

# Biodiesel: Exploration of Microalgae as Feedstock, Methods, Production, and Characterization,

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## Abstract

Microalgae have gained significant attention as a promising feedstock for biodiesel production because of their high lipid content, rapid growth rate, and low land requirement compared to conventional oil crops. This review presents a comprehensive overview of research developments on microalgae-based biodiesel from 2000 to 2025. The discussion covers microalgae species selection with high lipid productivity, cultivation strategies, oil extraction techniques, biodiesel production processes, and product characterization. Particular emphasis is given to ultrasonic-assisted and solvent-based extraction methods, as well as transesterification processes using acid and base catalysts. The physicochemical properties of the resulting biodiesel, including density, viscosity, and calorific value, are also evaluated. Microalgae offer several advantages such as sustainable cultivation, high biomass productivity, effective CO<sub>2</sub> sequestration, and the ability to produce valuable co-products like proteins and carbohydrates. However, major challenges remain, including optimization of lipid accumulation, extraction efficiency, and scalability of production systems. This review identifies current trends, research gaps, and future directions, highlighting the strong potential of microalgae to support sustainable biodiesel production and advance renewable energy development.

## 1. Introduction

Biodiesel is a renewable alternative fuel whose primary raw materials are derived from natural sources, namely plants and animals. Biodiesel is defined as a monoalkyl ester of vegetable oils and animal fats (Srivastava & Prasad, 2000). Chemically, biodiesel consists of monoalkyl esters produced through a transesterification process between triglycerides (vegetable oils or animal fats) and various types of alcohols using a base catalyst, or through a combination of esterification–transesterification, and is utilized as fuel or an energy source for diesel engines. Biodiesel is produced from vegetable oils and animal fats. Biodiesel feedstocks can be classified into edible oils, non-edible oils, and microalgae. Among these, microalgae offer several advantages, including lower land requirements as well as higher productivity and oil yield compared to other feedstocks. The oil yield from microalgae can be obtained through ultrasonic extraction methods (Budiman et al., 2018). The production of biodiesel from vegetable oils generally employs a transesterification process (Trisnawati et al., 2013). Transesterification is a reaction that produces esters, in which one of the reactants is also an ester compound. In biodiesel production, the formation of fatty acid methyl esters (FAME) occurs through a reversible esterification–transesterification process (Kumar et al., 2020). This transesterification reaction converts fatty acids in oils into methyl esters, commonly referred to as biodiesel. The reaction is an equilibrium process that proceeds relatively slowly; therefore, a catalyst is required to accelerate the reaction. Homogeneous catalysts are commonly used; however, recent attention has shifted toward heterogeneous catalysts. This shift is driven by several factors, including easier separation and purification of the reaction products and the avoidance of saponification, particularly in oils with high free fatty acid and moisture contents (Xie & Li, 2006).

## 2. Method

This review was conducted to provide a comprehensive overview of microalgae as a feedstock for biodiesel, focusing on extraction methods, production techniques, and product characterization. Relevant literature was systematically searched using databases such as Scopus, Web of Science, ScienceDirect, and Google Scholar, covering publications from 2000 to 2025. The search employed keywords including “microalgae biodiesel,” “oil extraction,” “ultrasonic extraction,” “transesterification,” “biodiesel production,” and “biodiesel characterization,” combined with Boolean operators to refine results. Inclusion criteria were studies that (1) investigated microalgae as a biodiesel feedstock, (2) reported methods for extraction,

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production, or characterization, (3) were published in peer-reviewed journals, and (4) were written in English. Studies unrelated to biodiesel or focused solely on other biofuels were excluded. Data extracted from the selected studies included microalgae species, lipid content, extraction methods, production conditions, catalysts used, and characterization parameters such as density, viscosity, acid number, and FAME content. The collected data were critically analyzed and synthesized to highlight trends, advantages, limitations, and research gaps in microalgae-based biodiesel development

