi.org/10.1016/j.heliyon.2020.e03725.

[2] S. H. Mohr, J. Wang, G. Ellem, J. Ward, and D. Giurco, "Projection of world fossil fuels by country," *Fuel*, vol. 141, pp. 120–135, 2015.

[3] IEA, *Key World Energy Trends*, Iea, Paris, France, 2016.

[4] L. Huang, G. Krigsvoll, F. Johansen, Y. Liu, and X. Zhang, "Carbon emission of global construction sector," *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 1906–1916, 2018.

[5] S. N. Naik, V. V. Goud, P. K. Rout, and A. K. Dalai, "Production of first and second generation biofuels: a comprehensive review," *Renewable and Sustainable Energy Reviews*, 2010, https://doi.org/10.1016/j.rser.2009.10.003.

[6] O. O. Olatunji, O. O. Ayo, S. Akinlabi, F. Ishola, N. Madushele, and P. A. Adedeji, "Competitive advantage of carbon efficient supply chain in manufacturing industry," *Journal of Cleaner Production*, 2019, https://doi.org/10.1016/j.jclepro.2019.117937.

[7] O. Olatunji, S. Akinlabi, A. Oluseyi et al., "Electric power crisis in Nigeria: a strategic call for change of focus to renewable sources," *IOP Conference Series: Materials Science and Engineering*, 2018, https://doi.org/10.1088/1757-899X/413/1/012053.

[8] M. H. Duku, S. Gu, and E. Ben Hagan, "A comprehensive review of biomass resources and biofuels potential in Ghana," *Renewable and Sustainable Energy Reviews*, 2011, https://doi.org/10.1016/j.rser.2010.09.033.

[9] P. S. Nigam and A. Singh, "Production of liquid biofuels from renewable resources," *Progress in Energy and Combustion Science*, 2011, https://doi.org/10.1016/j.pecs.2010.01.003.

[10] M. V. Rodionova, R. S. Poudyal, I. Tiwari et al., "Biofuel production: challenges and opportunities," *International Journal of Hydrogen Energy*, vol. 42, no. 12, pp. 8450–8461, 2017, https://doi.org/10.1016/j.ijhydene.2016.11.125.

[11] A. Gasparatos, P. Stromberg, and K. Takeuchi, "Sustainability impacts of first-generation biofuels," *Anim. Front.*, 2013, https://doi.org/10.2527/af.2013-0011.

[12] J. Sentanuhady, W. Saputro, and M. A. Muflikhun, "Metals and chemical compounds contaminants in diesel engine lubricant with B20 and B100 biofuels for long term operation," *Sustainable Energy Technologies and Assessments*, vol. 45, no. 101161, 2021.

[13] E. Supriyanto, J. Sentanuhady, A. Dwiputra, A. Permana, and M. A. Muflikhun, "The recent progress of natural sources and manufacturing process of biodiesel: a review," *Sustainability*, vol. 13, no. 5599, 2021.

[14] J. Sentanuhady, G. P. S. G. Atmaja, and A. Muflikhun, "Challenges of biofuel applications in industrial and automotive: a review," *Journal of Engineering Science and Technology Review*, vol. 14, pp. 119–134, 2021.

[15] H. B. Aditiya, T. M. I. Mahlia, W. T. Chong, H. Nur, and A. H. Sebayang, "Second generation bioethanol production: a critical review," *Renewable and Sustainable Energy Reviews*, 2016, https://doi.org/10.1016/j.rser.2016.07.015.

[16] G. Dragone, B. Fernandes, A. Vicente, and J. Teixeira, "Third generation biofuels from microalgae," *Curr. Res. Technol. Educ. Top. Appl. Microbiol. Microb. Biotechnol.*, 2010.

[17] D. Singh, D. Sharma, S. L. Soni, S. Sharma, P. Kumar Sharma, and A. Jhalani, *A Review on Feedstocks, Production Processes, and Yield for Different Generations of Biodiesel*, Fuel, 2020, https://doi.org/10.1016/j.fuel.2019.116553.

[18] M. A. Aziz, K. A. Kassim, W. A. W. A. Bakar et al., "The fourth-generation biofuel: a systematic review on nearly two decades of research from 2008 to 2019," in *Foss. Free Fuels*, https://doi.org/10.1201/9780429327773-12, 2019.

[19] B. Abdullah, S. A. F. ad Syed Muhammad, Z. Shokravi et al., "Fourth generation biofuel: a review on risks and mitigation strategies," *Renewable and Sustainable Energy Reviews*, 2019, https://doi.org/10.1016/j.rser.2019.02.018.

[20] S. Friedrich, *A World Wide Review of the Commercial Production of Biodiesel–A Technological, Economic and Ecological Investigation Based on Case Studies*, p. 164, 2004.

[21] A. E. Atabani, A. S. Silitonga, I. A. Badruddin, T. M. I. Mahlia, H. H. Masjuki, and S. Mekhilef, "A

comprehensive review on biodiesel as an alternative energy resource and its characteristics," *Renewable and Sustainable Energy Reviews*, 2012, https://doi.org/10.1016/j.rser.2012.01.003.

[22] M. Mahdavi, E. Abedini, and A. H. Darabi, "Biodiesel synthesis from oleic acid by nano-catalyst (ZrO2/Al2O3) under high voltage conditions," *RSC Advances*, 2015, https://doi.org/10.1039/c5ra07081c.

