Research and Reviews in Sustainability | Volume 2 (2026) | ISSN 2977-8441

Publish open access at Caravel Press

Research and Reviews in Sustainability

Journal homepage: sustainability-journal.com

Review article

A review on the chemical and physical characteristics of biodiesels produced from animal fat waste

Fozy Binhweel [1,2]*, Ehsan Shalfoh [1,3], Wardah Senusi [1] and Sami Alsaadi [1,4]

[1] *Environmental Technology Division, School of Industrial Technology, Universiti Sains Malaysia, 11800, Penang, Malaysia*
[2] *Faculty of Environmental Science and Marine Biology, Hadhramout University, Hadhramout, Yemen*
[3] *Libyan Medical Research Center, Zawia, Libya*
[4] *Faculty of Science, Biology Department, Hail University, Hail 81451, Saudi Arabia*

ABSTRACT

Biodiesel is a promising and eco-friendly energy resource that can substitute conventional diesel. It can be derived from both plant and animal-based feedstocks. Animal fat waste (AFW) is oil-rich material that can serve as a viable and affordable feedstock for biodiesel fuel. However, the characteristics of biodiesel synthesized from AFW raise important concerns. This review highlights the chemical composition of animal-based oils, which typically contain higher proportions of saturated fatty acids (SFAs) and monounsaturated fatty acids (MUFAs), and smaller proportions of polyunsaturated fatty acids (PUFAs). These compositional features strongly influence the physicochemical properties of biodiesel. The review further categories these properties into physical, cold-flow, thermal performance, and chemical stability properties. Animal fat-derived biodiesels generally exhibit favorable thermal and stability properties like the high cetane number, heating value, and flash point. Conversely, their poor cold-flow properties remain a major drawback which require improvement through techniques such as winterization, blending, and the use of cold-flow improvers (CFIs). Nonetheless, the applications of AFW in the biofuel industry have favorable implications that foster sustainability by supporting the waste-to-energy (WTE) principle and producing eco-friendly fuels that comply with standards.

ARTICLE INFO

Article History:
Received: 10 December 2025
Revised: 09 January 2026
Accepted: 15 January 2026

Keywords:
Biodiesel
Biofuel
Animal-based feedstock
Oil
Physicochemical properties
Waste

Article Citation:
Binhweel, F., Shalfoh, E., Senusi, W., & Alsaadi, S. (2026). A review on the chemical and physical characteristics of biodiesels produced from animal fat waste. Research and Reviews in Sustainability, 2(1), 31–48. https://doi.org/10.65582/rrs.2026.004

1. INTRODUCTION

Energy demand is rising globally due to the expanding economy driven by the growth of population worldwide. Dependence on fossil fuel as the main energy source triggers issues related to energy security and environmental pollution. Hence, transition to renewable energy offers promising solutions to enhance energy security, boost economic growth, and reduce environmental pollution (Friedlingstein et al., 2025). Biodiesel is a promising alternative fuel derived from plant and animal-based feedstocks that can substitute fossil diesel. Typically, biodiesel is synthesized by transesterification that involves oil, alcohol and a base catalyst. It

* Corresponding author. Email address: binhweel@student.usm.my (Fozy Binhweel)

consists of alkyl esters of long-chain fatty acids. It is biodegradable, produces lower emissions, and can be applied in compression-ignition diesel engines without significant modifications because of similar physicochemical properties (Elgharbawy et al., 2025).

The global biodiesel demand is increasing rapidly as nations and industries seek sustainable alternatives to fossil fuels. Figure 1 shows the global demand on biodiesel fuel from 2016 to 2028, as estimated by the International Energy Agency (IEA) under the accelerated case scenario. In 2016, the global demand for biodiesel was recorded at 33.3 billion liters. By 2020, this demand increased by 35.44%, reaching 45.1 billion liters, reflecting a steady growth trend. Estimations indicate that demand will continue to rise, reaching 60.6 billion liters by 2025. By 2028, demand is expected to increase by 60% compared to 2020 levels, reaching approximately 68.1 billion liters. Such statistics highlight the growing importance of biodiesel as a substitute for conventional diesel (IEA, 2023). Despite its promise, the biodiesel industry faces challenges related to feedstock availability and cost. The feedstock challenge significantly impacts production since it accounts for 70–95% of total expenses. Addressing this challenge is critical to ensuring the long-term sustainability of biodiesel (Bhuiya et al., 2020).

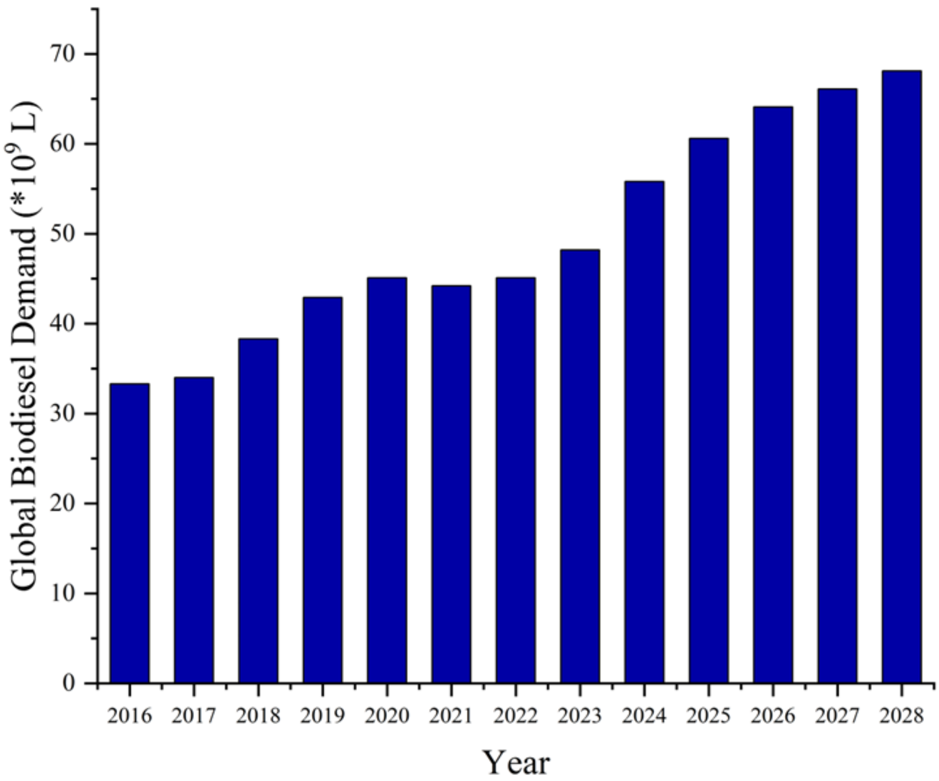

Figure 1. The global biodiesel demand from 2016 to 2028 (IEA, 2023)

Biodiesel is produced from four generations of feedstocks which are edible, inedible, algae, and genetically modified crops as presented in Figure 2. The first generation of edible oils contributes about 75% of global commercial biodiesel production. However, this reliance raises ethical, economic, and environmental concerns (Abeysinghe et al., 2025). The second generation involves inedible oils and waste materials. While non-food plant oils such as jatropha and rubber seed reduce competition with edible feedstocks, their limited availability cannot meet the growing biodiesel demand. Thus, waste-derived oils are considered the most significant contributors in this category (Elgharbawy et al., 2021). The third generation consists of algae and microalgae oils. Algae offer rapid growth and high productivity. However, they face drawbacks including high resource consumption, greenhouse gas emissions (GHGs), and relatively low lipid yields. Consequently, only species with lipid contents exceeding 5% are deemed feasible for producing biodiesel (Jeliani et al., 2021). The fourth generation introduces genetic modifications to enhance crops, addressing constraints of earlier feedstocks while improving sustainability. This advanced approach is recognized as a prospective pathway for bioenergy industry in the future (Kossalbayev et al., 2025).