### 3. Result and Discussion

#### Biodiesel Feedstocks

Biodiesel is produced from feedstocks that contain oil. Based on their generation, biodiesel feedstocks are classified into three categories: biodiesel derived from edible oils (first-generation biodiesel), biodiesel derived from non-edible oils (second-generation biodiesel), and biodiesel derived from microalgae (third-generation biodiesel). Initially, biodiesel feedstocks mainly consisted of vegetable oils classified as edible oils. However, over time, the use of edible oils has raised concerns regarding competition with national food security. Consequently, the idea emerged to develop biodiesel feedstocks from non-edible oils, namely oils that cannot be consumed by humans, as substitutes for edible vegetable oils. These second-generation feedstocks are obtained from oil-bearing plants or oil-containing waste materials (Budiman et al., 2018). Second-generation biodiesel feedstocks have several drawbacks. Feedstocks derived from plants may cause soil pollution due to the use of pesticides and herbicides to improve crop quality and yield. In addition, feedstocks obtained from waste, which generally have lower quality compared to other feedstock types, require relatively complex and lengthy processing steps before being converted into biodiesel (Budiman et al., 2018). Table 1 presents a comparison of productivity, oil yield, and land requirements for several biodiesel feedstocks.

**Table 1. Comparison of Productivity, Oil Yield, and Land Requirements of Various Biodiesel Feedstocks**

Type of Feedstock	Oil Yield (L oil/ha/year)	Land Area (m <sup>2</sup> -year/kg biodiesel)	Biodiesel Productivity (kg biodiesel/ha/year)
<i>Zea mays</i>	172	66	152
<i>Cannabis sativa</i>	363	31	321
<i>Glycine max</i>	636	18	562
<i>Jatropha curcas</i>	741	15	656
<i>Camelia sativa</i>	915	12	809
<i>Brasica napus</i>	974	12	62
<i>Helianthus annuus</i>	1.070	11	946
<i>Ricinus communis</i>	1.307	9	1.156
<i>Elaeis guineensis</i>	5.366	2	4.747
low lipid content	58.700	0,2	51.927
moderate lipid content	97.800	0,1	86.515
high lipid content	136.900	0,1	121.104

Source: (Budiman et al., 2018)

Based on the comparison of productivity, oil yield, and land requirements of various biodiesel feedstocks presented above, microalgae are identified as one of the most promising feedstocks compared to others. The data indicate that microalgae require a much smaller cultivation area, namely 0.1–0.2 m<sup>2</sup>-year/kg biodiesel, exhibit higher productivity of approximately 51,927–121,104 kg biodiesel/ha/year, and provide oil yields of about 58,700–136,900 L oil/ha/year, depending on the lipid content of the microalgae. According to Budiman et al. (2018), the lipid content of microalgae is strongly influenced by environmental conditions during the cultivation process.

## Microalgae as Biodiesel Feedstock

Microalgae are the most primitive plant organisms, microscopic (unicellular) in size, that inhabit aquatic environments, including both freshwater and marine ecosystems. Microalgae, commonly referred to as phytoplankton, act as primary producers in aquatic systems and possess photosynthetic capabilities similar to those of higher terrestrial plants. In addition to their abundant availability in Indonesian waters, microalgae have a very high oil content, which makes them one of the most promising feedstocks for biodiesel production (Mujizat Kawaroe & Sardin, 2019).



Figure 1. Microalgae (Source: samuderanesia.id)



Figure 2. Microalgae Biofuel Production (Source: samuderanesia.id)

As one of the biodiesel feedstocks, microalgae offer several advantages compared to other biodiesel feedstocks, including:

1. Do not compete with food supply or arable land use.
2. Microalgae are capable of absorbing significantly larger amounts of CO<sub>2</sub> compared to other plants; therefore, they are often utilized for capturing exhaust gas emissions to reduce CO<sub>2</sub> content.
3. Microalgae can be used as adsorbents for NH<sub>4</sub><sup>+</sup>, NO<sub>3</sub><sup>-</sup>, and PO<sub>4</sub><sup>3-</sup> ions in wastewater treatment processes.
4. Microalgae possess relatively high lipid content.
5. Compared to other feedstocks, microalgae exhibit higher productivity.
6. The harvesting cycle of microalgae requires only about 3–5 days.
7. Microalgae are able to grow under a wide range of environmental conditions.
8. Microalgae can produce valuable by-products such as biopolymers, proteins, carbohydrates, and residual biomass that can be utilized as fertilizers or animal feed.
9. Microalgae cultivation does not require pesticides or herbicides, unlike edible and non-edible oil crops, which can degrade soil structure.