[23] I. Ambat, V. Srivastava, and M. Sillanpää, "Recent advancement in biodiesel production methodologies using various feedstock: a review," *Renewable and Sustainable Energy Reviews*, 2018, https://doi.org/10.1016/j.rser.2018.03.069.

[24] M. H. Jayed, H. H. Masjuki, M. A. Kalam, T. M. I. Mahlia, M. Husnawan, and A. M. Liaquat, "Prospects of dedicated biodiesel engine vehicles in Malaysia and Indonesia," *Renewable and Sustainable Energy Reviews*, 2011, https://doi.org/10.1016/j.rser.2010.09.002.

[25] S. J. Santosa, "Palm oil boom in Indonesia: from plantation to downstream products and biodiesel," *Clean - Soil, Air, Water*, vol. 36, no. 5-6, pp. 453–465, 2008, https://doi.org/10.1002/clen.200800039.

[26] B. K. Barnwal and M. P. Sharma, "Prospects of biodiesel production from vegetable oils in India," *Renewable and Sustainable Energy Reviews*, vol. 9, no. 4, pp. 363–378, 2005, https://doi.org/10.1016/j.rser.2004.05.007.

[27] W. Körbitz, "Biodiesel production in Europe and North America, an encouraging prospect," *Renewable Energy*, https://doi.org/10.1016/s0960-1481(98)00406-6, 1999.

[28] A. Karmakar, S. Karmakar, and S. Mukherjee, "Biodiesel production from neem towards feedstock diversification: Indian perspective," *Renewable and Sustainable Energy Reviews*, 2012, https://doi.org/10.1016/j.rser.2011.10.001.

[29] E. Rashtizadeh and F. Farzaneh, "Transesterification of soybean oil catalyzed by Sr-Ti mixed oxides nanocomposite," *J. Taiwan Inst. Chem. Eng.*, 2013, https://doi.org/10.1016/j.jtice.2013.02.008.

[30] G. Antolín, F. V. Tinaut, Y. Briceo, V. Castao, C. Pérez, and A. I. Ramírez, "Optimisation of biodiesel production by sunflower oil transesterification," *Bioresource Technology*, https://doi.org/10.1016/S0960-8524(01)00200-0, 2002.

[31] T. Issariyakul, M. G. Kulkarni, L. C. Meher, A. K. Dalai, and N. N. Bakhshi, "Biodiesel production from mixtures of canola oil and used cooking oil," *The Chemical Engineering Journal*, 2008, https://doi.org/10.1016/j.cej.2007.09.008.

[32] R. Madhuvilakku and S. Piraman, "Biodiesel synthesis by TiO2-ZnO mixed oxide nanocatalyst catalyzed palm oil transesterification process," *Bioresource Technology*, 2013, https://doi.org/10.1016/j.biortech.2013.09.087.

[33] D. Kumar, G. Kumar, Poonam, and C. P. Singh, "Fast, easy ethanolysis of coconut oil for biodiesel production assisted by ultrasonication," *Ultrasonics Sonochemistry*, 2010, https://doi.org/10.1016/j.ultsonch.2009.10.018.

[34] F. Sanchez and P. T. Vasudevan, "Enzyme catalyzed production of biodiesel from olive oil," *Applied Biochemistry and Biotechnology*, 2006, https://doi.org/10.1385/ABAB:135:1:1.

[35] M. Ahmad, S. Rashid, M. A. Khan, M. Zafar, S. Sultana, and S. Gulzar, "Optimization of base catalyzed transesterification of peanut oil biodiesel," *African Journal of Biotechnology*, https://doi.org/10.5897/AJB2009.000-9076, 2009.

[36] Y. Devarajan, D. B. Munuswamy, B. Nagappan, and A. K. Pandian, "Performance, combustion and emission analysis of mustard oil biodiesel and octanol blends in diesel engine," *Heat Mass Transf. Und Stoffuebertragung.*, 2018, https://doi.org/10.1007/s00231-018-2274-x.

[37] R. Anr, A. A. Saleh, M. S. Islam, S. Hamdan, and M. A. Maleque, "Biodiesel production from crude jatropha oil using a highly active heterogeneous nanocatalyst by optimizing transesterification reaction parameters," *Energy & Fuels*, vol. 30, no. 1, pp. 334–343, 2016, https://doi.org/10.1021/acs.energyfuels.5b01899.

[38] M. Naik, L. Meher, S. Naik, and L. Das, "Production of biodiesel from high free fatty acid Karanja (Pongamia pinnata) oil," *Biomass and Bioenergy*, vol. 32, no. 4, pp. 354–357, 2008, https://doi.org/10.1016/j.biombioe.2007.10.006.

[39] B. Gurunathan and A. Ravi, "Process optimization and kinetics of biodiesel production from neem oil using copper doped zinc oxide heterogeneous nanocatalyst," *Bioresource Technology*, 2015, https://doi.org/10.1016/j.biortech.2015.04.101.

[40] S. Dixit, S. Kanakraj, and A. Rehman, "Linseed oil as a potential resource for bio-diesel: a review," *Renewable and Sustainable Energy Reviews*, 2012, https://doi.org/10.1016/j.rser.2012.04.042.

[41] M. Morshed, K. Ferdous, M. R. Khan, M. S. I. Mazumder, M. A. Islam, and M. T. Uddin, "Rubber seed oil as a potential source for biodiesel production in Bangladesh," *Fuel*, 2011, https://doi.org/10.1016/j.fuel.2011.05.020.

