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Article

# A Comparative Review of Vegetative and Animal-Based Biodiesel: Feedstock Selection, Synthesis Method, Characterization Technique, and Economic Perspective

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**Abstract:** The urgent need for sustainable energy solutions has intensified research into biodiesel as a viable alternative to fossil fuels. With rising concerns over greenhouse gas emissions and energy security, biodiesel derived from renewable feedstocks presents a promising pathway toward low-carbon development. However, the selection of optimal feedstocks and efficient extraction techniques remains critical to enhancing its economic viability and environmental sustainability. This review explores biodiesel production from both vegetative and animal-based feedstocks, focusing on their potential as renewable energy sources. Key extraction techniques, including mechanical, solvent, and advanced methods are critically examined for their effectiveness in lipid extraction. The review further evaluates five biodiesel production methods: transesterification, supercritical transesterification, pyrolysis, blending, and micro-emulsification, with a particular focus on transesterification due to its efficiency and favorable outcomes. The study emphasizes the physicochemical properties of biodiesel, ensuring compliance with ASTM 6751 and EN 14214 standards. By providing a comprehensive assessment of feedstock availability, process efficiency, and sustainability considerations, this review contributes to advancing the role of biodiesel in the transition toward climate-friendly energy solutions. The findings reinforce the role of biodiesel in mitigating climate change by reducing dependency on fossil fuels and promoting circular bioeconomy practices.

**Keywords:** biodiesel; vegetative feedstock; animal feedstock; physicochemical properties; sustainable energy

## 1. Introduction

The rising demand for energy has led to the swift depletion of limited petroleum reserves, exacerbating global warming and climate change two major challenges of the 21st century. Consequently, the decline of fossil fuel resources and their adverse environmental effects have fueled extensive research into identifying and developing sustainable and renewable energy alternatives (Bashir et al., 2022). Biofuels offer a promising avenue for mitigating both environmental pollution and energy-related concerns. Biodiesel has garnered substantial attention due to its potential as a renewable, eco-friendly alternative to conventional diesel (Neupane, 2023; Senusi et al., 2024a). Biodiesel serves as a versatile resource for the synthesis of various industries like lubricants and detergents. It is obtained from various natural sources, including edible animal waste fat, non-edible oils, and frying oils. The utilization of biodiesel presents an opportunity to address environmental challenges by recycling the $CO_2$ emitted during combustion via photosynthesis. This has the potential to mitigate the carbon dioxide effect and to enhance the protection of the environment. Notably, the advantages of biodiesel include its superior lubrication qualities, biodegradability, minimal sulphur content, and exceptional safety features. These attributes help to significantly decrease engine component wear, thereby extending the overall longevity of the engine (Mishra and Goswami, 2018; Ogunkunle and Ahmed, 2019; Gadore, Mishra and Ahmaruzzaman, 2024).

Nevertheless, animal fat waste can be selected as a preferred feedstock to avoid competing with the food supply. It is readily accessible from industrial and municipal sources (Mohiddin et al., 2021). A 2013 survey revealed that nearly 1.2 billion chickens were consumed in Turkey, generating substantial waste. Approximately 25% of this waste was processed through rendering, yielding around 100 million kilograms of chicken fat each year. Repurposing animal fat waste for biodiesel production eliminates disposal concerns while providing a cost-effective, economical, and environmentally friendly energy source. Compared to biodiesel derived from vegetable oils, biodiesel produced from animal fats boasts a higher cetane number due to its elevated saturated fatty acid content. This composition enhances oxidation stability and reduces nitrogen oxide ($NO_x$) (Alajmi et al., 2018; Hewavitharana et al., 2020; Binhweel, Ahmad and Shakir, 2025). Disposing of significant amounts of animal waste significantly affects both environmental safety and public health. These wastes, not only characterized by their strong odour and rapid decomposition but also laden with nutrients and potential pathogens, pose a risk of polluting soil, surface water, ground, and atmosphere. Despite these challenges, the nutrients within animal waste represent a valuable resource that can be reclaimed and employed. Besides containing significant moisture content, the key recoverable components of these waste materials are fat and other added value compounds. The fats extracted from the discarded skin of various animals, such as beef, fish, pigs, cattle, sheep, camel, and chickens, are notably rich in fatty acids (FAs) and exhibit favourable combustion properties, boasting a high net calorific value (Sbihi et al., 2014a; Mohiddin et al., 2018; J. Jayaprabakar et al., 2019; Cheng et al., 2021; Dias, Ramos and Rijo, 2022).

It is unclear if biodiesel made from edible and non-edible oils will be around long-term because it has problems like competing with food products and being pricier than fossil diesel. Presently, feedstock expenses account for nearly 80% of the total biodiesel production cost, emphasizing the urgent need for more economical alternatives. In response, researchers have increasingly turned their attention to animal fat as a promising low-cost feedstock, particularly from abundant sources like beef tallow and chicken fat. The primary advantage of utilizing waste animal fat (WAF) for biodiesel production lies in its affordability, making it a cost-effective alternative to conventional feedstocks while simultaneously mitigating disposal concerns (Senusi et al., 2024b). Moreover, the transesterification process for WAF is significantly less expensive than that of vegetable oils, further enhancing its economic feasibility. To ensure the large-scale commercial success of biodiesel, it is crucial to prioritize using low-cost raw materials and implement efficient processing technologies. A well-structured biodiesel supply chain plays a vital role in maximizing the economic and environmental benefits of biodiesel (Ivana B. Banković-Ilić et al., 2014; Habib et al., 2020; Mwenge et al., 2025)

In this context, this review offers a thorough analysis of recent progress in using animal fat waste for biodiesel production. It narratively categorizes the extraction techniques based on their efficiency in isolating key fuel constituents and critically examines the strengths and limitations of solvent-based and solvent-free approaches. Furthermore, it delves into recent advancements in extraction technologies and biodiesel synthesis methods, particularly emphasizing comparative outcomes between animal-based and plant-based feedstocks. Beyond extraction, emerging innovations in biodiesel synthesis are explored with a particular focus on optimizing animal-based biodiesel production. The study further examines the physicochemical properties of biodiesel derived from animal fats, benchmarking them against industry standards. Additionally, it offers an in-depth assessment of prospects, addressing techno-economic feasibility and strategies to enhance yield and sustainability. Previous works studied solely animal-based biodiesel or vegetative-based biodiesel. The current work is distinguished by bringing both animal-based and vegetative-based biodiesels into discussion. The study compared and integrated both feedstocks as potential, viable, cost-effective, and sustainable feedstocks, contributing to advancing circular bioeconomy and renewable energy solutions.

## 2. Vegetative and Animal Feedstocks for Biodiesel Production

The most common feedstocks utilized in the manufacturing of biodiesel and green diesel are triacylglycerols (also known as triglycerides), which are present in both vegetable oils and animal fats (Hájek et al., 2021; Abdulhussein Alsaedi et al., 2022). Animal fats provide a sustainable and economical feedstock for biodiesel production, serving as by-products of the meat industry and contributing to reducing environmental waste. Besides reducing production costs, animal fat-based biodiesel generally demonstrates an elevated cetane number and circumvents competition with food crops, thereby complying with circular economy and sustainability (Tabinda et al., 2024; Amal and Nizamuddin, 2025). Conversely, Vegetable oils, particularly soybean, and palm, are extensively utilized for biodiesel production owing to their abundant availability and established agricultural supply lines. These feedstocks provide a dependable source of biodiesel with advantageous chemical characteristics; nevertheless, their utilization may conflict with food production and might result in deforestation in certain areas, necessitating investigation into animal waste fat (Baharak Sajjadi, Abdul Aziz and Arandiyan, 2016; Almahdi, Al-abbasi and Almaki, 2024; Gerveni, Irwin and Hubbs, 2024).