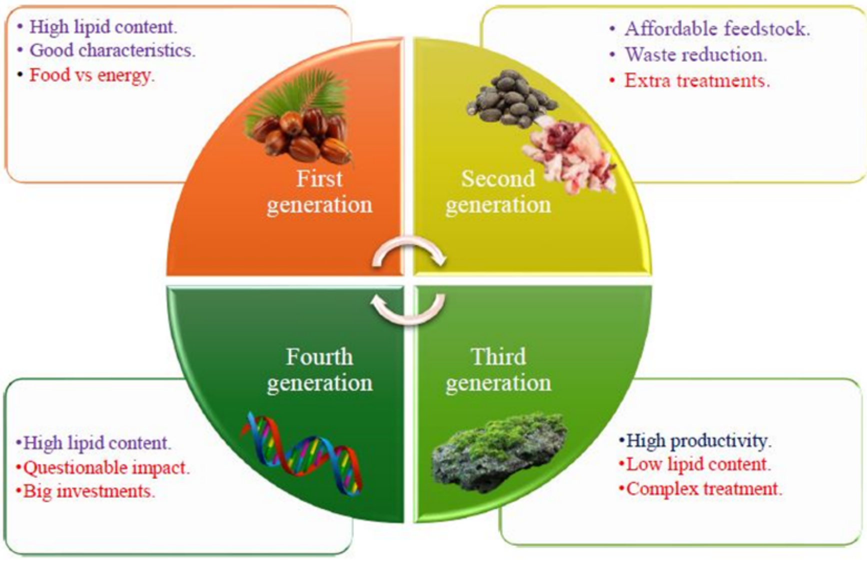

Figure 2. The four generations of biodiesel feedstocks

Animal fat waste (AFW) constitutes potential and lucrative feedstock for biodiesel production. The United States produces about 43.42 million tons of meat and poultry products, while Latin America and Caribbean contribute approximately 38 million tons, the European Union about 30 million tons, Australia 598 million tons, Sub-Saharan Africa 11.10 million tons, China 84.89 million tons, and India records 1,323.5 million heads of livestock. Beside edible goods, this industry generates vast amounts of non-edible by-products. 27.8 million tons/year are the estimated materials discarded from meat industry in North America. In Europe, the discarded materials from slaughterhouses were estimated around 29.41% out of 17 million tons. These residual wastes are commonly utilized as inputs for industries like leather tanning, textiles, detergents, fertilizers, and even biofuel production. Nonetheless, utilizing these by-products in bioenergy production promotes the ethical and sustainable waste-to-energy (WTE) principle. The present review narrows its focus to AFW as an affordable feedstock for biodiesel production, highlighting its chemical composition and physicochemical properties (Binhweel et al., 2023).

Despite its availability and cost-effectiveness, AFW offers favorable characteristics for biodiesel fuel. AFW contains triglycerides with high portions of saturated fatty acids (SFAs) and monounsaturated fatty acids (MUFAs), while containing smaller amounts of polyunsaturated fatty acids (PUFAs). Its high contents of SFAs and MUFAs enhance the oxidative stability of biodiesel by reducing oxidation reactions with atmospheric oxygen. Furthermore, AFW has relatively high heating values, which improve the thermal content of biodiesel and fuel efficiency, potentially leading to lower fuel consumption. Additionally, flash points of biodiesels synthesized from AFW are quite high which improve safety of handling, transport, and storage. Based on these advantages, exploring the characteristics of animal-based biodiesels holds significant value for promoting AFW as a viable source for biodiesel industry (Zeng et al., 2024; Zhou, Zhang, et al., 2024). Therefore, the current review aims to assess this topic by investigating the chemical composition of AFW lipids and its effects on biodiesel characteristics. It further categorizes the physicochemical properties of AFW biodiesels into physical, cold-flow, thermal performance, and chemical stability properties, while comparing existing literature with established standards.

2. CHEMICAL COMPOSITION OF ANIMAL-BASED LIPIDS

Characterizing lipids extracted from animal fat is crucial for evaluating its biodiesel and the alignment with established standards. Most biodiesel characteristics are inherited from the raw feedstock used in its synthesis, while certain characteristics like alcohol and glycerol content, suspended solids, and acid value are influenced by handling procedures and the synthesis method (Sharma et al., 2011; Singh et al., 2019). Lipids are primarily composed of fatty acids, while biodiesel is composed of esters of those fatty acids synthesized through transesterification. Fatty acids are defined as the organic compounds composed of carbon and hydrogen atoms, with a carboxyl group connected to the molecule end. They exist in the form of triglycerides where three fatty acids are connected to a glycerol backbone as illustrated in Figure 3 (Lin et al., 2023). There are hundreds of naturally occurring fatty acids and thousands more synthesized artificially. Fatty acids are classified according to the length of their carbon chain into short-chain (C2–C6), medium-chain (C6–C12), long-chain (C12–C24), and very long-chain (C >24). They are also categorized by their degree of saturation into SFAs lacking double bonds, MUFAs containing one double bond, and PUFAs containing multiple double bonds. MUFAs have one double bond, making them more stable and less prone to oxidation. In addition, they are liquid at room temperature. However, they may solidify at cooling conditions. In contrast, PUFAs contain multiple double bonds, less stable, and mostly liquid even at cooling conditions (Rustan & Drevon, 2005).

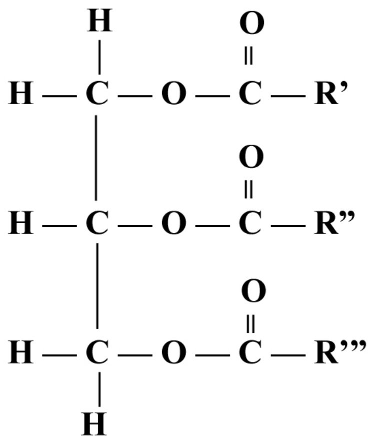

Figure 3. Triglycerides structure containing 3 fatty acids (R) and glycerol backbone

The chemical composition of lipids and their derived biodiesel including saturation level, degree of unsaturation, and carbon chain length is determined by the source of the feedstock (Singh & Singh, 2010). Fatty acid composition significantly impacts the properties of biodiesel fuel. For example, SFAs enhance cetane number and fuel stability but are also responsible for poor cold-flow properties, namely cloud point and pour point. Conversely, MUFAs and PUFAs increase the iodine value of the synthesized fuel. Additionally, factors such as atmospheric conditions, extreme temperatures, the presence of metals, peroxides, and radiation influence the composition of lipids and their derived fuels (Bajpai & Tyagi, 2006; Ramos et al., 2009). Figure 4 illustrates the fatty acid profiles of select animal-based lipids from previous studies. The effects of such fatty acid compositions are explored on biodiesel properties.

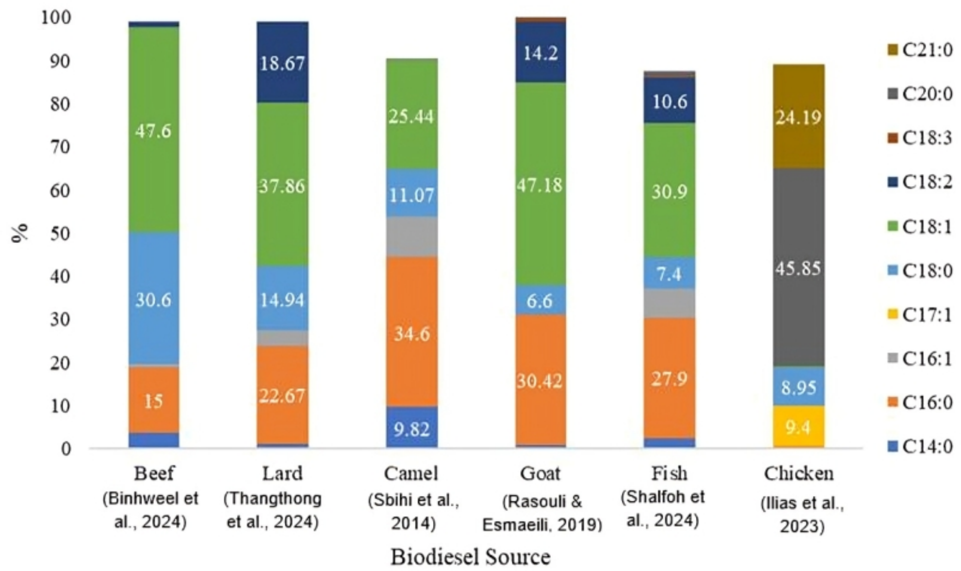

Figure 4. Fatty acid profiles for lipids extracted from various animal-based feedstocks

3. TRANSESTERIFICATION

Transesterification is the most practical, reliable, and widely used technique to convert lipids into biodiesel. This process involves the reaction of triglycerides with an alcohol in the presence of a base catalyst, producing fatty acid alkyl esters and glycerol as a by-product as shown in Figure 5. The reaction typically requires three moles of alcohol to react with one mole of triglyceride. However, to ensure complete conversion of triglycerides into alkyl ester, an excess of alcohol, usually six moles, is often used, with the surplus recovered afterward. Pretreatment is required when raw feedstock lipids have high acid values. lipids with free fatty acids (FFAs) content exceeding 2% are unsuitable for direct transesterification, as side reactions such as saponification and hydrolysis can occur, leading to excessive by-products and reduced biodiesel yields. To mitigate these issues, acidic esterification is used to reduce FFAs. This involves mixing the oil with alcohol and a strong acid catalyst, such as sulfuric or hydrochloric acid, under optimized conditions of temperature and time (Karmakar and Halder, 2019).