[42] J. M. Dias, J. M. Araújo, J. F. Costa, M. C. M. Alvim-Ferraz, and M. F. Almeida, "Biodiesel production from raw castor oil," *Energy*, vol. 53, pp. 58–66, 2013, https://doi.org/10.1016/j.energy.2013.02.018.

[43] L. Wen, Y. Wang, D. Lu, S. Hu, and H. Han, "Preparation of KF/CaO nanocatalyst and its application in biodiesel production from Chinese tallow seed oil," *Fuel*, 2010, https://doi.org/10.1016/j.fuel.2010.01.028.

[44] M. Takase, Y. Chen, H. Liu, T. Zhao, L. Yang, and X. Wu, "Biodiesel production from non-edible Silybum marianum oil using heterogeneous solid base catalyst under ultrasonication," *Ultrasonics Sonochemistry*, 2014, https://doi.org/10.1016/j.ultsonch.2014.04.003.

[45] Q. Li, W. Du, and D. Liu, "Perspectives of microbial oils for biodiesel production," *Applied Microbiology and Biotechnology*, 2008, https://doi.org/10.1007/s00253-008-1625-9.

[46] R. Yahyaee, B. Ghobadian, and G. Najafi, "Waste fish oil biodiesel as a source of renewable fuel in Iran," *Renewable and Sustainable Energy Reviews*, 2013, https://doi.org/10.1016/j.rser.2012.09.025.

[47] A. Jacob, B. Ashok, A. Alagumalai, O. H. Chyuan, and P. T. K. Le, "Critical review on third generation micro algae biodiesel production and its feasibility as future bioenergy for IC engine applications," *Energy Conversion and Management*, https://doi.org/10.1016/j.enconman.2020.113655, 2020.

[48] S. H. Teo, A. Islam, F. L. Ng, and Y. H. Taufiq-Yap, "Biodiesel synthesis from photoautotrophic cultivated oleoginous microalgae using a sand dollar catalyst," *RSC Advances*, 2015, https://doi.org/10.1039/c5ra05801e.

[49] R. Vallinayagam, S. Vedharaj, W. M. Yang, P. S. Lee, K. J. E. Chua, and S. K. Chou, "Pine oil-biodiesel blends: a double biofuel strategy to completely eliminate the use of diesel in a diesel engine," *Applied Energy*, 2014, https://doi.org/10.1016/j.apenergy.2013.11.025.

[50] N. Kaur and A. Ali, "Lithium ions-supported magnesium oxide as nano-sized solid catalyst for biodiesel preparation from mutton fat, Energy Sources, Part A Recover," *Util.*

Environ. Eff., https://doi.org/10.1080/15567036.2011.592912, 2013.

[51] J. Abraham, R. S. Kumar, F. Xavier, and D. Mathew, "Biodiesel production from broiler chicken waste," *Int. J. Agric. Biosyst. Eng.*, 2015.

[52] M. C. Math, S. P. Kumar, and S. V. Chetty, "Technologies for biodiesel production from used cooking oil - a review," *Energy Sustain. Dev.*, 2010, https://doi.org/10.1016/j.esd.2010.08.001.

[53] A. Karmakar, S. Karmakar, and S. Mukherjee, "Properties of various plants and animals feedstocks for biodiesel production," *Bioresource Technology*, 2010, https://doi.org/10.1016/j.biortech.2010.04.079.

[54] N. Kaushik, K. Kumar, S. Kumar, N. Kaushik, and S. Roy, "Genetic variability and divergence studies in seed traits and oil content of Jatropha (Jatropha curcas L.) accessions," *Biomass and Bioenergy*, 2007, https://doi.org/10.1016/j.biombioe.2007.01.021.

[55] X. Q. Yang, H. Pan, T. Zeng, T. F. Shupe, and C. Y. Hse, "Extraction and characterization of seed oil from naturally grown Chinese tallow trees, JAOCS," *Journal of the American Oil Chemists Society*, https://doi.org/10.1007/s11746-012-2178-8, 2013.

[56] S. P. Singh and D. Singh, "Biodiesel production through the use of different sources and characterization of oils and their esters as the substitute of diesel: a review," *Renewable and Sustainable Energy Reviews*, 2010, https://doi.org/10.1016/j.rser.2009.07.017.

[57] A. Demirbas and M. Fatih Demirbas, "Importance of algae oil as a source of biodiesel," *Energy Conversion and Management*, 2011, https://doi.org/10.1016/j.enconman.2010.06.055.

[58] H. N. Bhatti, M. A. Hanif, and M. Qasim, "Ata-ur-Rehman, Biodiesel production from waste tallow," *Fuel*, vol. 87, no. 13-14, pp. 2961–2966, 2008, https://doi.org/10.1016/j.fuel.2008.04.016.

[59] T. M. Mata, A. A. Martins, and N. S. Caetano, "Microalgae for biodiesel production and other applications: a review," *Renewable and Sustainable Energy Reviews*, 2010, https://doi.org/10.1016/j.rser.2009.07.020.

[60] S. Özgül-Yücel and S. Türkay, "Variables affecting the yields of methyl esters derived from in situ esterification of rice bran oil, JAOCS," *Journal of the American Oil Chemists Society*, https://doi.org/10.1007/s11746-002-0531-5, 2002.

[61] A. Demirbas, "Comparison of transesterification methods for production of biodiesel from vegetable oils and fats," *Energy Conversion and Management*, 2008, https://doi.org/10.1016/j.enconman.2007.05.002.