A comprehensive study of animal fats and vegetable oils demonstrates notable disparities across various categories. Table 1 explores a comparative analysis of animal-based and vegetative-based feedstocks for biodiesel production. Animal fats provide a consistent year-round supply as by-products of established meat industries, but the availability of vegetable oils is contingent upon cyclical agricultural cycles. Animal fats are more economically advantageous, costing roughly US$ $0.4–0.5 per liter, but vegetable oils are priced at US$ $0.6–0.8 per liter. Furthermore, animal fats mitigate the food-versus-fuel dilemma by utilizing waste materials, while vegetable oils compete with food resources, intensifying food security difficulties. Animal fats promote waste reduction and diminish greenhouse gas emissions,but cultivating vegetable oils frequently leads to deforestation and heightened demand for land and water resources. Despite increasing interest in the use of animal fats, their industrial application remains limited, primarily confined to pilot-scale operations. At the same time, vegetable oils benefit from a robust worldwide infrastructure that ensures excellent scalability. Vegetable oil-based biodiesel is more developed and broadly endorsed, whereas animal fat-based biodiesel has benefits, including elevated cetane levels and enhanced oxidative stability. Biodiesel derived from vegetable oils exhibits superior cold flow qualities. However, it often has a lower cetane rating. These disparities highlight the necessity for context-specific selection of feedstocks to optimize cost, performance, and sustainability (Ivana B. Banković-Ilić et al., 2014; Kianimanesh, Abbaspour-Aghdam and Derakhshan, 2017; Shahzad et al., 2017; Alajmi et al., 2018; Toldrá-Reig, Mora and Toldrá, 2020b; Abdul Hakim Shaah et al., 2021; Sohrab Hossain et al., 2021; Aniokete, Sadare and Daramola, 2022; Yaashikaa, Kumar and Karishma, 2022; Binhweel, Hossain and Ahmad, 2023).

***Table 1.*** Comparative assessment of vegetative - animal- based feedstock for biodiesel production.

| Criteria | Animal fats | Vegetative oils | References |
|---|---|---|---|
| **Availability** | Animal fats are continuously sourced from slaughterhouses and meat processing facilities. | Availability of vegetable oils Seasonal, contingent upon agricultural cycles | (Alajmi et al., 2018; Yaashikaa, Kumar and Karishma, 2022) |
| **Economic Cost** | Lower (US $0.4–0.5 per liter | Higher (US $0.6–0.8 per liter) | (Aniokete, Sadare and Daramola, 2022) |
| **Food versus fuel competitions** | The animal fats are little, they utilize waste by-products. | Vegetable oils pose a substantial clash with the food supply. | (Ivana B. Banković-Ilić et al., 2014; Abdul Hakim Shaah et al., 2021) |
| **Environmental impact** | Animal fats reduce landfill waste and greenhouse gas emissions. | Vegetable oils results in deforestation and significant land and water consumption. | (Abdul Hakim Shaah et al., 2021)(Shahzad et al., 2017) |
| **Technological maturity** | Although there is a burgeoning interest in animal fats, their economic availability remains constrained. | highly advanced, supported by a global infrastructure | (Kianimanesh, Abbaspour-Aghdam and Derakhshan, 2017; Binhweel, Hossain and Ahmad, 2023) |
| **Scalability** | moderate level, primarily in pilot or demonstration size. | high, with global commercialization | (Singh and Singh, 2010; Alptekin, Canakci and Sanli, 2014) |
| **Biodiesel quality** | Increased cetane number; enhanced oxidative stability | Improved cold flow; reduced cetane number. whereas | (Sohrab Hossain et al., 2021), (Toldrá-Reig, Mora and Toldrá, 2020b), (Silva et al., 2013) |

## 3. Lipid Extraction Techniques

The three main methods have been identified for oil/lipids extraction, including (i) Solvent Extraction, (ii) Mechanical Extraction, and (iii) Advanced Extraction. Figure 1 shows the types of lipid extraction methods.

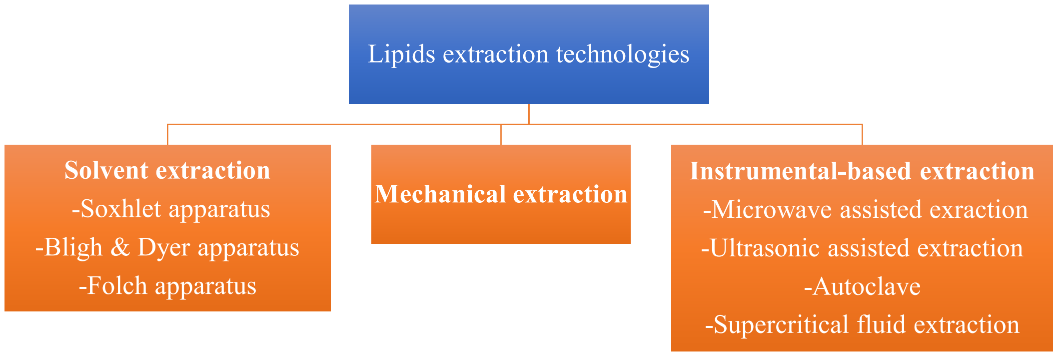


***Figure 1.*** Lipid extraction techniques from vegetative and animal-based feedstock.

### *3.1. Solvent-Based Extraction*

#### 3.1.1. Soxhlet Extraction

Soxhlet extraction has endured as a venerable method for extracting various volatile compounds from solid samples, including the separation of oils. The technique has stood the test of time and was recognized as a reference for numerous contemporary extraction methods (Bhargavi, Nageswara Rao and Renganathan, 2018; Shakir, Yhaya and Ahmad, 2017). In addition, this method proves superior compared to traditional approaches, save for thermolabile compound extraction. It utilizes a porous carrier termed a "thimble," typically crafted from filter paper or cellulose, to secure the plant material. The extraction solvent is introduced into the thimble, positioned on a designated holder. Heat is then applied to the sample-containing thimble within a bottom flask, causing solvent evaporation, condensation, and subsequent return into the flask. As the extraction chamber reaches the highest capacity, an automatic syphon empties it, facilitating solvent flow back to the boiling flask. This cycle repeats until a concentrated extract is obtained (Mat Yasin, Ahmad and Mohd Hanapi, 2021; Ebrahim, 2023). Despite its simplicity and directness, the Soxhlet extraction method has limitations that restrict its utility. One notable drawback is its time-consuming nature, requiring a minimum of 6 hours and sometimes up to 24 hours for specific extraction processes. Additionally, it involves multiple steps, such as preparing the thimble of the sample, setting up the connection between the three components, and the final separation process utilizing a vacuum rotary evaporator, all of which demand extra effort. Furthermore, using organic solvents in these extractions carries environmental risks due to their toxicity. Moreover, the flammable and hazardous nature of these chemicals represents a safety hazard to personnel (Binhweel, Hossain and Ahmad, 2023).