Transesterification is usually catalyzed by strong base catalysts. Those catalysts significantly accelerate the reaction, increasing the rate by up to 4000 times by lowering the activation energy which allows the process to occur under milder conditions (Binhweel et al., 2022). Common catalysts include homogeneous, heterogeneous, and enzymatic types. Homogeneous catalysts such as NaOH and KOH are highly efficient due to their solubility in alcohol and their uniform phase with the reactants. However, they are difficult to recover and reuse. In contrast, heterogeneous catalysts like CaO and MgO are easier to separate and reusable but often suffer from mass transfer limitations, which require longer reaction times. Enzymatic catalysts offer advantages such as selectivity, no soap formation, and easier purification, but they are slower and more expensive. Base catalysts remain the most widely used due to their high efficiency, fast reaction rate, and low cost (Mandari and Devarai, 2022).

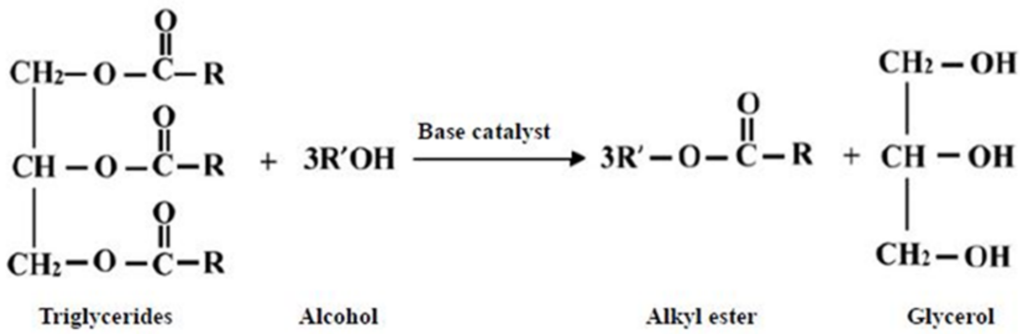

Figure 5. Transesterification reaction for converting triglycerides into alkyl ester (biodiesel) and glycerol

4. PHYSICOCHEMICAL PROPERTIES OF ANIMAL-BASED BIODIESEL

There are four key Determinants that influence the physicochemical properties of biodiesel which are feedstock source, lipid extraction, biodiesel synthesis, and refinery techniques for the extraction and synthesis (Singh et al., 2019). Biodiesel derived from animal-based feedstocks typically exhibits higher density and viscosity, reduced volatility, and poor cold-flow properties, which make it prone to gelling at low temperatures. These characteristics are attributed to the high SFAs content in animal fats. Performance deficiencies such as delays in pumping, limited atomization, partial combustion, nozzle plugging, and increased unfavorable emissions are greatly linked to these poor physicochemical properties (Nagappan et al., 2021). The physicochemical properties of AFW biodiesels can be categorized into physical, cold-flow, thermal performance, and chemical stability properties as illustrated in Figure 6.

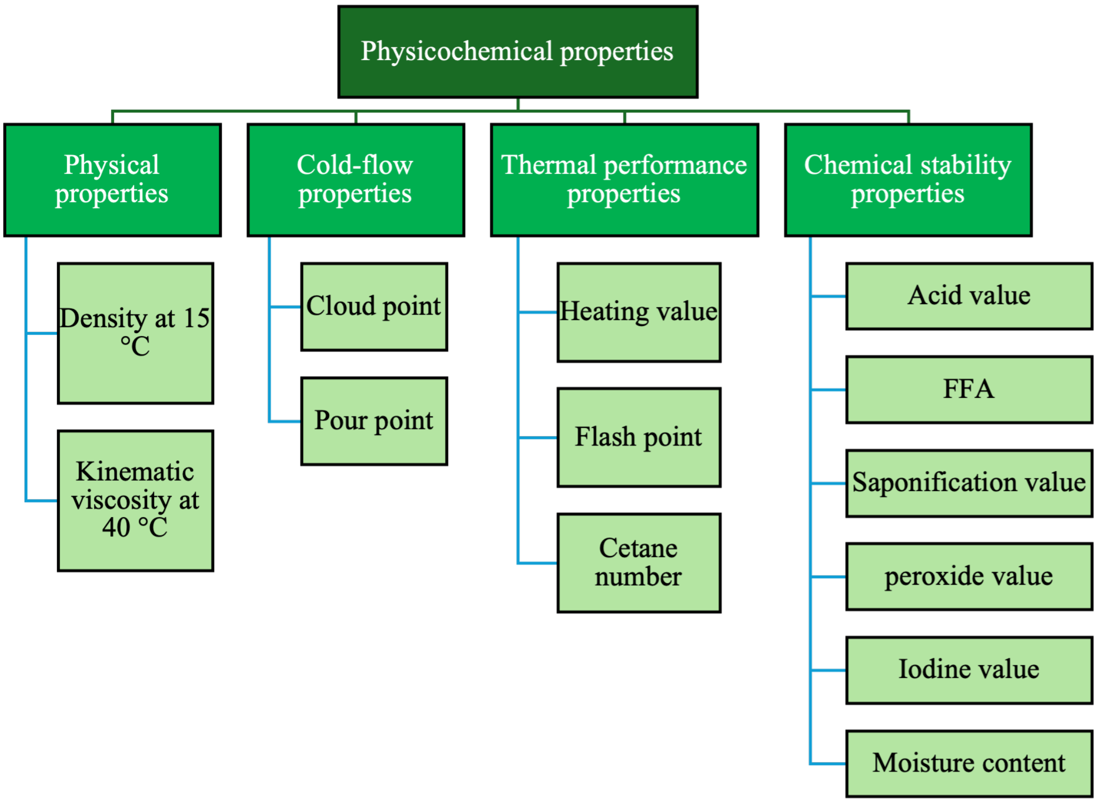

Figure 6. Categories of biodiesel physicochemical properties

5. PHYSICAL PROPERTIES

Physical properties of animal-based biodiesels are critical indicators of the fuel quality. These properties influence combustion efficiency, fuel injection, and engine performance as fuel injection is governed by volume linked to viscosity and density, while combustion is affected by the fuel mass ratio related to density.

5.1 DENSITY AT 15 °C

Biodiesel density is defined by its mass per unit of volume. It is typically reported in grams per cubic centimeter (g/cm^3) or kilograms per cubic meter (kg/m^3). As a standard, biodiesel density is measured at 15 °C, often referred to as "density at 15 °C" (Modi et al., 2024). Biodiesel composition plays a key role in shaping its density property. Unsaturated fatty acids (UFAs) typically lower density, while higher molecular weights and longer carbon chain lengths tend to increase it (Bukkarapu and Krishnasamy, 2022). Biodiesel density plays a critical role in diesel engine performance, particularly in the injection and combustion systems. The injection system delivers fuel based on volume, while combustion depends on the mass of fuel. As a result, density influences the ratio of air to fuel required for combustion and output energy per unit of fuel mass (Singh et al., 2019). Generally, biodiesel is denser than petroleum-based diesel fuel. In blended fuels, the addition of petroleum diesel reduces the overall density. Based on the data presented in Table 1 for animal-based biodiesels, density values varied from 844 kg/m^3 for fish biodiesel (Kannan et al., 2022) to 897 kg/m^3 for biodiesel derived from chicken fat (Odetoye et al., 2021).

5.2 KINEMATIC VISCOSITY AT 40 °C

Kinematic viscosity measures resistance of biodiesel to flow. It can be measured by calculating the time required for a specific biodiesel sample passing through a capillary tube and is expressed in square millimeters per second (mm^2/s). The standard measurement is conducted at 40 °C, referred to as “kinematic viscosity at 40 °C”. Length of the carbon chain and saturation degree of biodiesel composition directly influence kinematic viscosity. The longer carbon chains and higher levels of saturation result in higher viscosity, and vice versa

(Bukkarapu and Krishnasamy, 2022). Values of kinematic viscosity exceeding standard is undesirable, as it requires higher pumping pressure which can damage the fuel pump. Additionally, it leads to inadequate fuel atomization, reducing thermal efficiency and causing deposits on engine walls. Conversely, values of kinematic viscosity below the standard can result in fuel leakage and reduced lubrication in engine systems. Proper viscosity within the standard range facilitates the formation of small fuel droplets and improves fuel atomization, thereby increasing thermal efficiency. In comparison with conventional diesel, biodiesel usually exhibits higher kinematic viscosity (Singh et al., 2019). Table 1 shows that kinematic viscosities of animal-based biodiesels range from 3.39 mm^2/s for camel derived biodiesel (Sbihi et al., 2014) to 6.27 mm^2/s for biodiesel produced from beef tallow (Okwundu et al., 2019).