[62] D. Kusdiana and S. Saka, "Effects of water on biodiesel fuel production by supercritical methanol treatment," *Bioresource Technology*, 2004, https://doi.org/10.1016/S0960-8524(03)00201-3.

[63] Y. Li, S. Lian, D. Tong et al., "One-step production of biodiesel from Nannochloropsis sp. on solid base Mg-Zr catalyst," *Applied Energy*, 2011, https://doi.org/10.1016/j.apenergy.2010.12.057.

[64] O. D. Samuel, M. Eng, O. U. Dairo, and D. Ph, "A critical review of in-situ transesterification process for biodiesel production," *Pacific J. Sci. Technol.*, 2012.

[65] T. Cakmak, P. Angun, Y. E. Demiray, A. D. Ozkan, Z. Elibol, and T. Tekinay, "Differential effects of nitrogen and sulfur deprivation on growth and biodiesel feedstock production of Chlamydomonas reinhardtii," *Biotechnology and Bioengineering*, 2012, https://doi.org/10.1002/bit.24474.

[66] Z. Yaakob, M. Mohammad, M. Alherbawi, Z. Alam, and K. Sopian, "Overview of the production of biodiesel from Waste cooking oil," *Renewable and Sustainable Energy Reviews*, 2013, https://doi.org/10.1016/j.rser.2012.10.016.

[67] M. Catarino, M. Ramos, A. P. S. Dias, M. T. Santos, J. F. Puna, and J. F. Gomes, "Calcium rich food wastes based catalysts for biodiesel production," *Waste and Biomass Valorization*, 2017, https://doi.org/10.1007/s12649-017-9988-8.

[68] G. A. Ewunie, J. Morken, O. I. Lekang, and Z. D. Yigezu, "Factors affecting the potential of Jatropha curcas for sustainable biodiesel production: a critical review," *Renewable and Sustainable Energy Reviews*, p. 110500, 2020, https://doi.org/10.1016/j.rser.2020.110500.

[69] V. Hariram and R. Vagesh Shangar, "Influence of compression ratio on combustion and performance characteristics of direct injection compression ignition engine," *Alexandria Eng. J.*, 2015, https://doi.org/10.1016/j.aej.2015.06.007.

[70] G. Pohit and D. Misra, "Optimization of performance and emission characteristics of diesel engine with biodiesel using grey-taguchi method," *Journal of Engineering*, 2013, https://doi.org/10.1155/2013/915357.

[71] A. Sharma, N. K. Maurya, Y. Singh, N. K. Singh, and S. K. Gupta, "Effect of design parameters on performance and emissions of DI diesel engine running on biodiesel-diesel blends: taguchi and utility theory," *Fuel*, vol. 281, 2020 https://doi.org/10.1016/j.fuel.2020.118765.

[72] A. Jacob, B. Ashok, A. Alagumalai, O. H. Chyuan, and P. T. K. Le, "Critical review on third generation micro algae biodiesel production and its feasibility as future bioenergy for IC engine applications," *Energy Conversion and Management*, 2021, https://doi.org/10.1016/j.enconman.2020.113655.

[73] P. Nautiyal, K. A. Subramanian, and M. G. Dastidar, "Kinetic and thermodynamic studies on biodiesel production from Spirulina platensis algae biomass using single stage extraction-transesterification process," *Fuel*, 2014, https://doi.org/10.1016/j.fuel.2014.06.063.

[74] S. Erdoğan, M. K. Balki, S. Aydın, and C. Sayın, "Performance, emission and combustion characteristic assessment of biodiesels derived from beef bone marrow in a diesel generator," *Energy*, vol. 207, 2020, https://doi.org/10.1016/j.energy.2020.118300.

[75] S. Aydın, "Comprehensive analysis of combustion, performance and emissions of power generator diesel engine fueled with different source of biodiesel blends," *Energy*, vol. 205, 2020, https://doi.org/10.1016/j.energy.2020.118074.

[76] A. E. F. Abomohra, M. Elsayed, S. Esakkimuthu, M. El-Sheekh, and D. Hanelt, "Potential of fat, oil and grease (FOG) for biodiesel production: a critical review on the recent progress and future perspectives," *Progress in Energy and Combustion Science*, vol. 81, 2020 https://doi.org/10.1016/j.pecs.2020.100868.

[77] S. K. Hoekman, A. Broch, C. Robbins, E. Ceniceros, and M. Natarajan, "Review of biodiesel composition, properties, and specifications," *Renewable and Sustainable Energy Reviews*, 2012, https://doi.org/10.1016/j.rser.2011.07.143.

[78] P. Vesterinen, E. Alakangas, K. Veijonen, and M. Junginger, "Prospects of bioenergy in new industrial sectors – D2.3, Prospect," *Bioenergy New Ind. Sect.*, pp. 1–24, 2010.

[79] J. Van Gerpen, "Biodiesel processing and production," *Fuel Processing Technology*, 2005, https://doi.org/10.1016/j.fuproc.2004.11.005.

[80] M. J. Costa, M. R. L. Silva, E. E. A. Ferreira et al., "Enzymatic biodiesel production by hydroesterification using waste cooking oil as feedstock," *Chem. Eng. Process. - Process Intensif.*, 2020, https://doi.org/10.1016/j.cep.2020.108131.

[81] B. L. Salvi and N. L. Panwar, "Biodiesel resources and production technologies - a review," *Renewable and Sustainable Energy Reviews*, 2012, https://doi.org/10.1016/j.rser.2012.03.050.