#### 3.1.2. Bligh & Dyer Extraction

This straightforward method for extracting lipids from organic materials by providing quick outcomes (Eg, 1959). Using the Bligh and Dyer extraction method, biological tissues are mixed in a very specific way with chloroform, methanol, and water in a ratio of 2:2:1.8. The lipid-rich chloroform layer stands out from the non-lipid methanol-water layer because of this process. The lipids are subsequently extracted from the chloroform phase. Originally designed for lipid extraction and purification from fish tissue, this method has been adapted for a broader range of wet organic materials, such as fats, meats, and various food products. Over time, modifications have incorporated alternative organic solvents, such as ethanol and ethyl acetate, either as substitutes for or in combination with chloroform and methanol. These refinements have maintained the method’s simplicity and efficiency, enabling lipid recovery rates of up to 95%. Additionally, the process is cost-effective, as it requires minimal solvent consumption, with the added advantage that the solvents can be reclaimed and reused, further enhancing its economic and environmental feasibility (Ebrahim, 2023).

### 3.1.3. Folch Extraction

The Folch method employs a chloroform-methanol mixture (2:1 v/v) to extract lipids from animal fat. The process starts with lipid extraction using this solvent blend, followed by the addition of water to facilitate phase separation. The extracted lipids are then recovered through rotary evaporation. Importantly, this technique operates without the need for elevated temperatures or pressures, making it a reliable method for lipid extraction. While Folch is suitable for extracting lipids from numerous samples, its limitation is employing more hazardous reagents, posing risks to both human health and the environment (Zhou et al., 2022). Despite its speed and simplicity, the Folch method is less hazardous compared to other total lipid extraction methods (Bhargavi, Nageswara Rao and Renganathan, 2018).

## *3.2. Mechanical-Based Extraction*

The oldest methods for oil extraction involve mechanical presses or expellers. Mechanical expression entails forcefully extracting oil from the oleaginous material by applying pressure, whether through hydraulic or screw presses (Bhargavi, Nageswara Rao and Renganathan, 2018). Mechanical extraction is the primary method employed for extracting oil from edible seeds. This process involves pressing and crushing the seeds using a screw press or rotary press. It's important to note that mechanical pressing can only handle one type of feedstock at a time. The oil yield obtained through this technique depends on the seed's oil content and the pressure applied during processing. Excessive pressure can lead to seed rupture, facilitating the release of oil (Yaashikaa, Kumar and Karishma, 2022). Moreover, the typical approach for commercial Jatropha oil extraction involves mechanical pressing. When comparing mechanical pressing to solvent extraction, mechanical extraction is more favourable over solvent extraction. Despite yielding less oil, mechanical pressing is preferred due to its lower cost and greater safety. Unlike solvent extraction, mechanical pressing doesn't necessitate solvent separation and avoids the use of hazardous materials (Yate et al., 2020). Despite the advantages of mechanical extraction, this method has several drawbacks, including high residual oil content in the seed cake, limited efficiency, and the requirement for elevated temperatures (Yaashikaa, Kumar and Karishma, 2022).

## *3.3. Instrumental-Based Extraction*

### 3.3.1. Autoclave

The use of autoclave as an extraction method for the animal fat residue is increasingly capturing attention due to its simplicity. By employing an autoclave device, temperature and pressure are applied to the sample, causing the fatty masses to transform into liquid oil. While autoclaves are primarily intended for sterilization through temperature and pressure, they can also efficiently extract lipids using these same principles. Time also crucial role in the prediction of the yield percentage extracted from the animal-based fat residue. Notably, since no direct heat source is applied to the fat during autoclave treatment, the composition of fatty acids remains intact, offering a distinct advantage for this extraction method (Binhweel, Hossain and Ahmad, 2023).

### 3.3.2. Ultrasonic Assisted Extraction

Ultrasound-assisted extraction (UAE) is an advanced and widely recognized technique that aligns with the principles of sustainable "green" chemistry. This method utilizes ultrasonic waves to generate acoustic energy within a liquid medium, creating alternating high- and low-pressure cycles. During the low-pressure phase, microscopic vacuum bubbles form, which subsequently collapse with immense force during the high-pressure phase, leading to a phenomenon known as cavitation. This cavitation process generates intense localized pressure and powerful liquid microjets, which effectively break down the cellular structure of the targeted material. The resulting cell disruption significantly improves mass transfer efficiency, making UAE particularly effective for extracting lipids, especially from animal fat tissues. This enhanced extraction capability, combined with its environmentally friendly nature, makes UAE a promising approach for sustainable lipid recovery (Pikula et al., 2020). Previous studies utilizing ultrasound-assisted extraction have demonstrated the method's superiority over conventional lipid extraction techniques. Furthermore, the fatty acid composition obtained through ultrasound extraction remains largely unchanged, indicating minimal distortion caused by the application of ultrasound waves. The resulting fatty acids exhibit characteristics nearly identical to those obtained through the traditional Soxhlet method. This contemporary extraction approach is regarded as environmentally friendly due to its minimal solvent usage. The effectiveness of the method is evident in the high yield of undistorted fatty acids achieved within a short extraction time, highlighting its efficiency and eco-friendly nature as its major advantages (Binhweel, Hossain and Ahmad, 2023).

### 3.3.3. Microwave Assisted Extraction

Microwave-assisted extraction (MAE) is an advanced technique that utilizes microwave radiation to enhance the extraction process by generating heat. Operating within a frequency range of 300 MHz to 300 GHz, microwaves produce heating through the absorption of electromagnetic waves in the extraction medium. The efficiency of energy transfer is influenced by the electric field strength and the dielectric properties of the material being processed. Unlike conventional heating, where thermal energy is transferred from an external heat source to the medium, microwave heating generates heat directly within the irradiated material through energy dissipation. This internal heating mechanism makes microwave-assisted extraction significantly more efficient than traditional methods such as electrical resistance heating or thermal conduction, allowing for a much faster temperature rise. When edible oils are being extracted, microwaves are used to heat the sample. This is done mainly through two mechanisms: ionic conduction and dipole rotation. These mechanisms cause molecular agitation, leading to an increase in temperature and facilitating the release of lipids from the material. In recent years, MAE has gained widespread attention as an efficient method for oil extraction. Studies have demonstrated its effectiveness in continuous extraction systems, successfully extracting oils from various feedstocks, including soybeans and rice bran (Ibrahim, Omilakin and Betiku, 2019; Geow et al., 2021). Additionally, MAE has been successfully utilized for oil extraction from algal biomass, soybean, and rice bran. This technique enables the recovery of over 95% of the oil within just 20 minutes, whereas conventional solvent extraction and other traditional methods typically require several hours. A continuous MAE system has also demonstrated its effectiveness in extracting algal oil, achieving up to 77% lipid recovery from *S. obliquus* within 20 to 30 min using a 1:1 weight-to-volume ratio of algae to water (Kant Bhatia et al., 2021).