Table 1. Physical properties of animal-based biodiesels

Biodiesel source	**Density at 15 °C (kg/m^3)**	**Viscosity at 40 °C (mm^2/s)**	**References**
ASTM D6751	880	1.9 – 6.0	(Niu et al., 2025; Tefera et al., 2025)
EN 14214	860 – 900	3.5 – 5.0	
Beef	874	4.58	(Binhweel et al., 2025)
	883	4.8	(Rasouli and Esmaeili, 2019)
	883	4.6	(Ranjitha et al., 2020)
	859	6.27	(Okwundu et al., 2019)
	873	4.5	(Jambulingam et al., 2020)
Lard	-	4.63	(Ezekannagha et al., 2024)
	888	3.89	(Thangthong et al., 2024)
	-	3.89	(Roschat et al., 2020)
Goat	882	4.79	(Khalifeh and Esmaeili, 2021)
	883	4.8	(Rasouli and Esmaeili, 2019)
	890	5.5	(Esmaeili and Foroutan, 2018)
Sheep	875	3.73	(Jayaprabakar et al., 2019)
	865	4.34	(Alajmi et al., 2021)
Fish	844	3.5	(Kannan et al., 2022)
	-	5.14	(Smaisim et al., 2022)

Biodiesel source	Density at 15 °C (kg/m^3)	Viscosity at 40 °C (mm^2/s)	References
	872	4.15	(Shalfoh et al., 2024)
Chicken	869	-	(Ilias et al., 2023)
	-	4.11	(Ge et al., 2021)
	897	5.62	(Odetoye et al., 2021)
Camel	871	3.39	(Sbihi et al., 2014)
Goose	882	-	(Sander et al., 2018)
Duck	878	4.36	(Hamdan et al., 2017)

6. COLD-FLOW PROPERTIES

Cold-flow properties determine fluidity, operability, and performance of the fuel, particularly under low-temperature conditions. They are strongly influenced by the fuel chemical composition. Since animal-based biodiesels generally contain higher levels of SFAs, they tend to exhibit poorer cold-flow behavior. Thus, monitoring and improving these properties, including cloud point and pour point, are essential for ensuring biodiesel suitability and applicability.

6.1 CLOUD POINT

Cloud point is one of the essential characteristics of biodiesel, particularly in regions with cold weather. It is known as the lowest temperature where biodiesel starts to form waxy and cloudy crystals. The fatty acid composition of biodiesel significantly affects its cloud point as biodiesel rich in SFAs tends to rise cloud point, while biodiesel rich in UFAs exhibits lower cloud points. Using biodiesel with a poor high cloud point negatively impacts engine performance, especially in regions experiencing cold climates. At temperatures below the fuel cloud point, waxy crystals aggregate, increasing viscosity, obstructing fuel flow, and clogging the fuel system within the engine. Consequently, fuel combustion becomes uneven, atomization is incomplete, thermal efficiency decreases, emissions increase, and the engine may stall entirely. These effects can be mitigated by using biodiesel with favorable fatty acid profiles, blending it with petroleum-based diesel, or incorporating cold-flow improvers (CFIs) (Hazrat et al., 2020). The literature in Table 2 reveals that the highest cloud point, 15 °C, observed in sheep biodiesel (Jayaprabakar et al., 2019), while the lowest cloud point, -5 °C, is observed in chicken biodiesel (Ge et al., 2021).

6.2 POUR POINT

Pour point is another critical cold-flow property of biodiesel, particularly in regions with low ambient temperatures. It is known as the lowest temperature where biodiesel begins to lose its ability to flow due to the formation of gel-like materials. The pour point of biodiesel is strongly influenced by its fatty acid composition. A higher content of SFAs tends to increase pour point. Consequently, biodiesel derived from animal fats exhibits higher pour points compared to those synthesized from vegetative feedstocks. The solidification mechanism of biodiesel occurs at temperatures below the pour point, where SFAs crystallize, leading to increased viscosity. The effects of pour point on diesel engines are similar to those of cloud point where it disrupts fuel flow, clogs fuel filters and pipes, and results in poor atomization, uneven combustion, higher emissions, and reduced thermal efficiency. To address these challenges, biodiesel industry often selects feedstocks with favorable fatty acid profiles, blends biodiesel with conventional diesel, incorporates CFIs, or applies winterization techniques to meet regulatory standards. In comparison with conventional diesel, biodiesel consistently shows elevated pour point values (Hazrat et al., 2020). Table 2 presents pour points of various animal-based biodiesels, with the highest being 15.5 °C for camel fat biodiesel (Sbihi et al., 2014) and the lowest being -5 °C for fish-based biodiesel (Smaisim et al., 2022).

Table 2. Cold-flow properties of animal-based biodiesels

Biodiesel source	**Cloud point (°C)**	**Pour point (°C)**	**References**
ASTM D6751 EN 14214	-3 to -12	-15 to -16	(Çakırca & Akın, 2025; Tefera et al., 2025)
Beef	11	8	(Binhweel et al., 2025)
	11	8	(Rasouli and Esmaeili, 2019)
	3	- 2	(Ranjitha et al., 2020)
	14	15	(Okwundu et al., 2019)
	7	1	(Jambulingam et al., 2020)
Lard	9	6	(Ezekannagha et al., 2024)
	6	7	(Thangthong et al., 2024)
	8	5	(Roschat et al., 2020)
Goat	7	10	(Khalifeh and Esmaeili, 2021)
	11	8	(Rasouli and Esmaeili, 2019)
	7.85	1.85	(Esmaeili and Foroutan, 2018)
Sheep	15	11	(Jayaprabakar et al., 2019)
	11.2	15	(Alajmi et al., 2021)
Fish	1	-5	(Smaisim et al., 2022)
	3	-7	(Shalfoh et al., 2024)
Chicken	7	-2.08	(Ilias et al., 2023)
	-5	-	(Ge et al., 2021)
Camel	12.7	15.5	(Sbihi et al., 2014)
Goose	-	-	(Sander et al., 2018)

7. THERMAL PERFORMANCE PROPERTIES

Thermal performance properties are the characteristics associated with thermal content and ignition of the fuel. These properties include heating value, flash point, and cetane number which collectively influence the efficiency, ignition quality, and safety of biodiesel.

7.1 HEATING VALUE

Heating value of biodiesel, also referred to as calorific value, represents the total content of energy per unit of mass. It is typically expressed in megajoules per kilogram (MJ/kg). Biodiesel heating value is affected by the length of carbon chain and saturation degree in its fatty acid composition. Longer carbon chains in SFAs correlate with higher heating values, while shorter chains result in lower values. Conversely, an increase in double bonds within UFAs decreases the heating value (Bukkarapu and Krishnasamy, 2022). The oxygenated nature of biodiesel results in a lower heating value compared to conventional diesel, with an estimated energy content reduction of approximately 10% (D. Singh et al., 2019). As shown in Table 3, the greatest heating value of 41.1 MJ/kg is observed in lard-based biodiesel (Ezekannagha et al., 2024), while the lowest one is 35.77 MJ/kg found in biodiesel produced from sheep-fat (Jayaprabakar et al., 2019).

7.2 FLASH POINT

Flash point can be defined as the lowest temperature where biodiesel ignites when contacted with a source of heat. Biodiesel chemical composition significantly influences its flash point, with an emphasis on the length of carbon chain and double bonds. Flash point increases with longer carbon chains but decreases with a higher number of double bonds. Additionally, greater volatility raises the flash point, whereas increasing vapor pressure reduces it. Residual alcohol from the transesterification reaction also affects the flash point where higher alcohol content lowers flash point. In comparison with conventional diesel, biodiesel usually has an elevated flash point, making it safer to store, handle, and transport due to reduced fire risk (Bukkarapu and Krishnasamy, 2022). As shown in Table 3, biodiesel synthesized from beef tallow has the highest flash point of 184 °C (Okwundu et al., 2019), while biodiesel from fish-based feedstock exhibits the lowest value at 84 °C (Kannan et al., 2022).