(Budiman et al., 2018)

Microalgae are classified into three main groups: blue-green algae (Cyanobacteria), diatoms (Bacillariophyta), and green algae (Chlorophyta). The number of microalgae species is estimated to exceed 50,000 and they are distributed worldwide (Budiman et al., 2018). Several microalgae species possess abundant oil content and are considered highly potential as biodiesel feedstocks. This can be seen in Table 2.

**Table 2. Oil Content Composition of Several Microalgae Species**

No	Species	Oil Content (% dry weight)
1	<i>Scenedesmus obliquus</i>	35-55
2	<i>Scenedesmus dimorphus</i>	16-40
3	<i>Chlorella vulgaris</i>	56
4	<i>Chlorella emersonii</i>	63
5	<i>Chlorella protothecoides</i>	23-55
6	<i>Chlorella sorokiana</i>	22
7	<i>Chlorella minutissima</i>	57
8	<i>Dunaliella bioculata</i>	8
9	<i>Dunaliella salina</i>	14-20
10	<i>Neochloris oleoabundans</i>	35-65
11	<i>Spirulina maxima</i>	4-9
12	<i>Botryococcus braunii</i>	75

Source: (Banerjee et al., 2002)

Based on Table 2, it can be observed that microalgae species are highly potential as biodiesel feedstocks due to their abundant oil content. The table shows that *Botryococcus braunii* has the highest oil content, reaching up to 75%, compared to other species. The high oil and lipid contents of these microalgae species are supported by several studies. The following are some microalgae species that are considered potential biodiesel feedstocks, reviewed based on their lipid content as reported in various studies and presented in Table 2.

**Table 3. Studies on Microalgae as Biodiesel Feedstocks**

No	Research Findings	References
1	The evaluation of microalgae potential as biodiesel feedstocks was carried out using Nile Red (NR) staining. Based on observations using a fluorescence microscope, the microalgae species identified as the most promising for biodiesel feedstock development were <i>Cyclotella atomus</i> , <i>Cyclotella</i> sp., <i>Nitzschia</i> sp., <i>Chlorella</i> sp., <i>Desmodesmus</i> sp., <i>Chlorella ellipsoidea</i> , and <i>Chlorella vulgaris</i> .	(Jumiarni, 2018)
2	In this study, <i>Chlorella vulgaris</i> was used for textile wastewater (TWW) bioremediation and biodiesel production. The yield of fatty acid methyl esters (FAME) in diluted TWW was higher (11.07 mg/g) than that in undiluted TWW (9.12 mg/L). The dominant FAME components were palmitic acid (C16:0) and linolenic acid (C18:3), which are suitable for biodiesel production.	(Fazal et al., 2021)
3	In this study, biodiesel was produced using an electrolysis method from marine microalgae oils, namely <i>Chlorella vulgaris</i> and <i>Spirulina platensis</i> , employing methanol and CaO/KOH-Fe <sub>3</sub> O <sub>4</sub> nanocatalysts (55.91 nm) as well as KF/KOH-Fe <sub>3</sub> O <sub>4</sub> nanocatalysts (42 nm). The results showed that <i>Chlorella vulgaris</i> was a more favorable microalgae feedstock than <i>Spirulina platensis</i> , particularly when using the KF/KOH-Fe <sub>3</sub> O <sub>4</sub> catalyst under optimal conditions: catalyst loading of 1.5 wt%, a methanol-to-oil molar ratio of 1:6, temperature of 25 °C, stirring speed of 400 rpm, and a reaction time of 2 hours.	(Farrokheh, 2020)
4	In this study, 300 mg of biofuel was produced per gram of dry cell weight, consisting of 156 mg of FAME and 144 mg of bioethanol. This represents the highest yield reported to date from <i>Chlamydomonas</i> sp.	(Kim et al., 2020)
5	<i>Botryococcus braunii</i> microalgae produce an oil content of approximately 75% of dry weight. The oil from <i>Botryococcus braunii</i> consists predominantly of hydrocarbons (15-76% of dry weight), known as botryococcene. This type of hydrocarbon is highly potential as an energy source for biodiesel	(Amini & Susilowati, 2010)