[82] F. Ma and M. A. Hanna, "Biodiesel production: a review," *Bioresource Technology*, https://doi.org/10.1016/S0960-8524(99)00025-5, 1999.

[83] G. Knothe, "Analyzing biodiesel: standards and other methods, JAOCS," *Journal of the American Oil Chemists Society*, https://doi.org/10.1007/s11746-006-5033-y, 2006.

[84] L. Leng, P. Han, X. Yuan, J. Li, and W. Zhou, "Biodiesel microemulsion upgrading and thermogravimetric study of bio-oil produced by liquefaction of different sludges," *Energy*, 2018, https://doi.org/10.1016/j.energy.2018.04.087.

[85] V. Gude, P. Patil, E. Martinez-Guerra, S. Deng, and N. Nirmalakhandan, "Microwave energy potential for biodiesel production," *Sustain. Chem. Process.*, 2013, https://doi.org/10.1186/2043-7129-1-5.

[86] K. D. Maher and D. C. Bressler, "Pyrolysis of triglyceride materials for the production of renewable fuels and chemicals," *Bioresource Technology*, 2007, https://doi.org/10.1016/j.biortech.2006.10.025.

[87] A. Demirbas, "Biodiesel production from vegetable oils via catalytic and non-catalytic supercritical methanol transesterification methods," *Progress in Energy and Combustion Science*, 2005, https://doi.org/10.1016/j.pecs.2005.09.001.

[88] S. N. Gebremariam and J. M. Marchetti, "Biodiesel production technologies: Review," *AIMS Energy*, 2017, https://doi.org/10.3934/energy.2017.3.425.

[89] M. Ramos, A. P. S. Dias, J. F. Puna, J. Gomes, and J. C. Bordado, "Biodiesel production processes and sustainable raw materials," *Energies*, vol. 12, 2019 https://doi.org/10.3390/en12234408.

[90] S. Santos, J. Puna, and J. Gomes, "A review on bio-based catalysts (immobilized enzymes) used for biodiesel production," *Energies*, vol. 13, 2020 https://doi.org/10.3390/en13113013.

[91] A. K. Agarwal, J. G. Gupta, and A. Dhar, "Potential and challenges for large-scale application of biodiesel in automotive sector," *Progress in Energy and Combustion Science*, 2017, https://doi.org/10.1016/j.pecs.2017.03.002.

[92] R. R. Tan, A. B. Culaba, and M. R. I. Purvis, "Carbon balance implications of coconut biodiesel utilization in the Philippine automotive transport sector," *Biomass and Bioenergy*, 2004, https://doi.org/10.1016/j.biombioe.2003.10.002.

[93] I. Lozada, J. Islas, and G. Grande, "Environmental and economic feasibility of palm oil biodiesel in the Mexican transportation sector," *Renewable and Sustainable Energy Reviews*, 2010, https://doi.org/10.1016/j.rser.2009.06.034.

[94] S. S. Harsono and K. Siregar, "Peningkatan kinerja mesin diesel dengan produksi biodiesel Dari kelapa (coconut nufera) dan unjuk kinerjanya berbasis transesterifikasi dengan sistim injeksi langsung," *Jurnal Rona Teknik Pertanian*, vol. 11, pp. 1–11, 2018.

[95] W. Saputro, J. Sentanuhady, A. I. Majid, W. Prasidha, N. P. Gunawan, and T. Y. Raditya, "Karakteristik unjuk kerja mesin diesel menggunakan bahan bakar B100 dan B20," *Dalam Jangka Panjang*, vol. 2, pp. 125–136, 2020, https://doi.org/10.22146/jmdt.v2i2.55523.

[96] B. Ali and P. A. Nugroho, "Analisis pemakaian bahan bakar high speed diesel dan biodiesel (B30) terhadap konsumsi bahan bakar dan emisi gas buang mesin diesel PLTD 1.4 MW," *Presisi*, vol. 18, pp. 30–41, 2017.

[97] M. S. Islam, A. S. Ahmed, A. Islam, S. Abdul Aziz, L. C. Xian, and M. Mridha, "Study on emission and performance of diesel engine using castor biodiesel," *Journal of Chemistry*, 2014, https://doi.org/10.1155/2014/451526.

[98] J. San José Alonso, J. A. López Sastre, C. Romero-Ávila, and E. López, "A note on the combustion of blends of diesel and soya, sunflower and rapeseed vegetable oils in a light boiler," *Biomass and Bioenergy*, vol. 32, pp. 880–886, 2008, https://doi.org/10.1016/j.biombioe.2008.01.007.

[99] J. Sun, G. Yang, Y. Yoneyama, and N. Tsubaki, "Catalysis chemistry of dimethyl ether synthesis," *ACS Catalysis*, 2014, https://doi.org/10.1021/cs500967j.

[100] M. J. C. van der Stelt, H. Gerhauser, J. H. A. Kiel, and K. J. Ptasinski, "Biomass upgrading by torrefaction for the production of biofuels: a review," *Biomass and Bioenergy*, 2011, https://doi.org/10.1016/j.biombioe.2011.06.023.

[101] N. Indrawan, S. Thapa, S. F. Rahman et al., "Palm biodiesel prospect in the Indonesian power sector," *Environ. Technol. Innov.*, 2017, https://doi.org/10.1016/j.eti.2017.01.001.

[102] T. O. Somorin and A. J. Kolios, "Prospects of deployment of Jatropha biodiesel-fired plants in Nigeria's power sector," *Energy*, https://doi.org/10.1016/j.energy.2017.06.152, 2017.