7.3 CETANE NUMBER

Biodiesel cetane number measures its ignition quality, indicating how quickly and efficiently the fuel combusts in a diesel engine. It plays a crucial role in determining ignition delay, which is the time between injecting biodiesel into combustion chamber and ignition beginning. A higher cetane number corresponds to faster ignition. Therefore, cetane number is considered a critical biodiesel characteristic, particularly for use in both ignition and compression diesel engines. The chemical composition of biodiesel significantly influences its cetane number. It is directly proportional to carbon chain length and the saturation degree of the fatty acids it contains. Additionally, oxygenated content of biodiesel enhances ignition quality and overall combustion efficiency. The cetane number substantially affects biodiesel performance. A reduced cetane number corresponds to longer ignition delays, which cause biodiesel to accumulate in the combustion chamber. This can increase pressure within the chamber, potentially causing damage to engine components. It also results in incomplete combustion, reduced thermal efficiency, and higher NOx emissions. In comparison with conventional diesel, biodiesel usually possesses a higher cetane number. Additionally, animal-based biodiesel typically exhibits a higher cetane number than biodiesel from vegetative-based feedstocks due to the richness of SFAs content in animal fats (Bukkarapu and Krishnasamy, 2022; Pradana et al., 2024). Based on the data collected from literature in Table 3, lard biodiesel has the highest cetane number of 68 (Ezekannagha et al., 2024), while fish-based biodiesel has the lowest value of 48 (Kannan et al., 2022).

Table 3. Thermal performance properties of animal-based biodiesels

Biodiesel source	Heating value (MJ/kg)	Flash point (°C)	Cetane number	References
ASTM D6751	–	> 130	> 47	(Niu et al., 2025; Tefera et al., 2025)
EN 14214	–	> 101	> 51	
Beef	39.32	156	62	(Binhweel et al., 2025)
	-	162	-	(Rasouli and Esmaeili, 2019)
	36.5	160	50	(Ranjitha et al., 2020)
	-	184	-	(Okwundu et al., 2019)
	39.56	138	63	(Jambulingam et al., 2020)
Lard	41.1	135	68	(Ezekannagha et al., 2024)
Goat	-	164	-	(Khalifeh and Esmaeili, 2021)
	-	162	-	(Rasouli and Esmaeili, 2019)
	-	180	-	(Esmaeili and Foroutan, 2018)
Sheep	35.77	178	-	(Jayaprabakar et al., 2019)
		97		(Alajmi et al., 2021)
Fish	39.20	141	55.16	(Shalfoh et al., 2024)
	40.70	84	48	(Kannan et al., 2022)
	-	152	49	(Smaisim et al., 2022)
Chicken	39.63	-	-	(Ilias et al., 2023)
	40.20	170	56	(Ge et al., 2021)
Bovine	-	139	-	(De Freitas et al., 2019)
Camel	39.52	158	58.7	(Sbihi et al., 2014)
Goose	39.83	-	-	(Sander et al., 2018)

8. CHEMICAL STABILITY PROPERTIES

Chemical stability properties are essential for determining biodiesel degradation, oxidation, and reactivity. These properties have significant role to paly in the quality, storage, and usability of the fuel. The chemical stability properties of biodiesel fuel include acid value, FFAs, saponification value, peroxide value, iodine value, and moisture content.

8.1 ACID VALUE

The acid value of biodiesel represents the amount of potassium hydroxide (KOH) in milligrams required to neutralize the FFAs in one gram of the biodiesel sample, and expressed in mg KOH/g. The acid value is considered as an indicator for FFAs content and other acidic compounds existed in biodiesel fuel. It also contributes to the lubricity of biodiesel within the standard limit of 0.5 mg KOH/g. However, higher acid values are not recommended, as they negatively affect the process of biodiesel synthesis and performance in diesel engines. Lipids with higher acid values tend to reduce biodiesel yield and form soap during transesterification. Hence, pretreatment process, like esterification, must be conducted to minimize the acidity of lipids. Biodiesel with an acid value above the specified limit may cause corrosion in fuel delivery systems and harm internal engine parts (Singh et al., 2019). Acid values of biodiesels derived from animal-based feedstocks are presented in Table 4. Based on the data, the highest acid value, 0.48 mg KOH/g, is measured in beef tallow biodiesel (Okwundu et al., 2019), while the lowest, 0.08 mg KOH/g, is measured in lard biodiesel (Thangthong et al., 2024).

8.2 FREE FATTY ACIDS

FFAs are fatty acids that are disconnected from glycerol and existing as free molecules. Each FFA contains a hydrocarbon chain and a carboxyl group at the end of its structure. FFAs can naturally occur in oils and fats or result from hydrolysis, oxidation, and enzymatic degradation of feedstocks. FFAs are often expressed as oleic acid equivalents (% oleic) because oleic acid is a common in oils extracted from plant and animal sources, serving as a reference. Lipids with high levels of FFAs are undesirable because they promote the formation of soap rather than methyl esters during the transesterification reaction. To mitigate this, an acid-catalyzed esterification process is used to convert elevated FFAs into methyl esters. Although there is no standard specification for FFAs in biodiesel, their presence reduces biodiesel quality and can cause corrosion to diesel engine components. Proper storage of biodiesel is crucial to prevent oxidation and hydrolysis reactions, which can regenerate FFAs (Jayaprabakar et al., 2024). Table 4 presents the FFAs values for various animal-based biodiesels, 0.12% for beef tallow biodiesel (Jambulingam et al., 2020), 0.14% for biodiesel synthesized from lard (Ezekannagha et al., 2024) and chicken (Ilias et al., 2023), 0.20% for fish-based biodiesel (Shalfoh et al., 2024), and 0.21% for beef-based biodiesel (Binhweel et al., 2025).

8.3 SAPONIFICATION VALUE

Saponification value of biodiesel refers to the alkali concentration required to saponify a specific amount of biodiesel. It is reported in mg KOH/g of the sample. Saponification value is influenced significantly by fatty acids molecular weights, which correspond to the length of their carbon chains. Shorter carbon chains have lower molecular weights and result in higher saponification values, while longer carbon chains correspond to higher molecular weights and lower saponification values. Therefore, the saponification value serves as an indicator of the carbon chain length in fatty acids. Elevated saponification values are associated with biodiesel having lower viscosity, higher volatility, better cold-flow properties, and enhanced combustion efficiency. Conversely, reduced saponification values indicate higher viscosity and poorer cold-flow properties (Ivanova et al., 2022). The saponification values of animal-based biodiesels, as shown in Table 4, range from the highest value of 218.70 mg KOH/g (Odetoye et al., 2021) to the lowest value of 144 mg KOH/g (Ilias et al., 2023) for biodiesel derived from chicken feedstocks.

8.4 PEROXIDE VALUE

Peroxide value of biodiesel measures the concentration of peroxides and hydroperoxides which are primary oxidation products. It is reported in milliequivalents of active oxygen per kilogram of biodiesel (meq/kg) and serves as an indicator of oxidative stability. Monitoring the peroxide value is crucial for quality control, as it reflects the fuel susceptibility to oxidation. Peroxides and hydroperoxides eventually break down, yielding secondary oxidation products like aldehydes, ketones, and acids. These compounds increase the fuel acidity, negatively impacting biodiesel performance by reducing combustion efficiency and causing potential deposits and corrosion in engine components. Maintaining lower values is essential for fuel durability and engine longevity (Singh et al., 2019; Zhang et al., 2021). Table 4 presents the peroxide value of 8.60 meq/kg for biodiesel derived from fish feedstock, 5.90 meq/kg for chicken-based biodiesel (Ilias et al., 2023), and 2.20 meq/kg for discarded beef tallow biodiesel (Binhweel et al., 2025).

8.5 IODINE VALUE

The iodine value of biodiesel indicates the number of grams of iodine that can react with the double bonds present in 100 grams of the sample. It is reported in g I_2/100 g of sample. The iodine value reflects the degree of unsaturation in biodiesel fuel. Biodiesel with a higher content of UFAs exhibits higher iodine values. Therefore, the iodine value reflects the degree of unsaturation in the fuel. Biodiesel with high iodine value is less desirable because unsaturated esters react with atmospheric oxygen, forming peroxides and hydroperoxide radicals as primary products. These compounds initiate further reactions, resulting in secondary products such as gums, sediments, and deposits. The rate of these oxidative reactions increases at higher temperatures, leading to deterioration of the fuel quality and potential damage to diesel engines due to deposits in injectors and combustion chambers. Biodiesels synthesized from animal-based feedstocks have lower iodine values, which comply with standards, due to their lower content of UFAs (Díez Valbuena et al., 2024). As presented in Table 4, the iodine value for beef based-biodiesel is the lowest at 26.40 g I_2/100 g (Ranjitha et al., 2020), while chicken-based biodiesel has the highest iodine value at 85.49 g I_2/100 g (Ilias et al., 2023).