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- |       |  |                      |
|-------|--|----------------------|
| 6     | Nannochloropsis sp. microalgae achieved optimal conditions at a temperature of 70 °C and a reaction time of 90 minutes, with biodiesel conversion based on total lipids and lipid conversion efficiencies of 84.2% and 96.7%, respectively. The highest biodiesel production reached 155.7 mg per gram of dry cell weight.   | (Kwon & Yeom, 2015)  |
| <hr/> |  |                      |
| 7     | Biodiesel production from *Chlorella* sp. microalgae oil using a dodecylbenzenesulfonate catalyst achieved optimal conditions for esterification and transesterification reactions at a process temperature of 373.15 K, a residence time of 30 minutes, a methanol-to-oil ratio of 30, and a catalyst loading of 11 wt%, resulting in a yield of 99%. The effect of water content was also evaluated, and the results indicated that to achieve biodiesel yields above 90%, the water content must be lower than 0.5 wt%. | (Jazie et al., 2019) |
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## Extraction Methods

Several biodiesel feedstocks, particularly microalgae, are produced through cultivation processes. Cultivation aims not only to meet the required quantity of feedstock but also to enable biochemical and genetic engineering approaches intended to increase lipid content and enhance growth rates. Successful cultivation methods include photobioreactor systems and open pond cultivation. Another strategy to increase lipid content is nitrogen starvation (Budiman et al., 2018). To convert the feedstock into biodiesel, an extraction stage is required. The extraction process is carried out to recover the oil contained within the feedstock. Several extraction methods have been reported, including mechanical extraction using an expeller press, solvent extraction, supercritical fluid extraction, ultrasonic extraction, extraction using ionic liquids, hydrothermal processing, and osmotic extraction (Budiman et al., 2018)..



Figure 3. Ultrasonic Extraction Method

Ultrasonic extraction methods have been increasingly developed in recent years. Ultrasonic extraction utilizes the assistance of ultrasonic waves and is also known as a sonochemical method. Sonochemistry is a technique that employs ultrasonic waves to induce and enhance chemical changes, offering higher efficiency and shorter operating times compared to conventional extraction methods (Wati et al., 2010). The application of ultrasonic waves is carried out at lower pressure and temperature conditions, reducing the consumption of raw materials and solvents, minimizing the number of synthesis steps, and simultaneously improving final selectivity. In addition, this method allows the use of lower-purity raw materials and solvents and enhances catalyst activity.

The steps involved in the ultrasonic extraction method are as follows: the ultrasonic extraction apparatus is first assembled. A total of 40 g of dried microalgae powder is placed into a 500 mL round-bottom flask and then mixed with an extraction solvent at a temperature of 50 °C for 1 hour. The solvent containing the extracted microalgae oil is separated using filter paper. Subsequently, the extracted oil is separated from the solvent through a distillation process to obtain the microalgae oil. Further analyses are then conducted, including physical property analysis of the oil (density and viscosity), acid value analysis, saponification value analysis, and GC–MS analysis (Wati et al., 2010).