[103] E. S. Tan, K. P, T. M. I. Indra, K. Tokimatsu, and K. Yoshikawa, "Impact of biodiesel application on fuel savings and emission reduction for power generation in Malaysia," *Energy Procedia*, vol. 158, pp. 3325–3330, 2019, https://doi.org/10.1016/j.egypro.2019.01.969.

[104] P. Barua, T. Chowdhury, H. Chowdhury, R. Islam, and N. Hossain, "Potential of power generation from chicken waste-based biodiesel, economic and environmental analysis: Bangladesh's perspective," *SN Appl. Sci.*, https://doi.org/10.1007/s42452-020-2113-9, 2020.

[105] M. D. A. Dágosto, M. A. Vieira Da Silva, C. M. De Oliveira et al., "Evaluating the potential of the use of biodiesel for power generation in Brazil," *Renewable and Sustainable Energy Reviews*, https://doi.org/10.1016/j.rser.2014.11.055, 2015.

[106] H. Y. Park, K. Han, G. S. Yu et al., "Properties of bioliquids and their impacts on combustion and boiler operation," *Energy*, vol. 193, p. 116782, 2020, https://doi.org/10.1016/j.energy.2019.116782.

[107] W. Scott, "Impacts of biodiesel development on the palm oil industry," *Malaysian Journal of Economic Studies*, vol. 43, pp. 113–135, 2006.

[108] B. Bazooyar, A. Ghorbani, and A. Shariati, "Combustion performance and emissions of petrodiesel and biodiesels based on various vegetable oils in a semi industrial boiler," *Fuel*, vol. 90, no. 10, pp. 3078–3092, 2011, https://doi.org/10.1016/j.fuel.2011.05.025.

[109] A. Ghorbani, B. Bazooyar, A. Shariati, S. M. Jokar, H. Ajami, and A. Naderi, "A comparative study of combustion performance and emission of biodiesel blends and diesel in an experimental boiler," *Applied Energy*, vol. 88, no. 12, pp. 4725–4732, 2011, https://doi.org/10.1016/j.apenergy.2011.06.016.

[110] J. Gonza, "Study of combustion process of biodiesel/gasoil mixture in a domestic heating boiler of 26.7 kW," *Biomass and Bioenergy*, vol. 60, pp. 178–188, 2013, https://doi.org/10.1016/j.biombioe.2013.10.024.

[111] B. Bazooyar, S. H. Hashemabadi, and A. Shariati, "NOX formation of biodiesel in utility power plant boilers; Part B. Comparison of NO between biodiesel and petrodiesel," *Fuel*, vol. 182, pp. 323–332, 2016, https://doi.org/10.1016/j.fuel.2016.05.018.

[112] B. Bazooyar, A. Shariati, and S. H. Hashemabadi, "Economy of a utility boiler power plant fueled with vegetable oil, biodiesel, petrodiesel and their prevalent blends," *Sustainable Production and Consumption*, vol. 3, pp. 1–7, 2015, https://doi.org/10.1016/j.spc.2015.06.001.

[113] A. Ghorbani and B. Bazooyar, "Optimization of the combustion of SOME (soybean oil methyl ester), B5, B10, B20 and petrodiesel in a semi industrial boiler," *Energy*, 2012, https://doi.org/10.1016/j.energy.2012.06.035.

[114] J. Dias, M. Costa, and J. L. T. Azevedo, "Test of a small domestic boiler using different pellets," *Biomass and Bioenergy*, 2004, https://doi.org/10.1016/j.biombioe.2003.07.002.

[115] B. Sungur and B. Topaloğlu, "Experimental analysis of combustion performance of biodiesel absorbed pellets in a domestic boiler," *Energy*, vol. 201, 2020 https://doi.org/10.1016/j.energy.2020.117653.

[116] G. Kilic, B. Sungur, B. Topaloglu, and H. Ozcan, "Experimental analysis on the performance and emissions of diesel/butanol/biodiesel blended fuels in a flame tube boiler," *Applied Thermal Engineering*, vol. 130, pp. 195–202, 2018, https://doi.org/10.1016/j.applthermaleng.2017.11.006.

[117] A. Macor and P. Pavanello, "Performance and emissions of biodiesel in a boiler for residential heating," *Energy*, vol. 34, no. 12, pp. 2025–2032, 2009, https://doi.org/10.1016/j.energy.2008.08.021.

[118] H.-H. Yang, S. M. Arafath, K.-T. Lee, Y.-S. Hsieh, and Y.-T. Han, "Chemical characteristics of filterable and condensable PM2.5 emissions from industrial boilers with five different fuels," *Fuel*, vol. 232, pp. 415–422, 2018, https://doi.org/10.1016/j.fuel.2018.05.080.

[119] R. García-Contreras, J. D. Martínez, O. Armas, R. Murillo, and T. García, "Study of a residential boiler under start-transient conditions using a tire pyrolysis liquid (TPL)/diesel fuel blend," *Fuel*, vol. 158, pp. 744–752, 2015, https://doi.org/10.1016/j.fuel.2015.06.046.

[120] M. F. Chong, K. P. Lee, H. J. Chieng, and I. I. Syazwani Binti Ramli, "Removal of boron from ceramic industry wastewater by adsorption-flocculation mechanism using palm oil mill boiler (POMB) bottom ash and polymer," *Water Research*, vol. 43, no. 13, pp. 3326–3334, 2009, https://doi.org/10.1016/j.watres.2009.04.044.