8.6 MOISTURE CONTENT

Moisture content of biodiesel measures the concentration of water present in a biodiesel sample. This water may originate from the feedstock used for biodiesel synthesis or from the surrounding environment, as biodiesel is hygroscopic and tends to absorb moisture from the air. Additionally, water can be introduced during biodiesel production processes such as preparation, esterification, transesterification, separation, and purification. Elevated moisture levels in oil and biodiesel are considered impurities. Water in oil or biodiesel can exist in the form of dissolved water or as fine suspended droplets. Oil with high moisture content are unsuitable for biodiesel production because water promotes hydrolysis, producing FFAs that react with base catalysts to form soap rather than methyl esters. Moreover, biodiesel with high moisture content negatively affects fuel quality, storage tanks, and diesel engines. High moisture reduces biodiesel heating value, accelerates hydrolysis, promotes microbial growth, and leads to fuel foaming. It can also cause gradual corrosion of storage tanks and reduce combustion efficiency in engines. In cold climates, moisture can crystallize, clogging fuel supply pipes (Aisyah et al., 2019; Zhou, Tse, et al., 2024). Table 4 records moisture contents of 0, 440, 495, and 790 mg/kg for biodiesels produced from camel (Sbihi et al., 2014), beef (Binhweel et al., 2025), bovine (De Freitas et al., 2019), and sheep (Alajmi et al., 2021) feedstocks, respectively.

Table 4. Chemical stability properties of animal-based biodiesels

Biodiesel source	Acid value (mg KOH/g)	FFAs (%)	Saponification value (mg KOH/g)	Peroxide value (meq/kg)	Iodine value (g I_2/100g)	Moisture content (mg/kg)	References
ASTM D6751	< 0.5	–	< 370				(Çakırca & Akın, 2025; Singh et al., 2019; Tefera et al., 2025)
EN 14214	< 0.5	–	–		< 120	< 500	
Beef	0.42	0.21	211	2.20	43.07	440	(Binhweel et al., 2025)
	0.1	–	194.36	-	26.4	-	(Ranjitha et al., 2020)

Biodiesel source	Acid value (mg KOH/g)	FFAs (%)	Saponification value (mg KOH/g)	Peroxide value (meq/kg)	Iodine value (g I_2/100g)	Moisture content (mg/kg)	References
	0.48	–	-	-	43.1	-	(Okwundu et al., 2019)
	0.23	0.12	-	-	-	-	(Jambulingam et al., 2020)
Lard	0.28	0.14	199.7	-	32.42	-	(Ezekannagha et al., 2024)
	0.08	-	-	-	-	-	(Thangthong et al., 2024)
Goat	0.37	-	-	-	-	-	(Roschat et al., 2020)
Sheep	0.10					790	(Alajmi et al., 2021)
Fish	0.40	0.20	158.54	8.60	91.6	–	(Shalfoh et al., 2024)
Chicken	0.28	0.14	144	5.90	85.49	-	(Ilias et al., 2023)
	-	-	-	-	-	-	(Ge et al., 2021)
	0.43	-	218.70	-	57.45	-	(Odetoye et al., 2021)
Bovine	0.12	-	-	-	31	495	(De Freitas et al., 2019)
Camel	-	-	202.3	-	65.3	0	(Sbihi et al., 2014)

9. COMPARING THE PROPERTIES OF ANIMAL AND PLANT-BASED BIODIESELS

Biodiesels derived from animal-based feedstocks exhibit characteristics different from those synthesized from plant-based feedstocks. AFW biodiesels tend to have higher values of density and kinematic viscosity due to their high contents of SAFs and longer chains of carbons. This saturation content also results in higher values in cetane number that improves ignition quality and combustion efficiency within diesel engines. Additionally, the higher content of SFAs enhances oxidative stability of AFW biodiesel, making it more resistant for the degradation and rancidity during storage and transportation. However, these advantages are counterbalanced by the poor cold-flow properties resulted from the high saturation content of AFW biodiesel. These biodiesels exhibit higher values of cloud point and pour point which limit their usability, particularly in cold climates where additional treatments become necessity. Collectively, these characteristics make AFW biodiesels applicable in regions with warm climates and fuel stability is prioritized over cold-flow performance (Osman et al., 2024).

In contrast, plant-based biodiesels contain higher proportions of unsaturated fatty acids, namely MUFAs and PUFAs. This unsaturation condition leads to lower values in density and kinematic viscosity which promote fuel atomization and smoother engine operation. However, unsaturation condition reduces values of cetane number, compromises ignition quality, and degrades fuel during storage. Despite such disadvantages, the good cold-flow properties of plant-based biodiesels make it usable at regions with wide ranges of cold and warm climates since they remain fluid even at the lower temperatures. Hence, biodiesel stabilizers and antioxidants are required wherever plant-based biodiesels are in use to prevent degradation and extend the storage period of the fuel (Binhweel et al., 2021; Osman et al., 2024).

10. CONCLUSION

Biodiesels synthesized from animal fat waste (AFW) exhibit characteristics distinct from those derived from vegetable-based feedstocks and conventional diesel. In terms of chemical composition, AFW biodiesels are rich in saturated fatty acids (SFAs) and monounsaturated fatty acids (MUFAs), with smaller amounts of polyunsaturated fatty acids (PUFAs) inherited from the animal fat source. This composition strongly influences their physicochemical properties. AFW biodiesels typically show higher density, viscosity, and thermal properties, but lower iodine values. Their high SFAs content contributes to superior cetane numbers and oxidative stability while simultaneously worsening cold-flow properties, particularly in colder regions. These limitations can be mitigated through winterization, blending, or the use of cold-flow improvers (CFIs). Optimization studies are highly recommended to achieve the best properties of AFW biodiesels. Furthermore, testing biodiesels derived from AFW feedstocks in diesel engines is strongly encouraged to evaluate their performance. Regardless the properties, AFW represents a viable and affordable second-generation feedstock for sustainable biodiesel production that meets ASTM D6751 and EN 14214 standards.

DATA ACCESSIBILITY STATEMENT

No new datasets were generated or analysed during the current study. All data supporting the findings of this review are derived from previously published sources, which are appropriately cited throughout the manuscript.

AUTHOR CONTRIBUTIONS

Fozy Binhweel: Conceptualization, Data curation, Formal analysis, Visualization, and Writing – original draft. Ehsan Shalfoh: Conceptualization, Formal analysis, and Writing – review and editing. Wardah Senusi: Conceptualization, Data curation, and Writing – review and editing. Sami Alsaadi: Conceptualization, Visualization, and Writing – review and editing.

DECLARATION OF COMPETING INTERESTS

The authors declare no competing financial or personal interests.

FUNDING

The work was supported by the Ministry of Higher Education in Malaysia [FRGS/1/2022/STG05/USM/02/9 (203.PTEKIND.6712137)].

REFERENCES

Abeysinghe, S., Jeong, W. G., Kwon, E. E., & Baek, K. (2025). Use of dairy sludge for biodiesel production and soil amendment. Journal of Cleaner Production, 490, 144731. https://doi.org/10.1016/j.jclepro.2025.144731

Aisyah, L., Bethari, S. A., Wibowo, C. S., Hermawan, N., Alwi, D. U., Rulianto, D., & Anggarani, R. (2019). Water content in biodiesel for diesel fuel blends: Measurement using centrifuge and coulometric titration method. IOP Conference Series: Materials Science and Engineering, 494(1), 012082. https://doi.org/10.1088/1757-899X/494/1/012082

Alajmi, F., Alajmi, A., Alrashidi, A., Alrashidi, N., Adam, N. M., & Hairuddin, A. A. (2021). Development of solar powered biodiesel reactor for kuwait sheep tallow. Processes, 9(9), 1623. https://doi.org/10.3390/pr9091623

Bajpai, D., & Tyagi, V. K. (2006). Biodiesel: Source, Production, Composition, Properties and its Benefits. Journal of Oleo Science, 55(10), 487–502. https://doi.org/10.5650/jos.55.487

Bhuiya, M. M. K., Rasul, M. G., Khan, M. M. K., & Ashwath, N. (2020). Biodiesel production and characterisation of poppy (Papaver somniferum L.) seed oil methyl ester as a source of 2nd generation biodiesel feedstock. Industrial Crops and Products, 152, 112493. https://doi.org/10.1016/j.indcrop.2020.112493

Binhweel, F., Ahmad, M. I., H.P.S., A. K., Hossain, M. S., Shakir, M. A., Senusi, W., Shalfoh, E., & Alsaadi, S. (2024). Kinetics, thermodynamics, and optimization analyses of lipid extraction from discarded beef tallow for bioenergy production. Separation Science and Technology, 1–20. https://doi.org/10.1080/01496395.2024.2387277

