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Shifting fossil fuel dependence to biodiesel alternative: Understanding the feasibility

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ABSTRACT

Biodiesel is a promising renewable energy carrier, providing a sustainable alternative to conventional petroleum diesel. Produced primarily through the transesterification of oils and fats into fatty acid methyl esters (FAME), biodiesel offers several environmental and performance advantages, including reduced greenhouse gas emissions, carbon neutrality, biodegradability, and a higher cetane number. Despite its technical feasibility and established commercial applications, large-scale adoption is constrained by production costs, feedstock limitations, and fuel property challenges such as cold flow behaviour. This review consolidates current knowledge on biodiesel production with a particular focus on the role of feedstocks, technological methodologies, and process equipment. This review work compares edible and non-edible vegetable oils, animal fats, waste oils, and microalgae with respect to their advantages, limitations, and sustainability profiles. Production techniques – including base-catalysed transesterification, acid esterification, supercritical alcohol processes, and thermochemical routes – have been critically examined alongside reactor designs, separation units, and purification systems. The review also highlights quality testing standards such as ASTM D6751 and EN 14214, which govern biodiesel commercialization. The findings of this research work suggest that future development of biodiesel depends on diversifying sustainable feedstocks, advancing catalysts and reactor technologies, and integrating cost-effective waste valorization strategies. This work finally concludes with the observation that biodiesel can become a cornerstone in achieving low-carbon transport systems supporting the global transition to renewable energy.

Keywords: fossil fuel, biodiesel, transesterification, renewable energy, algae.

INTRODUCTION

The transportation sector remains heavily reliant on liquid fossil fuels, contributing substantially to greenhouse gas (GHG) emissions, air pollution, and energy insecurity. Biodiesel, a renewable fuel primarily composed of fatty acid alkyl esters, offers an environmentally friendly substitute to petroleum diesel. It is typically produced from vegetable oils, animal fats, waste cooking oils, and increasingly, microalgae-derived lipids [1,2]. Compared with petroleum-based diesel, biodiesel exhibits several favorable characteristics: it is biodegradable, non-toxic, sulfur-free, and has a relatively high flash point and cetane number, ensuring safe storage, efficient combustion, and improved ignition quality [3,4]. One of biodiesel's most significant advantages lies in its carbon balance. The carbon dioxide released during combustion is largely offset by the CO_2 absorbed during the growth of feedstocks, thereby lowering net GHG emissions [1,2]. Consequently, many countries have incorporated biodiesel into their renewable energy strategies, using policy incentives and blending mandates to decarbonize the transport sector [3]. Global biodiesel production expanded from 3.5 million tons in 2005 to nearly 29 million tons by 2016, with projections indicating it may exceed 36 million tons by 2025 [4]. This trajectory underscores its strategic importance in the broader renewable energy transition. Despite its benefits, biodiesel is not without technical and economic limitations. The cost of refined vegetable oils remains the single largest contributor to production expenses, and the glycerol by-product generated during transesterification (10–20% of total output) poses additional processing and disposal challenges [1,[2]. Moreover, biodiesel's intrinsic fuel properties – such as higher viscosity, oxygen content (10–12% by weight), and poor cold flow performance – limit its direct use as a petroleum diesel substitute. These issues are typically addressed through blending (e.g., B20, a 20% biodiesel–diesel blend) or through fuel property modifications [3]. Research is ongoing to improve cost efficiency, optimize catalysts, and enhance the performance characteristics of biodiesel to facilitate wider adoption. The present review work aims to undertake a feasibility analysis promoting biodiesel as an alternative to fossil fuel based on promising feedstock, its economic and technical sustainability overcoming production challenges. This study also highlights diversified environment friendly production technologies ensuring its applicability as future alternative to petroleum fuels.

The selection of feedstock is critical to biodiesel economics, fuel quality, and sustainability. Globally, the choice of feedstock is strongly influenced by regional availability, oil content, cost, and environmental considerations [5]. For instance, soybean oil is prevalent in the United States, rapeseed oil dominates in Europe, palm oil in Southeast Asia, while non-edible oils and waste-based feedstocks are gaining traction in developing regions [1,2]. Early commercial biodiesel production relied extensively on edible vegetable oils such as soybean, rapeseed, and palm oil. These feedstocks offer high oil yields and low levels of impurities, ensuring efficient transesterification [5]. Used cooking oil (UCO) and restaurant grease represent cost-effective and sustainable biodiesel feedstocks. Their utilization reduces waste disposal issues while contributing to circular economy practices. In the United Kingdom, nearly 89% of biodiesel feedstock by 2019 originated from used cooking oil [3]. However, high FFA and contaminant levels in UCO require pre-treatment through filtration, drying, and esterification [2]. However, their use raises significant food-versus-fuel concerns, as diverting edible oils to fuel production competes with global food supply chains [2]. To mitigate food security concerns, attention has shifted toward non-edible oils such as jatropha and castor bean. These crops thrive on marginal land, reducing competition with food production. However, their high free fatty acid (FFA) content requires pretreatment (acid esterification) to avoid soap formation during base-catalyzed transesterification [5]. Animal-derived fats such as tallow, lard, chicken fat, and fish oil are widely used in biodiesel production in regions with large meat-processing industries. These feedstocks yield biodiesel with high cetane numbers due to their saturated fatty acid content, though they suffer from poor cold-flow properties [3,4]. Blending with petroleum diesel or unsaturated biodiesel is often necessary to enhance operability in colder climates. Microalgae have gained increasing attention due to their exceptionally high lipid productivity, which can surpass traditional oilseed crops by an order of magnitude [6]. Moreover, algae cultivation does not compete with agricultural land and can contribute to CO_2 mitigation by capturing emissions from industrial sources. Despite these advantages, large-scale algae-based biodiesel remains in the pilot stage, with economic challenges stemming from energy-intensive harvesting and oil extraction processes [3,6].