### 3.3.4. Supercritical Fluid Extraction (SFE)

Supercritical fluid extraction is a highly efficient technique that utilizes supercritical fluids, which exist in a unique state where they simultaneously exhibit the properties of both liquids and gases. This occurs when the fluid is subjected to temperatures and pressures that exceed its critical point (Ishwarya and Nisha, 2021). The low viscosity and high diffusivity of supercritical fluids facilitate diffusion and mass transfer, leading to a significant reduction in the extraction time (Uwineza and Waśkiewicz, 2020; Binhweel et al., 2024). Supercritical carbon dioxide stands as the predominant supercritical fluid employed in food processing applications. Its utilization is favored due to various advantages, notably its affordability, ready availability in pure form, and innocuous nature. Operating at lower temperatures during processing conserves the composition of heat-labile compounds, ultimately enhancing the quality and functional properties of the extracted compounds (Khaw et al., 2017). In addition, SFE has been widely employed in oil extraction processes. The incorporation of co-solvents such as water, ethanol, and methanol serves to augment the solubility capacity of carbon dioxide, facilitating the extraction of polar compounds more effectively (Picot-Allain et al., 2021). Supercritical fluid extraction (SFE) involves two key stages: solute extraction from the sample and the subsequent separation process. Initially, the fluid is heated and pressurized until it reaches its supercritical state before being introduced into the reactor. Inside the reactor, the supercritical fluid effectively dissolves and extracts the target compounds from the sample. The extracted solute is then separated in a designated separator, where the fluid undergoes decompression and returns to its gaseous state. In this phase, the solubility of the solute in the fluid diminishes, allowing it to separate naturally through gravity. As a result, the extracted compound accumulates at the bottom of the separator for collection, while the gaseous fluid can either be recycled for further use or safely released into the atmosphere (Geow et al., 2021). As an example, In recent research, the rubber seed oil was extracted using supercritical dimethyl ether (DME) with a yield of 41% (wt.) (Boonnoun et al., 2019).

The comparative analysis of diverse lipid extraction methods is provided in Table 2. It demonstrates notable variations in lipid production, scalability, toxicity, and energy requirements, contingent upon the technique and feedstock. Solvent-based extraction methods, such as Soxhlet, Folch, and Bligh & Dyer, proved the highest lipid yields, ranging from 75.4% to 98.8% (Yaashikaa, Kumar and Karishma, 2022; Demesa et al., 2024) The Soxhlet extraction of Phoenix tree seeds a yield of 98.8%, demonstrating its efficiency (Khan et al., 2021). However, solvent-based methods are typically limited to lab-scale applications because of high toxicity and moderate to high energy requirements, which constrain their practical scalability and environmental sustainability. Conversely, mechanical extraction by a screw press results in much reduced lipid content reaching 25.39% for Jatropha seeds (Yate et al., 2020), yet provides enhanced scalability and diminished toxicity, rendering it more suitable for industrial applications despite moderate to high energy used. Instrumental techniques such as ultrasonic, microwave, and supercritical extraction provide a balance between yield and operational sustainability.

Ultrasonic and microwave methods generate intermediate lipid outputs reaching 63.48% and 72.20%, respectively, exhibiting medium scalability, moderate toxicity, and reduced energy requirements relative to solvent-based methods (Ideris et al., 2021; Yaashikaa, Kumar and Karishma, 2022; Demesa et al., 2024; Lozano Pérez, Lozada Castro and Guerrero Fajardo, 2024). Supercritical $CO_2$ extraction, albeit less hazardous and scalable, is advantaged by significant energy consumption, as evidenced by the 77.2,86.10, and 41% yield in fish waste, discarded beef tallow, and rubber seed extraction respectively. Although Jatropha Curcas seeds purportedly get a 100% yield with this method, such outcomes require careful interpretation due to possible discrepancies or exaggerated lab circumstances. The choice of an extraction method must equilibrate yield efficiency, environmental effect, scalability, and energy consumption, highlighting the necessity for additional research into more sustainable, scalable alternatives that provide high lipid (Boonnoun et al., 2019; Hassim et al., 2021; Singh et al., 2021; Binhweel, Ahmad and Shakir, 2025; Shalfoh et al., 2025). Therefore, Table 2 provides a structured comparison of these extraction methods, offering insight into their performance, limitations, and industrial applicability.

***Table 2.*** Comparison of lipid extraction techniques based on yield, scalability, toxicity, and energy demand.

| Extraction principle | Extraction method | Feedstock | Lipid yield (%) | scalability | toxicity | Energy Demand | Reference |
|---|---|---|---|---|---|---|---|
| **Solvent-based extraction** | Soxhlet | Phoenix tree seed | 98.8 | Limited-lab scale | High | Modrate - high | (Khan et al., 2021; Yaashikaa, Kumar and Karishma, 2022; Demesa et al., 2024) |
| | | Cow fat | 95.3 | - | - | - | |
| | Folch | Goat fat | 93.8 | Limited-lab scale | High | Moderate - high | |
| | Bligh & Dyer | Lamb fat | 75.4 | Limited-lab scale | High | Moderate - high | |
| **Mechanical based extraction** | Mechanical screw press | Jatropha seed | 25.39 | High | Low | Moderate - high | (Yate et al., 2020) |
| **Instrumental based extraction** | Ultrasonic | Kernel (*Canarium Odontophyllum*) | 63.48 | Medium | Medium | Low-modrate | (Ideris et al., 2021; Demesa et al., 2024) |
| | Microwave | Sanbox seed oil | 72.20 | Medium | Medium | Modrate | (Yaashikaa, Kumar and Karishma, 2022; Lozano Pérez, Lozada Castro and Guerrero Fajardo, 2024) |
| | Autoclave | Yellowfin tuna heads | 12.80 | | | | (Lanka, Lanka and Jayewardenepura, 2022) |
| | Supercritical extraction | Rubber seed | 41 | Medium | Low | High | (Boonnoun et al., 2019) |
| | | Fish waste | 77.2 | | | | (Shalfoh et al., 2025) |
| | | Discarded beef tallow | 86.10 | | | | (Binhweel, Ahmad and Shakir, 2025) |
| | | Jatropha Curcas seeds | 100 | | | | (Hassim et al., 2021; Singh et al., 2021) |

Additionally, a summary of the key advantages and disadvantages associated with each extraction technique is presented in Table 3**.** This comparison helps to contextualize their operational feasibility, safety concerns, and economic or environmental trade-offs, further guiding the selection of appropriate methods for biodiesel feedstock processing.

***Table 3.*** The advantages and disadvantages of the lipid extraction methods.

| **Extraction Method** | **Benefits** | **Drawbacks** | **Reference** |
|---|---|---|---|
| **1: Solvent extraction** | | | |
| Soxhlet | • Inexpensive straightforward operation efficient extraction | • Extended extraction duration, substantial reagent usage, and energy consumption are notable drawbacks. | |
| Folch | • Quick and convenient for processing a large volume of samples, with a gentle overall process. | • Posing risks to both human health and the environment, Hazardous reagents are utilized. | (Zhou et al., 2022; Rashd et al., 2024) |
| Bligh& Dyer | • separation can be simultaneously accomplished and lipid extraction | • These extractive agents are toxic and have limited alternatives, resulting in high costs. | |
| **2: Mechanical extraction** | • The need for fresh oil is higher. | • Requires additional time and labor. | (Mohiddin et al., 2021) |
| | • Operating costs are comparatively lower. | • Produces comparatively lower oil yield. | |
| **3: Instrumental Extraction** | | | |
| Supercritical Fluid Extraction | • Sustainable technology.<br>• Does not use toxic organic solvent. | • The cost for the equipment is high. | (Subroto et al., 2017; Abdul Hakim Shaah et al., 2021) |
| Microwave Assisted Extraction | • Improve the productivity of extracting oil.<br>• Reduce the amount of solvent utilized.<br>• The extraction time is short compared with solvent extraction. | • The operating temperature changes depending on the boiling point of the solvent.<br>• Commonly, employed as a preliminary step before solvent extraction. | (Liew et al., 2016; Ibrahim, Omilakin and Betiku, 2019) |
| Ultrasound Assisted Extraction | • The method boasts minimal initial investment requirements.<br>• The efficiency is high.<br>• Fatty acids are conserved-.<br>• Short extraction time. | • The adverse effects associated with organic solvents. | (Chemat et al., 2017; Karmakar and Halder, 2019; Binhweel, Hossain and Ahmad, 2023) |
| Autoclave | • Environmentally friendly<br>• Fatty acids will not be damaged. | • Decreased pressure values that are applicable. | (Binhweel, Hossain and Ahmad, 2023) |

## 4. Production Technologies

Biodiesel manufacturing encompasses various methods tailored for different types of feedstocks, processing environments, and desired biodiesel properties. Among the several techniques available, five have notably stood out for their effectiveness and practicality: These technologies include pyrolysis, transesterification, micro emulsification, and supercritical transesterification, and blending. Each approach comes with its distinct strengths and obstacles, shaping its applicability to situations. The subsequent sections delve into each method, delving into its operational complexities, advantages, and constraints. Figure 2 Shows the five methods of biodiesel production.