Binhweel, F., Ahmad, M. I., & Shakir, M. A. (2025). Harnessing waste lipids for biodiesel: Optimization and thermodynamic investigation of beef tallow transesterification. International Journal of Green Energy, 1–13. https://doi.org/10.1080/15435075.2025.2508474

Binhweel, F., Ahmad, M. I., & Zaki, S. A. (2022). Utilization of Polymeric Materials toward Sustainable Biodiesel Industry: A Recent Review. Polymers, 14(19), 3950. https://doi.org/10.3390/polym14193950

Binhweel, F., Bahadi, M., Pyar, H., Alsaedi, A., Hossain, S., & Ahmad, M. I. (2021). A comparative review of some physicochemical properties of biodiesels synthesized from different generations of vegetative oils. Journal of Physics: Conference Series, 1900(1), 012009. https://doi.org/10.1088/1742-6596/1900/1/012009

Binhweel, F., Hossain, M. S., & Ahmad, M. I. (2023). Recent Trends, Potentials, and Challenges of Biodiesel Production from Discarded Animal Fats: a Comprehensive Review. BioEnergy Research, 16(2), 778–800. https://doi.org/10.1007/s12155-022-10527-w

Bukkarapu, K. R., & Krishnasamy, A. (2022). A critical review on available models to predict engine fuel properties of biodiesel. Renewable and Sustainable Energy Reviews, 155, 111925. https://doi.org/10.1016/j.rser.2021.111925

Çakırca, E. E., & Akın, A. N. (2025). Parametric Study of Biodiesel Synthesis from Waste Cooking Oil Using Ca-Rich Mixed Metal Oxides. ACS Omega, 10(17), 17907–17916. https://doi.org/10.1021/acsomega.5c00916

De Freitas, O. N., Cardoso Rial, R., Fontoura Cavalheiro, L., dos Santos Barbosa, J. M., Domingues Nazário, C. E., & Viana, L. H. (2019). Evaluation of the oxidative stability and cold filter plugging point of soybean methyl biodiesel/bovine tallow methyl biodiesel blends. Industrial Crops and Products, 140, 111667. https://doi.org/10.1016/j.indcrop.2019.111667

Díez Valbuena, G., García Tuero, A., Díez, J., Rodríguez, E., & Hernández Battez, A. (2024). Application of machine learning techniques to predict biodiesel iodine value. Energy, 292, 130638. https://doi.org/10.1016/j.energy.2024.130638

Elgharbawy, A. S., Abdel-Kawi, M. A., Saleh, I. H., Hanafy, M. A., & Ali, R. M. (2025). Optimizing biodiesel production: Energy efficiency and kinetic performance of microwave and ultrasonic transesterification vs. conventional techniques. Biomass and Bioenergy, 193, 107593. https://doi.org/10.1016/j.biombioe.2025.107593

Elgharbawy, A. S., Sadik, W. A., Sadek, O. M., & Kasaby, M. A. (2021). A review on biodiesel feedstocks and production technologies. Journal of the Chilean Chemical Society, 65(1), 5098–5109. https://doi.org/10.4067/S0717-97072021000105098

Esmaeili, H., & Foroutan, R. (2018). Optimization of biodiesel production from goat tallow using alkaline catalysts and combining them with diesel. Chemistry and Chemical Technology, 12(1), 120–126. https://doi.org/10.23939/chcht12.01.120

Ezekannagha, C. B., Onukwuli, O. D., Nnanwube, I. A., Ezeamaku, U. L., & Ohaegbulam, C. M. (2024). Green hetero-alkali catalyst in optimized waste lard oil transesterification for biodiesel synthesis. Results in Chemistry, 11, 101797. https://doi.org/10.1016/j.rechem.2024.101797

Friedlingstein, P., O'Sullivan, M., Jones, M. W., Andrew, R. M., Hauck, J., Landschützer, P., Le Quéré, C., Li, H., Luijkx, I. T., Olsen, A., Peters, G. P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J. G., Ciais, P., Jackson, R. B., Alin, S. R., … Zeng, J. (2025). Global Carbon Budget 2024. In Earth System Science Data (Vol. 17, Issue 3, pp. 965–1039). https://doi.org/10.5194/essd-17-965-2025

Ge, S., Brindhadevi, K., Xia, C., Elesawy, B. H., Elfasakhany, A., Unpaprom, Y., & Doan, H. Van. (2021). Egg shell catalyst and chicken waste biodiesel blends for improved performance, combustion and emission characteristics. Fuel, 306, 121633. https://doi.org/10.1016/j.fuel.2021.121633

Hamdan, S. H., Chong, W. W. F., Ng, J. H., Ghazali, M. J., & Wood, R. J. K. (2017). Influence of fatty acid methyl ester composition on tribological properties of vegetable oils and duck fat derived biodiesel. Tribology International, 113, 76–82. https://doi.org/10.1016/j.triboint.2016.12.008

Hazrat, M. A., Rasul, M. G., Mofijur, M., Khan, M. M. K., Djavanroodi, F., Azad, A. K., Bhuiya, M. M. K., & Silitonga, A. S. (2020). A Mini Review on the Cold Flow Properties of Biodiesel and its Blends. Frontiers in Energy Research, 8. https://doi.org/10.3389/fenrg.2020.598651

IEA. (2023). Transport biofuels – Renewables 2023. International Energy Agency. https://www.iea.org/reports/renewables-2023/transport-biofuels

Ilias, M. K. M., Balakrishnan, V., Zuknik, M. H., Al-Gheethi, A., Ghfar, A. A., & Hossain, M. S. (2023). Supercritical CO2 separation of lipids from chicken by-product waste for biodiesel production: optimization, kinetics, and thermodynamics modeling. Biomass Conversion and Biorefinery, 13(15), 13403–13417. https://doi.org/10.1007/s13399-021-02092-7

Ivanova, M., Hanganu, A., Dumitriu, R., Tociu, M., Ivanov, G., Stavarache, C., Popescu, L., Ghendov-Mosanu, A., Sturza, R., Deleanu, C., & Chira, N. A. (2022). Saponification Value of Fats and Oils as Determined from1H-NMR Data: The Case of Dairy Fats. Foods, 11(10), 1466. https://doi.org/10.3390/foods11101466

Jambulingam, R., Srinivasan, G. R., Palani, S., Munir, M., Saeed, M., & Mohanam, A. (2020). Process optimization of biodiesel production from waste beef tallow using ethanol as co-solvent. SN Applied Sciences, 2(8), 1454. https://doi.org/10.1007/s42452-020-03243-7

Jayaprabakar, J., Dawn, S. S., Anish, M., Giri, J., Sudhakar, K., Alarfaj, A. A., & Guru, A. (2024). Development of Free Fatty Acid (FFA) monitoring device for evaluation of oil samples used for biodiesel production. Heliyon, 10(17), e37118. https://doi.org/10.1016/j.heliyon.2024.e37118

Jayaprabakar, J., Dawn, S. S., Ranjan, A., Priyadharsini, P., George, R. J., Sadaf, S., & Rajha, C. R. (2019). Process optimization for biodiesel production from sheep skin and its performance, emission and combustion characterization in CI engine. Energy, 174, 54–68. https://doi.org/10.1016/j.energy.2019.02.140

Jeliani, Z. Z., Fazelian, N., & Yousefzadi, M. (2021). Introduction of macroalgae as a source of biodiesel in Iran: Analysis of total lipid content, fatty acid and biodiesel indices. Journal of the Marine Biological Association of the United Kingdom, 101(3), 527–534. https://doi.org/10.1017/S0025315421000382

Kannan, B. T., Sathish, T., Sathyamurthy, R., & Erko, K. G. (2022). Use of waste fish oil biodiesel blended with aluminium oxide nanoparticle in IC engines: an experimental on performance, combustion and emission study. Scientific Reports, 12(1), 12930. https://doi.org/10.1038/s41598-022-17059-5

Karmakar, B., & Halder, G. (2019). Progress and future of biodiesel synthesis: Advancements in oil extraction and conversion technologies. Energy Conversion and Management, 182, 307–339. https://doi.org/10.1016/j.enconman.2018.12.066

Khalifeh, R., & Esmaeili, H. (2020). Biodiesel production from goat fat using calcium oxide nanocatalyst and its combination with diesel fuel to improve fuel properties. International Journal of Sustainable Engineering, 14(5), 1–10. https://doi.org/10.1080/19397038.2020.1780336