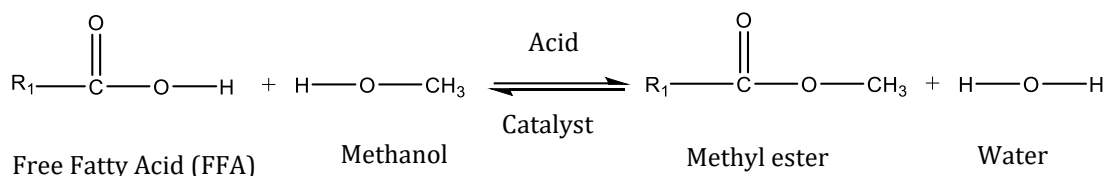
## Biodiesel Production

During the biodiesel production process, several stages occur to convert fatty acids into esters and subsequently into alkyl esters. The production method of a product generally consists of three main stages: pre-treatment, synthesis/production, and post-treatment. Pre-treatment is the stage of preparing the feedstock before it is reacted to produce the final product. Synthesis/production is the main stage of

biodiesel production, in which the reactants from the pre-treatment stage are reacted under specific conditions to form biodiesel. Post-treatment, on the other hand, aims to purify the main reaction product so that its quality meets the required specifications and market demands (Budiman et al., 2018)..

### Pre-treatment

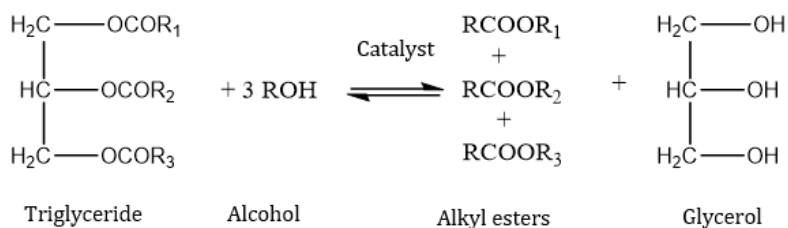
Pre-treatment aims to reduce excessively high levels of free fatty acids in the oil. Pre-treatment methods include steam distillation, extraction using alcohols, and esterification using acid catalysts. Acid-catalyzed esterification is considered the most optimal pre-treatment method, as it is more effective in converting free fatty acids into biodiesel compared to other methods.



Esterification is the stage in which free fatty acids are converted into esters using alcohol. In this process, a strong acid catalyst is used, such as sulfuric acid, organic sulfonic acids, and others. To facilitate the reaction, the temperature is kept low, excess alcohol is added, and the water produced during the reaction is separated from the oil phase. Esterification is necessary when vegetable oils contain free fatty acid levels above 5%, because if biodiesel production is forced with free fatty acid content higher than 5%, the reaction between the fatty acids and alcohol will produce soap, thereby reducing the quality of the resulting biodiesel.

### Production/Synthesis

In the biodiesel production or synthesis process, transesterification takes place. Transesterification is the conversion of triglycerides (vegetable oils) into alkyl esters. This reaction involves alcohol and produces glycerol as a by-product. Methanol is the most commonly used alcohol due to its cost-effectiveness. The transesterification reaction is typically catalyzed by a strong base (such as hydroxides), which provides high conversion rates while minimizing side reactions. The direct conversion to biodiesel occurs via intermediates under relatively low temperature and pressure conditions. Sometimes, transesterification is carried out twice to reduce alcohol consumption. This process is usually performed after the removal of free fatty acids during the esterification stage (Risnoyatiningih, 2010).



Transesterification is a chemical process that involves the reaction of the alcohol group in an ester with an alcohol. To accelerate this reaction, a catalyst, either acidic or basic, is required. Acidic catalysts facilitate the reaction by donating a proton to the alcohol group, increasing its reactivity. Chemically, transesterification targets triglyceride molecules or complex fatty acids, neutralizes large fatty acids, and produces glycerol or esters, forming alkyl esters. In practice, this can be carried out by mixing alcohol with sodium hydroxide to produce sodium methoxide, which is then reacted with vegetable oils. All three reactions are equilibrium reactions that are accelerated by the presence of an acid catalyst (H<sub>2</sub>SO<sub>4</sub> or HCl) or a base catalyst, usually an alkoxide ion. These catalysts are used in an anhydrous system because water

can hydrolyze the esters. In practice, this is typically carried out by dissolving a certain amount of sodium in alcohol, which is then added to the ester (Risnoyatningsih, 2010).