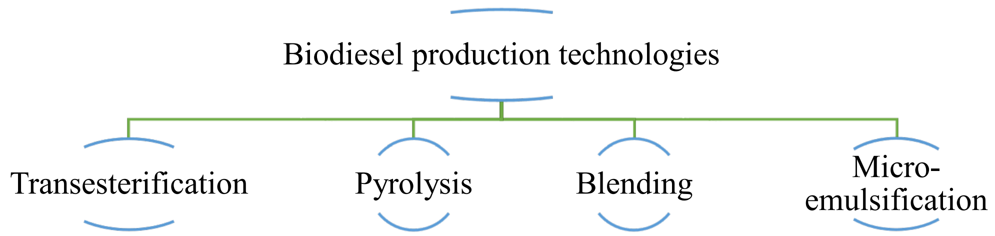


***Figure 2.*** Biodiesel production technologies.

## *4.1. Transesterification*

Transesterification is the most used technique for transforming different oils and lipid-based feedstocks into biodiesel. This chemical reaction involves triglycerides naturally occurring fats and oils reacting with an alcohol, usually methanol, in the presence of a catalyst. This process speeds up the production of fatty acid esters, specifically known as fatty acid methyl esters (FAME). Since the majority of oils obtained from biological sources exist in the form of triglycerides, removing glycerol is a crucial step to ensure the formation of ester chains from fatty acids, which exhibit fuel properties comparable to conventional diesel. Triglycerides are broken down step by step by the transesterification reaction, which is helped along by a catalyst. It starts with diacylglycerols and monoacylglycerols and ends with glycerol as a byproduct. Throughout this process, methyl esters are continuously generated, making transesterification an essential and efficient technique for biodiesel production (Pandit et al., 2023; Binhweel, Ahmad and Shakir, 2025) Transesterification is utilized for biodiesel production from different vegetative and animal-based oils. Previous studies were conducted on chicken fat (Toldrá-Reig, Mora and Toldrá, 2020a), fish fat (Smaisim et al., 2022), sheep fat (J. Jayaprabakar et al., 2019), goat fat (Khalifeh and Esmaeili, 2020), fish waste (Shalfoh et al., 2025), and camel waste fat (Sbihi et al., 2014b). The reported results were encouraged in terms of the biodiesel conversion. Previous study performed transesterification on *Silurus triostegus* heckel fish oil using an alkaline catalyst and verified that the physical and chemical characteristics of the resulting methyl ester met the requirements outlined in biodiesel standards (Fadhil and Ali, 2013). Specifically, either chemical or biological catalysts can facilitate transesterification. Chemical catalysts are broadly categorized into two main types: homogeneous and heterogeneous catalysts. Homogeneous catalysts function in the same phase as the reactants and typically involve the use of acid or alkali compounds to facilitate the reaction. In contrast, heterogeneous catalysts operate in a different phase than the reactants and include a diverse range of materials, such as those derived from biomass waste, solid acids and bases, bifunctional acid-base catalysts, and advanced nanocatalysts. The choice of an appropriate catalyst is influenced by multiple factors, including the composition and purity of the oil feedstock, the concentration of free fatty acids (FFA), reaction conditions, catalytic efficiency, economic feasibility, and overall availability (Tacias-Pascacio et al., 2019).

### 4.1.1. Homogeneous Catalyst

Catalyst selection is crucial for cost-effective biodiesel production. In addition, the acid value and FFA levels in the feedstock oils determine the choice of catalyst. The traditional method for biodiesel production initially uses homogeneous catalysts, which are in the same phase as the reactants (Mandari and Devarai, 2022). Owing to their high efficiency, homogeneous alkali catalysts are extensively utilized in large-scale biodiesel production through the transesterification process. Among these, alkali metal hydroxides such as potassium hydroxide (KOH) and sodium hydroxide (NaOH), along with alkoxide compounds like sodium methoxide ($CH_3ONa$), are the most commonly utilized catalysts. Their widespread application is attributed to their ability to accelerate reaction rates significantly while operating under relatively mild temperature and pressure conditions, making them highly effective for large-scale biodiesel synthesis (Mandari and Devarai, 2022). Homogeneous alkali catalysts yield higher and purer resultants, especially when processing extra-pure virgin oils with low levels of FFA and acid values below 0.5% and 1 mg KOH/g, respectively. When oils with higher FFA content are used, soap formation can occur, resulting in reduced yield and challenges in separating the products (Lam, Lee and Mohamed, 2010). Dias et al. (2008) investigated the performance of various alkali catalysts in the transesterification process, conducting a comparative analysis between virgin oils and waste cooking oils. Their study revealed that biodiesel production from virgin oils resulted in a yield of 97%, whereas waste cooking oils exhibited a slightly lower yield of 92%. Homogeneous alkali catalysts have notable limitations, including soap formation due to high free fatty acid (FFA) levels in the feedstock oil and the requirement for premium-quality, highly purified edible oils. These issues can be addressed by using homogeneous acid catalysts. Unlike alkali catalysts, acid catalysts remain unaffected by the FFA content in the feedstock and are capable of catalyzing both esterification and transesterification reactions at the same time. As a result, cost-effective raw materials with high FFA content, such as non-edible oils, waste cooking oils, and animal fats, can be efficiently processed using acid catalysts. (Mandari and Devarai, 2022). Brønsted acids such as sulfuric acid ($H_2SO_4$), sulfonic acid ($H_2SO_3$), hydrochloric acid (HCl), and ferric sulphate ($Fe_2(SO_4)_3$) demonstrate low sensitivity to free fatty acids (FFA) to active sites. Among these acids, sulfuric acid is especially favored for its high performance under moderate temperature and atmospheric pressure conditions. Homogeneous catalysts enhance efficiency by providing greater exposure (Li et al., 2009; Maafa, 2022).