Kossalbayev, B. D., Kakimova, A. B., Sadvakasova, A. K., Bauenova, M. O., Balouch, H., Lyaguta, M. A., Ahmad, F., Kirbayeva, D. K., Ozgul, S., & Allakhverdiev, S. I. (2025). Strategies for genetic modification of microalgae to improve the production efficiency of liquid biofuel. International Journal of Hydrogen Energy, 100, 1301–1314. https://doi.org/10.1016/j.ijhydene.2024.12.306

Lin, G.-S., Peng, W., Gao, J., Wahlen, A., & Tong, Z. (2023). Functional naturally derived materials to improve the environment: Chemical structures, modifications, applications, and future perspectives (pp. 93–144). https://doi.org/10.1016/bs.aibe.2023.02.001

Mandari, V., & Devarai, S. K. (2022). Biodiesel Production Using Homogeneous, Heterogeneous, and Enzyme Catalysts via Transesterification and Esterification Reactions: a Critical Review. BioEnergy Research, 15(2), 935–961. https://doi.org/10.1007/s12155-021-10333-w

Modi, V., Rampure, P. B., Babbar, A., Kumar, R., Nagaral, M., Bhowmik, A., Pandey, S., Hasnain, S. M. M., Ali, M. M., & Bashir, M. N. (2024). Nanoparticle-enhanced biodiesel blends: A comprehensive review on improving engine performance and emissions. Materials Science for Energy Technologies, 7, 257–273. https://doi.org/10.1016/j.mset.2024.02.001

Nagappan, B., Devarajan, Y., Kariappan, E., Philip, S. B., & Gautam, S. (2021). Influence of antioxidant additives on performance and emission characteristics of beef tallow biodiesel-fuelled C.I engine. Environmental Science and Pollution Research, 28(10), 12041–12055. https://doi.org/10.1007/s11356-020-09065-9

Niu, J., Ou, Q., Chen, Y., Wang, Y., Ling, P., Song, X., & Feng, X. (2025). Comprehensive evaluation of wild Camellia oleifera germplasm for biodiesel production in Hainan Island. Industrial Crops and Products, 232, 121282. https://doi.org/10.1016/j.indcrop.2025.121282

Odetoye, T. E., Agu, J. O., & Ajala, E. O. (2021). Biodiesel production from poultry wastes: Waste chicken fat and eggshell. Journal of Environmental Chemical Engineering, 9(4), 105654. https://doi.org/10.1016/j.jece.2021.105654

Okwundu, O. S., El-Shazly, A. H., & Elkady, M. (2019). Comparative effect of reaction time on biodiesel production from low free fatty acid beef tallow: a definition of product yield. SN Applied Sciences, 1(2), 140. https://doi.org/10.1007/s42452-018-0145-1

Osman, W. N. A., Rosli, M. H., Mazli, W. N. A., & Samsuri, S. (2024). Comparative review of biodiesel production and purification. Carbon Capture Science & Technology, 13, 100264. https://doi.org/10.1016/j.ccst.2024.100264

Pradana, Y. S., Makertihartha, I. G. B. N., Indarto, A., Prakoso, T., & Soerawidjaja, T. H. (2024). A Review of Biodiesel Cold Flow Properties and Its Improvement Methods: Towards Sustainable Biodiesel Application. Energies, 17(18), 4543. https://doi.org/10.3390/en17184543

Ramos, M. J., Fernández, C. M., Casas, A., Rodríguez, L., & Pérez, Á. (2009). Influence of fatty acid composition of raw materials on biodiesel properties. Bioresource Technology, 100(1), 261–268. https://doi.org/10.1016/j.biortech.2008.06.039

Ranjitha, J., Gokul Raghavendra, S., Vijayalakshmi, S., & Deepanraj, B. (2020). Production, optimisation and engine characteristics of beef tallow biodiesel rendered from leather fleshing and slaughterhouse wastes. Biomass Conversion and Biorefinery, 10(3), 675–688. https://doi.org/10.1007/s13399-019-00501-6

Rasouli, H., & Esmaeili, H. (2019). Characterization of MgO nanocatalyst to produce biodiesel from goat fat using transesterification process. 3 Biotech, 9(11), 429. https://doi.org/10.1007/s13205-019-1963-6

Roschat, W., Phewphong, S., Moonsin, P., Pholsupho, P., & Yapan, S. (2020). Physicochemical properties of biodiesle product derived from lard oil using eggshells as a green catalyst. Suranaree Journal of Science and Technology, 27(3), 030025-1-030025–030028.

Rustan, A. C., & Drevon, C. A. (2005). Fatty Acids: Structures and Properties. In Encyclopedia of Life Sciences. Wiley. https://doi.org/10.1038/npg.els.0003894

Sander, A., Košćak, M. A., Kosir, D., Milosavljević, N., Vuković, J. P., & Magić, L. (2018). The influence of animal fat type and purification conditions on biodiesel quality. Renewable Energy, 118, 752–760. https://doi.org/10.1016/j.renene.2017.11.068

Sbihi, H. M., Nehdi, I. A., Tan, C. P., & Al-Resayes, S. I. (2014). Production and characterization of biodiesel from Camelus dromedarius (Hachi) fat. Energy Conversion and Management, 78, 50–57. https://doi.org/10.1016/j.enconman.2013.10.036

Shalfoh, E., Ahmad, M. I., Binhweel, F., Shaah, M. A., Senusi, W., Hossain, M. S., & Alsaadi, S. (2024). Fish waste oil extraction using supercritical CO2 extraction for biodiesel production: Mathematical, and kinetic modeling. Renewable Energy, 220, 119659. https://doi.org/10.1016/j.renene.2023.119659

Sharma, V., Das, L., Pradhan, R. C., Naik, S. N., Bhatnagar, N., & Kureel, R. S. (2011). Physical properties of tung seed: An industrial oil yielding crop. Industrial Crops and Products, 33(2), 440–444. https://doi.org/10.1016/j.indcrop.2010.10.031

Singh, D., Sharma, D., Soni, S. L., Sharma, S., & Kumari, D. (2019). Chemical compositions, properties, and standards for different generation biodiesels: A review. Fuel, 253, 60–71. https://doi.org/10.1016/j.fuel.2019.04.174

Singh, S. P., & Singh, D. (2010). 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, 14(1), 200–216. https://doi.org/10.1016/j.rser.2009.07.017

Smaisim, G. F., Prabu, N. M., A P, S., & Abed, A. M. (2022). Synthesis of biodiesel from fish processing waste by nano magnetic catalyst and its thermodynamic analysis. Case Studies in Thermal Engineering, 35, 102115. https://doi.org/10.1016/j.csite.2022.102115

Tefera, N. T., Nallamothu, R. B., Lakew, G. A., & Kurse, T. K. (2025). Optimization of biodiesel production from cottonseed oil using response surface methodology and artificial neural network techniques. Scientific African, 28, e02665. https://doi.org/10.1016/j.sciaf.2025.e02665

Thangthong, A., Roschat, W., Pholsupho, P., Thammayod, A., Phewphong, S., Leelatam, T., Moonsin, P., Yoosuk, B., Janetaisong, P., & Promarak, V. (2024). Physicochemical properties of lard oil and rubber seed oil blends and their comprehensive characterization. Chinese Journal of Chemical Engineering, 75, 1–13. https://doi.org/10.1016/j.cjche.2024.07.010

Zeng, Z., Qin, X., Wang, H., Chen, Z., Huang, D., Xiang, D., & Liu, X. (2024). Effect of the chemical composition and structural properties of beef tallow from different adipose tissues on bread quality. Lwt, 192, 115736. https://doi.org/10.1016/j.lwt.2024.115736

Zhang, N., Li, Y., Wen, S., Sun, Y., Chen, J., Gao, Y., Sagymbek, A., & Yu, X. (2021). Analytical methods for determining the peroxide value of edible oils: A mini-review. Food Chemistry, 358, 129834. https://doi.org/10.1016/j.foodchem.2021.129834

Zhou, L., Tse, T. J., Shen, J., Meda, V., & Reaney, M. J. T. (2024). Water-modification of micro- and nano-adsorbents: A strategy for enhancing biodiesel refining efficiency. Energy Conversion and Management: X, 23, 100592. https://doi.org/10.1016/j.ecmx.2024.100592

Zhou, L., Zhang, T., Zheng, M., Wang, S., Li, B., Hu, Z., Nie, Q., He, D., Hu, C., Zheng, J., Lei, F., & Zhang, Q. (2024). Physicochemical properties and flavor substances analyses of refined beef tallow with dry fractionation treatment. Food Chemistry, 460, 140736. https://doi.org/10.1016/j.foodchem.2024.140736