[121] C. Y. Yin, S. A. S. A. Kadir, Y. P. Lim, S. N. Syed-Ariffin, and Z. Zamzuri, "An investigation into physicochemical characteristics of ash produced from combustion of oil palm biomass wastein a boiler," *Fuel Processing Technology*, vol. 89, no. 7, pp. 693–696, 2008, https://doi.org/10.1016/j.fuproc.2007.12.012.

[122] C. Song, G. Chen, N. Ji, Q. Liu, Y. Kansha, and A. Tsutsumi, "Biodiesel production process from microalgae oil by waste heat recovery and process integration," *Bioresource Technology*, 2015, https://doi.org/10.1016/j.biortech.2015.06.116.

[123] A. Intang, "Analisa exergi sistem pembangkit uap pilot plant biodiesel," *FLYWHEEL J. Tek. Mesin Untirta.*, 2015.

[124] W. W. S. Ho, H. K. Ng, and S. Gan, "Development and characterisation of novel heterogeneous palm oil mill boiler ash-based catalysts for biodiesel production," *Bioresource Technology*, vol. 125, pp. 158–164, 2012, https://doi.org/10.1016/j.biortech.2012.08.099.

[125] A. S. Nejad and A. R. Zahedi, "Optimization of biodiesel production as a clean fuel for thermal power plants using renewable energy source," *Renewable Energy*, 2018, https://doi.org/10.1016/j.renene.2017.11.087.

[126] J. F. Costa, M. F. Almeida, M. C. M. Alvim-Ferraz, and J. M. Dias, "Biodiesel production using oil from fish canning industry wastes," *Energy Conversion and Management*, 2013, https://doi.org/10.1016/j.enconman.2013.04.032.

[127] A. Keskin, M. Şen, and A. O. Emiroğlu, "Experimental studies on biodiesel production from leather industry waste fat and its effect on diesel engine characteristics," *Fuel*, 2020, https://doi.org/10.1016/j.fuel.2020.118000.

[128] R. Piloto-Rodríguez, E. A. Melo, L. Goyos-Pérez, and S. Verhelst, "Conversion of by-products from the vegetable oil industry into biodiesel and its use in internal combustion engines: a review," *Brazilian Journal of Chemical Engineering*, https://doi.org/10.1590/0104-6632.20140312s00002763, 2014.

[129] M. K. Lam, K. T. Lee, and A. R. Mohamed, "Homogeneous, heterogeneous and enzymatic catalysis for transesterification of high free fatty acid oil (waste cooking oil) to biodiesel: a review," *Biotechnology Advances*, 2010, https://doi.org/10.1016/j.biotechadv.2010.03.002.

[130] S. Chongkhong, C. Tongurai, P. Chetpattananondh, and C. Bunyakan, "Biodiesel production by esterification of palm fatty acid distillate," *Biomass and Bioenergy*, 2007, https://doi.org/10.1016/j.biombioe.2007.03.001.

[131] S. Martínez-Martínez, L. Pérez-Villarejo, D. Eliche-Quesada, B. Carrasco-Hurtado, P. J. Sánchez-Soto, and G. N. Angelopoulos, "Ceramics from clays and by-product from biodiesel production: processing, properties and microstructural characterization," *Applied Clay Science*, https://doi.org/10.1016/j.clay.2015.12.003, 2016.

[132] S. Nagappan, P. C. Tsai, S. Devendran, V. Alagarsamy, and V. K. Ponnusamy, "Enhancement of biofuel production by microalgae using cement flue gas as substrate," *Environmental Science & Pollution Research*, 2020, https://doi.org/10.1007/s11356-019-06425-y.

[133] J. X. Wang, K. T. Chen, B. Z. Wen, Y. H. Ben Liao, and C. C. Chen, "Transesterification of soybean oil to biodiesel using cement as a solid base catalyst," *J. Taiwan Inst. Chem. Eng.*, 2012, https://doi.org/10.1016/j.jtice.2011.08.002.

[134] E. G. Al-Sakkari, S. T. El-Sheltawy, N. K. Attia, and S. R. Mostafa, "Kinetic study of soybean oil methanolysis using cement kiln dust as a heterogeneous catalyst for biodiesel production," *Applied Catalysis B: Environmental*, 2017, https://doi.org/10.1016/j.apcatb.2017.01.008.

[135] M. A. Sukiran, F. Abnisa, S. Syafiie et al., "Experimental and modelling study of the torrefaction of empty fruit bunches as a potential fuel for palm oil mill boilers," *Biomass and Bioenergy*, vol. 136, p. 105530, 2020, https://doi.org/10.1016/j.biombioe.2020.105530.

[136] Asosiasi Produsen Biofuel Indonesia, *Produksi Biodiesel Terus Meningkat Dalam Empat Tahun Terakhir*, Databoks, Daerah Khusus Ibukota Jakarta 12980, Indonesia, 2021.

[137] A. Mulyani, F. Agus, and D. Allelorung, "Potensi sumber daya lahan untuk pengembangan jarak pagar (jatropha)," *J. Litbang Pertan.*vol. 25, pp. 130–138, 2006.

[138] M. Syakir, "Prospek dan Kendala Pengembangan Jarak Pagar (Jatropha curcas L.) Sebagai Bahan Bakar Nabati di Indonesia," *Perspektif*, vol. 9, pp. 55–65, 2015, https://doi.org/10.21082/p.v9n2.2010.