### 4.1.2. Heterogeneous Catalysts

Heterogeneous catalysts, typically found in solid form, play a crucial role in various phases of liquid reaction mixtures. In recent years, a diverse range of solid catalysts has been utilized in biodiesel manufacturing. These catalysts are becoming increasingly important because have the ability to handle FFA and water content in the raw materials. Their presence in different phases simplifies catalyst retrieval from the reaction mixture, enabling multiple reuses. By employing heterogeneous catalysts, the formation of soap is reduced, and the reusability of solid catalysts across multiple cycles enhances the economic viability of biodiesel production (Wang et al., 2016). Solid catalysts with heterogeneous properties enable continuous biodiesel production in fixed-bed reactors, facilitating increased output at an industrial level (Mandari and Devarai, 2022). Furthermore, heterogeneous catalysts are broadly divided into acidic and alkaline types. In biodiesel production, heterogeneous acid catalysts play a crucial role by enabling both esterification and transesterification reactions, making them a viable substitute for homogeneous acid catalysts. Their solid structure contains Brønsted and Lewis acid active sites, which contribute to their superior industrial performance. Due to their effectiveness and reusability, heterogeneous acid catalysts are often considered more beneficial than homogeneous acid catalysts in large-scale applications (Guldhe et al., 2017). Unlike homogeneous acid catalysts, heterogeneous acid catalysts overcome major challenges such as equipment corrosion and harmful environmental impacts. They exhibit strong resistance to high free fatty acid (FFA) levels and water content in feedstock oils, allowing the use of lower-quality and more cost-effective raw materials for biodiesel production without the need for prior acid treatment (Mansir et al., 2017). The development of heterogeneous catalysts supports the continuous production of biodiesel by efficiently utilizing affordable feedstocks such as animal fats, waste cooking oils (WCO), and other oil-derived waste materials. This innovation significantly improves the economic feasibility of biodiesel production, making it a more cost-effective and sustainable alternative (Nata et al., 2017). Solid alkali catalysts are known for their superior catalytic performance compared to solid acid catalysts. Considerable research has been dedicated to resolving the challenges associated with using homogeneous alkali catalysts in biodiesel production. Heterogeneous alkali catalysts are typically made up of various compounds, including alkaline oxides, oxides of alkaline earth metals, hydrotalcites, metallic salts, anion exchange resins, and zeolites. These materials are strategically distributed across a broad surface area to maximize their catalytic activity and efficiency in biodiesel synthesis (Mandari and Devarai, 2022). Among the various solid alkali catalysts, alkaline earth metal oxides are widely utilized due to their cost-effectiveness and pronounced basicity. Single-metal oxides have shown remarkable efficiency in catalyzing biodiesel production. Additionally, introducing dopants into these catalysts can significantly improve their performance by increasing surface area and refining their physicochemical properties, thereby enhancing their overall catalytic activity (Sulaiman et al., 2019). The operational parameters and resulting biodiesel yields for various feedstocks using the transesterification method are summarized in Table 4.

***Table 4.*** Transesterification parameters and biodiesel yields from various feedstocks.

| Feedstocks | Transesterification Parameters | | | | Biodiesel Yield | References |
|---|---|---|---|---|---|---|
| | Alcohol type/ molar ratio (mol/mol) | Catalyst type/ amount (wt%) | Time reaction (h) | Temperature reaction (°C) | | |
| Sheep skin fat | Methanol /1:6 | NaOH/0.5 | 2 | 65 | 92 | (J Jayaprabakar et al., 2019) |
| Goat fat | Methanol / 1:12 | MgO/1 | 3 | 70 | 93.12 | (Rasouli and Esmaeili, 2019a) |
| Beef tallow | Methanol / - | NaOH/−1.5 | - | - | - | (Nagappan et al., 2021) |
| Soybean oil | Non/1:6 | NaOH/0.2 | 1.30 | 50 | 90 | (Demirbas, 2005) |
| Sunflower oil | Non/ 1:20 | CaZN/3 | 2 | 78 | 95 | (Puna et al., 2010) |

## *4.2. Pyrolysis*

Pyrolysis refers to the process of converting a material into different chemical compounds by exposing it to elevated temperatures, typically between 300 and 1300 °C. This transformation occurs in an oxygen-free environment and can take place through two primary mechanisms. The first, known as thermal cracking, relies solely on heat to break down the substance. The second, called catalytic cracking, involves the application of heat in combination with a suitable catalyst while maintaining oxygen exclusion. Without the presence of oxygen, the reaction takes place in an inert atmosphere, preventing unwanted oxidation. On a molecular level, this process disrupts the chemical bonds within the material, leading to the decomposition of complex structures into a variety of smaller compounds. This procedure bears similarities to the method employed in producing petroleum diesel, thereby producing a product with its combustion properties and minimizing waste generation while avoiding pollution (Akram et al., 2022). The material employed in pyrolysis can include vegetable oils, animal fats, naturally occurring fatty acids, or methyl esters derived from fatty acids. Occasionally, this method yields a higher quantity of products compared to the transesterification process, which is commonly utilized. While there is a possibility of generating low-value by-products, pyrolysis produces consistent products that are chemically similar (Özçimen, Gülyurt and İnan, 2012). Pyrolysis is generally classified into three main types based on its operating conditions: slow (or conventional), fast, and flash pyrolysis. The distinction between these methods is determined by several key factors, including reaction temperature, the speed at which heat is applied, the duration for which solid materials remain in the reactor, and the size of the biomass particles being processed. The composition and yield of the resulting products vary depending on the specific pyrolysis technique used and the particular conditions under which the process is carried out (Singh et al., 2024). The products derived from pyrolysis exhibit several advantageous properties similar to biodiesel, including low viscosity, minimal sulfur and water content, and an elevated cetane number. Despite these benefits, certain drawbacks exist, such as undesirable levels of ash and residual carbon. Additionally, the process generates lower alkanes in the form of non-condensable gases, which are typically regarded as secondary by-products (Akram et al., 2022). Ito et al. (2012) utilized the pyrolysis technique to convert waste cooking oil into biodiesel. Their study revealed that biodiesel derived from pyrolysis demonstrated a notable enhancement, approximately −5 °C, in the pseudo-cold filter plugging point compared to biodiesel obtained through transesterification.

## 4.3. Blending

The blending technique involves mixing biodiesel, derived from vegetable oils or waste cooking oils, with petroleum-based diesel in specific ratios to create a compatible fuel mixture. In some cases, preheating and filtration are necessary to optimize the blend by reducing viscosity and enhancing fuel volatility. The use of biodiesel-diesel blends has been successfully demonstrated in various studies. For example, researchers tested a mixture containing 20% biodiesel (B20) and 80% diesel in a diesel engine, which operated efficiently without requiring modifications (Firdaus et al., 2022). Another study examined a 1:1 ratio of biodiesel to conventional diesel (B50), and the engine functioned effectively without adjustments. Additionally, waste cooking oils have been converted into biodiesel and blended with petroleum diesel for marine applications. One formulation consisting of 100% biodiesel from filtered waste cooking oil (B100) was successfully used in ship diesel engines, leading to improved thermal efficiency (Tabatabaei et al., 2019). Mixing biodiesel with petroleum diesel is one of the most straightforward and economical methods for producing alternative fuels. However, the quality of the resulting blend may be influenced by several factors, including increased density, higher viscosity, potential oxidative instability, and the presence of free fatty acids (FFA). Additionally, the lower volatility and the chemical composition of biodiesel can impact engine performance. When used in unmodified diesel engines, high-percentage biodiesel blends may lead to delayed fuel injection, altered combustion characteristics, and higher emissions of nitrogen oxides (NOx). These factors can affect engine performance and longevity, requiring regular maintenance to mitigate potential issues. Despite these challenges, biodiesel-diesel blends (such as B20 and B50) are widely used and offer environmental benefits, including reduced carbon emissions and improved lubrication properties (Akhihiero and Ebhodaghe, 2020; Binhweel, Hossain and Ahmad, 2023)