### Post-treatment

The products of the transesterification reaction are esters (biodiesel) and glycerol. These two products have different densities, resulting in the formation of two liquid phases. Several steps are involved in separating and purifying these products during the post-treatment process, including phase separation, neutralization, alcohol recovery, glycerol purification, and water removal (Budiman et al., 2018). During the purification stage of the transesterification products, several procedures are applied: the product is filtered using a Buchner funnel with the assistance of a vacuum pump; the upper biodiesel layer is separated from methanol and glycerol in the lower layer using a separating funnel; the crude biodiesel is then washed twice with distilled water, followed by separation of the crude biodiesel from the water using a separating funnel (Septianto et al.).

### Characterization Analysis

The quality requirements of biodiesel are tested according to the Indonesian National Standard (SNI) issued by the National Standardization Agency (BSN), which ensures compliance with technical requirements or standardized criteria. These technical requirements relate to safety, security, health, environmental protection, scientific and technological development, practical experience, and current as well as future advancements, in order to provide benefits for Indonesia. SNI is formulated in accordance with the WTO Code of Good Practice. The following are the standards and specifications for vegetable-based fuels (biofuels), specifically biodiesel, marketed domestically, in accordance with biodiesel quality standards as referred to in SK Dirjen EBTKE No. 189.K/10/DJE/2019 concerning Standards and Specifications for Vegetable-Based Fuels (Biofuel) (Pahnla et al., 2018).

**Table 4. Biodiesel Quality Standards (SNI 7182:2019)**

No	Parameter and Unit	Test Method	Requirement	Unit, Min/Max
1	Density at 40 °C	SNI 7182:2019	850–890	kg/m <sup>3</sup>
2	Kinematic viscosity at 40 °C	SNI 7182:2019	2.3–6.0	mm <sup>2</sup> /s (cSt)
3	Cetane number	SNI 7182:2019	51	Min
4	Flash point (closed cup)	SNI 7182:2019	130	°C, Min
5	Copper strip corrosion (3 h, 50 °C)	SNI 7182:2019	No. 1	0 °C, Min
6	Carbon residue (in original sample or 10% distillation residue)	SNI 7182:2019	0.05 / 0.30	% mass, Max
7	Distillation temperature 90%	SNI 7182:2019	360	°C, Max
8	Sulfated ash	SNI 7182:2019	0.02	% mass, Max
9	Sulfur	SNI 7182:2019	10	mg/kg, Max
10	Phosphorus	SNI 7182:2019	4	mg/kg, Max
11	Acid number	SNI 7182:2019	0.4	mg KOH/g, Max
12	Free glycerol	SNI 7182:2019	0.02	% mass, Max
13	Total glycerol	SNI 7182:2019	0.24	% mass, Max
14	Methyl ester content	SNI 7182:2019	96.5	% mass, Min
15	Iodine value	SNI 7182:2019	115	% mass, Max
16	Oxidation stability - Induction period (Rancimat method)	SNI 7182:2019	600	Min
	Oxidation stability - Induction period (PetroOxi method)	SNI 7182:2019	45	Min
17	Monoglycerides	SNI 7182:2019	0.55	% mass, Max
18	Color	ASTM D-1500	3	Max
19	Water content	ASTM D-6304	350	ppm, Max

20	CFPP (Cold Filter Plugging Point)	–	15	°C, Max
21	Metal I (Na + K)	EN 14108	5	mg/kg, Max
22	Metal II (Ca + Mg)	EN 14109	5	mg/kg, Max
23	Total contaminants	EN 12662	20	mg/L, Max
24	Halphen test	–	Eliminated	–
25	Water and sediment	SNI 7182:2019	Eliminated	% vol, Max
26	Cloud point	SNI 7182:2019	Eliminated	°C, Max