[139] U.S. Energy Information Administration, *International Energy Data, Monthly Update*, EIA, Washington, D.C..

[140] Asosiasi Produsen Biofuel Indonesia, *Palm Oil Is the Most Efficient Land Use - APROBI*, APROBI, Daerah Khusus Ibukota Jakarta 12980, Indonesia, 2021.
[141] Chart, *Which Countries Produce the Most Palm Oil?*, Statista, Hamburg, Germany, 2020.
[142] United States Department of Agriculture, *Oil, Palm Explorer*, Washington, D.C., 2009.
[143] M. F. Awalludin, B. B. Sulaiman, S. H. Hashim et al., "An overview of the oil palm industry in Malaysia and its waste utilization through thermochemical conversion, specifically via liquefaction," *Renewable and Sustainable Energy Reviews*, 2015, https://doi.org/10.1016/j.rser.2015.05.085.
[144] A. Johari, B. B. Nyakuma, S. H. Mohd Nor et al., "The challenges and prospects of palm oil based biodiesel in Malaysia," *Energy*, vol. 81, pp. 255–261, 2015, https://doi.org/10.1016/j.energy.2014.12.037.
[145] V. B. Borugadda and V. V. Goud, "Biodiesel production from renewable feedstocks: status and opportunities," *Renewable and Sustainable Energy Reviews*, 2012, https://doi.org/10.1016/j.rser.2012.04.010.
[146] M. Mohibbeazam, fnm au, and N. au, *Feasibility of Solar Thermal Power Plant in India*, Energy Centre at MANIT, Bhopal India, 2011.
[147] M. M. Azam, A. Waris, and M. A. Nahar, "Biodiesel fromPongamia pinnataL. Oil: a promising alternative bioenergy source," *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, vol. 29, no. 16, pp. 293–302, 2005, https://doi.org/10.1016/j.biombioe.2005.05.001.
[148] M. Ahmad, M. Zafar, M. Khan, and S. Sultana, "Biodiesel from Pongamia pinnata L. Oil: a promising alternative bioenergy source, energy sources Part A-recovery util," *Environ. Eff.*vol. 31, pp. 1436–1442, 2009, https://doi.org/10.1080/15567030802092882.
[149] A. F. Amigun, R. d. C. d. S. Müller-Langer, J. A. von Blottnitz et al., "Predicting the costs of biodiesel production in Africa: learning from Germany," *Energy Sustain. Dev.*no. 12, https://doi.org/10.1016/S0973-0826(08)60415-9, 2008.
[150] A. F. Porte, R. D. C. D. S. Schneider, J. A. Kaercher et al., "Sunflower biodiesel production and application in family farms in Brazil," *Fuel*, vol. 89, pp. 3718–3724, 2010, https://doi.org/10.1016/j.fuel.2010.07.025.
[151] D. A.H., S. D. A. Nuva, P. A.A, A. R, and D. A. B B, "Pengembangan bioenergi di Indonesia: peluang dan tantangan kebijakan industri biodiesel, Pengemb. Bioenergi Di Indones. Peluang Dan Tantangan Kebijak," *Ind. Biodiesel.*, https://doi.org/10.17528/cifor/006975, 2018.
[152] M. H. Zulqarnain, M. Yusoff, M. Ayoub, F. R. Jusoh, and A. A. Abdullah, "Progressive biodiesel policy in Indonesia: does the Government's economic proposition hold?" *Renewable and Sustainable Energy Reviews*, vol. 8, pp. 1–18, 2020, https://doi.org/10.3390/pr8101244.
[153] A. Halimatussadiah, D. Nainggolan, S. Yui, F. R. Moeis, and A. A. Siregar, "Progressive biodiesel policy in Indonesia: does the Government's economic proposition hold?" *Renewable and Sustainable Energy Reviews*, vol. 150, p. 111431, 2021, https://doi.org/10.1016/j.rser.2021.111431.
[154] European Biodiesel Board 2008-2009, *EU Biodiesel Industry Shows Resilience amid Unfair International Competition and Degraded Market Conditions*, EBB, Etterbeek, Belgium, 2009.
[155] J. Malça and F. Freire, "Life-cycle studies of biodiesel in Europe: a review addressing the variability of results and modeling issues," *Renewable and Sustainable Energy Reviews*, https://doi.org/10.1016/j.rser.2010.09.013, 2011.
[156] K. B. Ã, M. G. au, fnm au, and M. N. au, "Biodiesel as an alternative motor fuel: production and policies in the European Union," *Renewable and Sustainable Energy Reviews*, vol. 12, pp. 542–552, 2008, https://doi.org/10.1016/j.rser.2005.06.001.
[157] M. H. Anwar, M. A. Rasul, N. Ashwath, and M. D. N. Nabi, "The potential of utilising papaya seed oil and stone fruit kernel oil as non-edible feedstock for biodiesel production in Australia-A review," *Procedia Engineering*, vol. 5, pp. 280–297, 2019, https://doi.org/10.1016/j.egyr.2019.02.007.
[158] M. H. Hassan and M. A. Kalam, "An overview of biofuel as a renewable energy source: development and challenges," *Procedia Eng.*vol. 56, pp. 39–53, 2013, https://doi.org/10.1016/j.proeng.2013.03.087.
[159] Y. J. Xu, G. X. Li, and Z. Y. Sun, "Development of biodiesel industry in China: upon the terms of production and consumption," *Renewable and Sustainable Energy Reviews*, 2016, https://doi.org/10.1016/j.rser.2015.10.035.