## 4.4. Micro-Emulsification

Biodiesel can be produced using the micro-emulsification technique, which involves forming a stable emulsion by mixing two or more immiscible liquids. Under equilibrium conditions, this process generates uniform liquid microstructures ranging in size from 1 to 150 nm, resulting in a dispersed colloidal solution. To improve the physicochemical properties of biodiesel, such as viscosity, fluidity, and nitrogen oxide (NOx) emissions, vegetable oils and animal fats undergo micro-emulsification. Various solvent surfactants, including methanol, ethanol, butanol, hexanol, and other alcohol-based compounds, are commonly utilized in this process. The final product is a thermodynamically stable biodiesel that does not produce any undesirable by-products (Karmakar and Halder, 2019). Scientists have successfully developed various biodiesel microemulsions using different feedstocks and surfactants. In one study, methanol and 2-octanol were employed as surfactants to create a stable microemulsion from soybean oil. To enhance its performance, a cetane booster was added, enabling this soybean-based biodiesel to efficiently power a 200-horsepower diesel engine. Another formulation involved blending peanut oil with conventional diesel, where peanut oil acted as the surfactant. The resulting microemulsion met the necessary physicochemical requirements for biodiesel standards. For biodiesel synthesis from rapeseed oil, researchers incorporated 1-butanol as a solvent and water as a surfactant. This formulation demonstrated reduced viscosity and remained stable for nine months. Additionally, palm oil was combined with sorbitan monooleate and octanol to create another biodiesel microemulsion, further expanding the range of viable biofuel alternatives (Attaphong et al., 2017). A comparative overview of the advantages and disadvantages of different biodiesel production technologies is presented in Table 5.

*Table 5.* Comparison of biodiesel production techniques with their advantages and disadvantages.

| Techniques | Advantages | Disadvantages | Refences |
|---|---|---|---|
| **Transesterification** | High conversion efficiency Mild reaction conditions Well established process | Sensitive to feedstock impurities (e.g., water, free fatty acids) Requires catalyst separation and purification | (Tabatabaei et al., 2019; Farouk et al., 2024) |
| **Pyrolysis** | Can process a wide range of biomass feedstocks Produces bio-oil and valuable by-products | Bio-oil has undesirable properties (e.g., high acidity, instability) Requires upgrading for fuel use | (Tabatabaei et al., 2019; Osman et al., 2023) |
| **Micro-emulsification** | Simple process. Can improve fuel properties. Suitable for high-viscosity feedstocks | Stability issues. Potential engine corrosion. High surfactant costs | (Sharma, Singh and Upadhyay, 2008; Tabatabaei et al., 2019) |
| **Blending** | Easy implementation. No chemical reaction required. Immediate use in existing engines | Limited blend ratios to maintain engine performance Potential for increased emissions at higher blends | (Wu, Ge and Choi, 2020) |

## 5. Biodiesel Characterization

### *5.1. Fatty Acids Composition*

The fatty acid composition of biodiesel significantly impacts its overall properties, as the proportions of different fatty acids determine key fuel characteristics. Variations in fatty acid content influence aspects such as viscosity, oxidative stability, cold flow properties, and combustion performance (Khethiwe, Clever and Jerekias, 2020). Vegetative oils and animal fats predominantly comprise triacylglycerols. These compounds are characterized by long-chain fatty acids bonded chemically to a glycerol (1,2,3-propanetriol) backbone. Triglycerides exhibit potential as viable substitutes for traditional diesel fuels in engine applications (Mishra and Goswami, 2018). Table 6 exhibits the literature of fatty acids profiles for animal and vegetative-based feedstocks.

*Table 6.* Literature of fatty acid compositions for animal and vegetative-based oils.

| Fatty acids profile | C16:0 (palmitic) | C16:1 (palmitoleic) | C18:0 (stearic) | C18:1 (oleic) | C18:2 (linoleic) | C18:3 (linolenic) | References |
|---|---|---|---|---|---|---|---|
| **1: Animal Fat waste** | | | | | | | |
| Chicken fat | 19.82 | 5.6 | 3.06 | 37.62 | 20.5 | 0.0 | (Shi et al., 2013; Chavan et al., 2017) |
| Beef tallow | 19.3 | 2.0 | 42.4 | 2.9 | 0.9 | 2.9 | (da Cunha et al., 2009; Singh and Singh, 2010) |
| salmon | 14.8 | - | 3.2 | 15.6 | 2.1 | 11.4 | (Chiou et al., 2008),(Jay, Kawaroe and Effendi, 2018) |
| Sheep fat | 27.0 | 2.0 | 24.1 | 40.7 | - | 1.2 | (Ivana B Banković-Ilić et al., 2014) |
| *Camelus dromedaruis* fat (camel) | 26.16 ± 0.32 | 9.56 ± 0.15 | 10.07 ± 0.15 | 33.35 ± 0.81 | 2.67 ± 0.12 | - | (Sbihi, Nehdi and Al-Resayes, 2013) |
| **2: Vegetative oil** | | | | | | | |
| Soybean oil | 12.13 | 0.3 | 3.49 | 23.41 | 54.18 | 6.5 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Palm oil | 39.83 | 0.17 | 5.33 | 41.9 | 11.46 | 0.15 | (Singh et al., 2024) |
| Mustered oil | 4.32 | 0.21 | 1.25 | 9.26 | 13.79 | 18.79 | (Fadhil and Abdulahad, 2014; Sanjid et al., 2014; Li and Khanal, 2016) |
| Cotton seed oil | 22.9 | 0.0 | 3.1 | 18.5 | 54.2 | 0.5 | (Ramírez-Verduzco, Rodríguez-Rodríguez and del Rayo Jaramillo-Jacob, 2012) |

### *5.2. Physicochemical Properties and Biodiesel Quality*

The properties of biodiesel generations vary significantly. In addition, The feedstock composition, oil extraction method, synthesis technique, and refining processes for both the oil and the resulting biodiesel are the primary determinants of the physicochemical properties of biodiesel (Singh, Sharma, S. L. Soni, et al., 2019). In contrast to biodiesels sourced from vegetative origins, those derived from waste animal fat demonstrate inferior physicochemical attributes. These encompass heightened density and viscosity metrics, reduced volatility, and challenges associated with cold ignition. These adverse traits stem primarily from the augmented prevalence of saturated fatty acids (SFA) within animal fats (Nagappan et al., 2021). Globally, efforts are underway to enhance the quality of biodiesel. Given its production from various plants with differing scales, origins, and features, it becomes crucial to set universal quality standards to guarantee optimal engine functionality. Adherence to internationally recognized biodiesel standards like ASTM 6751 or EN 14 214 is vital. These standards encompass key physicochemical attributes necessary for precisely evaluating biodiesel quality (Mishra and Goswami, 2018). some of these physiochemical properties are displayed in Table 7

Biodiesel must adhere to the EN 14214:2012 + A2:2019 and ASTM D6751 standards, which delineate permissible ranges for various qualities and specify measuring methodologies. Although these requirements encompass the majority of essential qualities, many significant aspects-especially those pertaining to biodiesel efficacy at low temperatures-are governed by national rules (Díez-Valbuena et al., 2024).