The quality requirements for biodiesel according to SNI 7182-2015 cover multiple parameters. Density at 40 °C must be within the specified range, as higher density can increase engine wear and damage. Kinematic viscosity at 40 °C affects fuel flow, pumping, and ignition; overly viscous fuel hinders flow, while overly thin fuel causes poor atomization and potential leaks. Cetane number indicates the fuel's self-ignition ability, with unsaturated fatty acid methyl esters having lower cetane numbers than saturated ones. Flash point relates to safety and handling, indicating the fuel's volatility and flammability. Copper strip corrosion predicts the relative corrosiveness of biodiesel. Carbon residue should be low to prevent cylinder abrasion and deposition on pistons. 90% distillation temperature should meet the standard of 360 °C, while values up to 370 °C are still acceptable for biodiesel use. Sulfated ash reflects contaminants and oxidized residues that can form deposits in engines. Sulfur content must be minimal to avoid corrosion and environmental pollution. Phosphorus is limited to 10 ppm to prevent damage to catalytic converters and reduce particulate emissions. Acid number indicates free fatty acid content, with lower values showing reduced free acids in the feedstock. Free and total glycerol are key quality parameters, as incomplete conversion during transesterification or reverse reactions can lead to deposits in fuel systems. Iodine value reflects the degree of unsaturation; high iodine values (>115) increase polymerization tendencies, causing deposits in injectors and pistons. Oxidation stability depends on unsaturated bonds, with higher polyunsaturated content reducing stability and producing acids, aldehydes, ketones, peroxides, or alcohols that affect fuel properties and combustion. Monoglycerides can cause fouling and deposit formation in injectors and valves. Color serves as a production and quality control indicator, though it is not a definitive measure of fuel quality. Water content, both dissolved and free, must be minimized, as free water can settle and be drained, but residual water can lower combustion efficiency, produce foam, act corrosively, and crystallize at low temperatures to block fuel lines.

The characterization of biodiesel involves several analyses. Cold Filter Plugging Point (CFPP) is defined as the lowest temperature at which biodiesel can still flow through a standardized filter within 60 seconds, according to ASTM D6371 (Pahnila et al., 2018). Density analysis is carried out using a pycnometer, which is first cleaned, dried, and weighed empty ( $P_0$ ), then filled with the sample, immersed in distilled water at 40 °C for 30 minutes, dried, and weighed again ( $P_i$ ) (Balabin et al., 2011). Viscosity determination uses an Ostwald viscometer filled with distilled water to establish flow time from the upper to lower mark, and the same procedure is repeated with the biodiesel sample at 40 °C (Dogra & Dogra, 2009). Acid number and free fatty acid (FFA) content are analyzed by weighing 2 g of sample into a 250 mL Erlenmeyer flask, adding 50 mL of 95% ethanol, heating with stirring for 10 minutes, cooling, adding 2–3 drops of phenolphthalein, and titrating with 0.1 N KOH until a stable pink color appears (Batista et al., 2016). Water content analysis is performed by heating evaporating dishes at 105 °C for 30 minutes, cooling in a desiccator for 15 minutes, weighing, adding 2 g of sample, drying again at 105 °C for 30 minutes, cooling, and repeating the process until the weight remains constant (Petchsoongsakul et al., 2020).

#### 4. Conclusion

Biodiesel feedstocks are classified into edible oils, non-edible oils, and microalgae. Among these, microalgae are the most promising feedstock because they require the smallest cultivation area while providing the highest productivity and oil yield, along with several other advantages. Oil yield is obtained using the ultrasonic extraction method. Biodiesel production involves three main stages: pre-treatment, synthesis, and post-treatment. In the transesterification process, a catalyst is required to accelerate the reaction. Characterization analyses include free fatty acid (FFA) and acid number analysis, viscosity

analysis, density analysis, and water content analysis, all of which must meet the biodiesel quality standards as specified in SNI 7182:2019.

## Author Contributions

Sri Rahmawati contributed to the conceptualization of the study, conducted the literature search and selection, prepared the original draft of the manuscript, and provided overall supervision. Sri Wahyuni performed data extraction from the selected studies, contributed to writing, reviewing, and editing the manuscript, and prepared the figures and tables. Sri Rahmawati serves as the corresponding author.

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