***Table 7.*** Physiochemical properties of some animal–based and vegetative-based biodiesel.

| Feedstock | Density at 15 °C (kg/m$^3$) | Kinematic viscosity at 40 °C (mm$^2$/s) | Acid value (mg KOH/g) | Iodine value (g $I_2$/100g) | Cetene number | Flash point (°C) | Cloud point (°C) | Pour point (°C) | Refence |
|---|---|---|---|---|---|---|---|---|---|
| ASTM 6751 | 880 | 1.9-6.0 | (Maximum) 0.5 | - | (Minimum) 47 | (Minimum)130 | -3 to -12 | -15 to -16 | (Sohrab Hossain et al., 2021) |
| EN 14 214 | 860-900 | 3.5-5.0 | (Maximum) 0.5 | (Maximum) 120 | (Minimum) 51 | (Minimum) 101 | - | - | |
| Goat fat | 832 | 3 | - | - | - | 82 | 2 | -7 | (Rasouli and Esmaeili, 2019b) |
| Beef fat | 872 | 4.54 | 0.20 | 44.4 | 52 | 180 | 3.20 | 2.50 | (Mata et al., 2014; Esther Olubunmi et al., 2022; Binhweel, Hossain and Ahmad, 2023) |
| Chicken fat | 895 | 4.06 | 0.43 | 101.6 | 52.60 | 183 | 11 | 1 | (Odetoye, Agu and Ajala, 2021; Binhweel, Hossain and Ahmad, 2023; Faisal et al., 2023) |
| *C. dromedaruis* fat (camel) | 871 | 3.39 | 0.96 | 65.3 | 58.7 | 158 | 12.7 | 15.5 | (Sbihi et al., 2014b) |
| Jatropha | 879 | 4.84 | 0.38 | - | 51 | 191 | 2.8 | 3 | (Abdul Hakim Shaah et al., 2021) |
| Neem | 876 | 5.16 | 0.61 | - | 55 | 170 | 15 | 8.5 | |
| Rubber | 870 | 3.7 | 0.07 | - | 43 | 110 | -6 | -2 | (Onoji et al., 2016) |
| Tobacco | 888 | 4.22 | 0.3 | 136 | 51 | 165 | - | - | (Kumar and Tomar, 2019) |
| Coconut oil | 867 | 3.14 | 0.18 | 118.5 | 64.65 | 118.5 | -1.6 | -8.3 | (Singh, Sharma, S L Soni, et al., 2019; Sohrab Hossain et al., 2021) |
| Soybean oil | 882 | 4.15 | 0.18 | 117 | 58.1 | 160 | 0 | -3.2 | |
| Sunflower oil | 869 | 4.10 | 0.357 | 128.7 | 49 | 183 | 1 | -2 | |
| Palm oil | 880 | 4.52 | 0.25 | 50.5 | 54.6 | 175 | 14.25 | 14.33 | |

## 6. Economic and Sustainability Perspective

Biodiesel are obtained from vegetative oils, as well as animal waste fat. it has similar characteristics to petroleum-derived diesel (Abdul Hakim Shaah et al., 2021). Animal waste fat, such as beef tallow (Singh et al., 2020), chicken fat (Maafa, 2022), and goat fat (Khalifeh and Esmaeili, 2021), is utilized in biodiesel production, alongside vegetative oils like soybean oil (Muranaka et al., 2023), coconut oil (Čedík et al., 2020), and palm oil (Yusoff et al., 2021). Currently, more than 95% of biodiesel is derived from edible oil sources. However, the reliance on these oils for biofuel production has sparked considerable debate, particularly due to its implications for the global food market. Large-scale biodiesel manufacturing using edible oil crops has the potential to disrupt food supply chains, creating an imbalance that could worsen food shortages and contribute to global food insecurity, particularly in low- and middle-income countries (Abdul Hakim Shaah et al., 2021). Moreover, cultivating feedstock crops for biodiesel demands considerable resources arable land, freshwater, fertilizers, and energy which undermines the environmental benefits of biofuels. The expansion of oil crop plantations contributes to deforestation, biodiversity loss, and ecosystem degradation, especially in tropical regions (Binhweel, Ahmad and Shakir, 2025). These challenges highlight the pressing need to transition from food-based to waste-derived, non-edible feedstocks to ensure long-term sustainability and ethical production. In this context, waste animal fats-such as beef tallow, chicken fat, goat fat, and another slaughterhouse by-products-offer a sustainable and cost-effective alternative. These materials are abundantly available as by-products of meat processing industries and typically require minimal additional input for biodiesel production. Their utilization aligns with circular economy principles by repurposing organic waste into clean energy, thereby reducing landfill burden and associated methane emissions**.** This approach supports waste-to-energy (WTE) strategies and helps mitigate environmental and public health risks linked to improper waste disposal (Jafarihaghighi et al., 2022)**.** From an economic perspective, feedstock costs account for the largest share of biodiesel production expenses, comprising approximately 70–95% of the total cost (Bhuiya et al., 2020). Currently, edible oils are used in around 75% of global biodiesel production, raising concerns about cost, sustainability, and food security (Vlnieska et al., 2022). Therefore, using low-cost and locally available waste animal fats significantly enhances the financial viability of biodiesel projects. The transesterification cost of biodiesel derived from animal fat is estimated between US $0.4–0.5 per liter, compared to US $0.6–0.8 for vegetable oils, making the former a more economically favorable option**.** Moreover, animal fats generally contain a higher proportion of saturated fatty acids, resulting in superior cetane numbers and better combustion stability, which are desirable for engine performance (Ivana B. Banković-Ilić et al., 2014). Production costs can be further optimized through the application of advanced extraction technologies. For example, supercritical carbon dioxide (SC-$CO_2$) extraction has been shown to improve lipid yield, reduce solvent use, and shorten processing time (Guo et al., 2022)**.** This not only enhances resource efficiency but also lowers operational costs. Additionally, the commercialization of glycerol a by-product of transesterification can provide supplementary revenue, with market values around $0.30/kg. Scaling production facilities also plays a critical role; increasing output from 8,000 to 125,000 tons/year can reduce unit costs by up to 67% (Al-attab et al., 2017)**.** Similarly, Banković-Ilić et al. (2014) reported that a plant producing 100,000 tons/year of animal-fat-based biodiesel could achieve production costs as low as $0.30 per liter. In conclusion, transitioning to non-edible, waste-derived feedstocks particularly animal fats provide a viable pathway for achieving sustainable, low-cost biodiesel production. This strategy supports environmental stewardship, enhances energy security, reduces dependence on food-based resources, and contributes to the advancement of circular bioeconomy practices.

## 7. Conclusion

The urgent demand for sustainable and low-emission energy sources has driven increasing global interest in biodiesel as a viable substitute for fossil fuels. This review critically examined biodiesel derived from both plant-based oils and animal fats, focusing on feedstock availability, extraction techniques, production technologies, and physicochemical performance. Among the key findings, animal fat-based biodiesel was recognized for its economic and environmental advantages, particularly due to its low cost, abundant availability, and alignment with circular economy practices. Compared to vegetable oils, animal fats offer higher cetane numbers and enhanced oxidative stability, while also avoiding competition with food supplies.

A comprehensive analysis of lipid extraction techniques from conventional solvent-based to advanced methods such as ultrasound, microwave, and supercritical $CO_2$ demonstrated the trade-offs between yield, scalability, environmental impact, and cost. Similarly, the review highlighted that transesterification remains the most practical and efficient method for biodiesel synthesis, especially for waste-derived animal fats, although other methods such as pyrolysis and micro-emulsification have potential under specific conditions. Furthermore, biodiesel produced from various feedstocks was evaluated against international fuel standards (ASTM D6751 and EN 14214), with many samples meeting or exceeding the required parameters. However, challenges such as cold flow properties and scalability of animal fat-based biodiesel production still need to be addressed through continued innovation and investment in processing technologies. Ultimately, this review underscores the importance of integrating waste-based feedstocks, especially animal fats, into biodiesel supply chains to enhance sustainability, reduce environmental burdens, and improve economic feasibility. The adoption of such approaches contributes directly to global sustainability goals, promotes energy diversification, and supports the ongoing transition to a greener, low-carbon energy future.

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