Biomass is the product from living beings such as food products (soybeans, corn, sugarcane, etc.), non-food products (agricultural and municipality wastes, woods, etc.), and from organic matter by the action of algae, bacteria, etc. Among the above feedstocks, non-food categories are achieving attention for its not creating future food security challenges. This recent trend encompasses wastes of organic as well municipal types [7–9]. Being biodegradable, biodiesel is an effective alternative to fossil fuel. Its production is mainly done via transesterification process, which involves three tier process of converting vegetable oil to alkyl esters and glycerol. The transesterification process converts first triglycerides to diglycerides and then finally to monoglycerides before becoming glycerol [10,11].

Other very common biodiesel feedstock is animal fat and waste oil from diverse sources. Biodiesel synthesis and involved purification is the key to reaching the low carbon emission behaviour from it. Many recent technologies show impressive results in biodiesel production. This has been achieved by the involvement of catalysts in transesterification, in addition to blending with fossil fuel, micro-emulsion, and thermal cracking [12].

In recent studies, conversion of agricultural waste to biodiesel producing catalysts are gaining worldwide popularity. Some examples of biowaste are peels of banana and orange, coconut husk, ash, etc. to name a few. To make these waste to usable catalysts, the collected waste is subjected to some physical processes that include cleaning, drying, grinding, sieving to uniform size, and then finally converted to powder form. This follows the calcination process which is also known as heat treatment. These waste catalysts are known as heterogeneous catalysts [13–15].

In addition, intensified reactor systems such as reactive distillation, membrane-assisted transesterification, spinning-disc reactors, and continuous ultrasonic reactors; integration of machine learning and CFD-based reactor optimisation; and advanced valorisation routes for glycerol beyond conventional refining prove themselves to be cost-effective throughout the entire biodiesel production process.

There is growing dominance in the renewable fuels market of FAME biodiesel. HVO has become the fastest-growing renewable diesel technology globally. It is also possible to compare the use of straight oils and their blends, as well as their use in dual-fuel engines. Apart from transesterification conversion process, waste cooking oil (high FFA feedstock), fat (animal), PFAD are utilized for FAME production through a process known as esterification. Homogeneous catalyst work in low temperature while heterogeneous need high temperature for conversion process [7,14].

Worldwide biodiesel production and its application are being promoting in diverse ways. Whether be edible or non-edible feedstock, algae based or fourth generation feedstocks, all are subjected to several layers of screening in different forms to make them sustainable alternative to fossil fuels. Hence this study will shed light on all of them.

Table 1 summarizes the key advantages, limitations, and regional adoption of major biodiesel feedstocks. The shift from edible oils to non-edible, waste, and algal sources reflects the industry's effort to balance cost, sustainability, and performance. This study is considering all feedstocks mentioned in Table 1. Since it is a review study, hence all raw feedstocks are considered for conversion to biodiesel.

CONVERSION METHODS

Conversion technologies for biodiesel production

Figure 1 presents the conversion technology for biodiesel production. This diagram is based on understanding from literature survey. To make it easy understanding and generalised different feedstocks and diversified chemicals to be used, no specific chemical formula has been assigned in Figure 1.

Base-catalyzed transesterification

The most widely used method for biodiesel production is base-catalyzed transesterification, where triglycerides in oils and fats react with methanol or ethanol in the presence of an alkaline catalyst such as sodium hydroxide (NaOH) or potassium hydroxide (KOH). This process yields biodiesel and glycerol as a by-product [16]. Reaction conditions typically involve 60° C at atmospheric pressure with reaction times of 1–2 hours, achieving conversion rates of over 95% under optimized conditions [17].

Acid esterification is beneficial in feedstocks with high FFA, owing to its capability to lower the FFA to desired level before transesterification [2].

Table 1. Comparison of biodiesel feedstocks

Feedstock type	Materials	Advantages	Challenges	Typical regions used
Edible vegetable oils	Soybean, rapeseed, palm oil	High yield, low impurities	Food-vs-fuel debate	US, EU, Southeast Asia
Non-edible oils	Jatropha, castor bean	Grows on marginal land, avoids food competition	High FFA content, needs pretreatment	India, Africa
Animal fats	Tallow, lard, chicken fat	High cetane number, sustainable byproduct	Poor cold flow, odor, high saturation	UK, US
Waste oils	Used cooking oil, grease	Cheap, reduces waste, good sustainability profile	High contaminants and FFA; needs heavy pretreatment	UK, EU, Urban Areas
Algae	Microalgae species	Very high oil yield, CO_2 absorption, no land use issue	High cost, energy-intensive processing	Pilot: US (Iowa), Spain

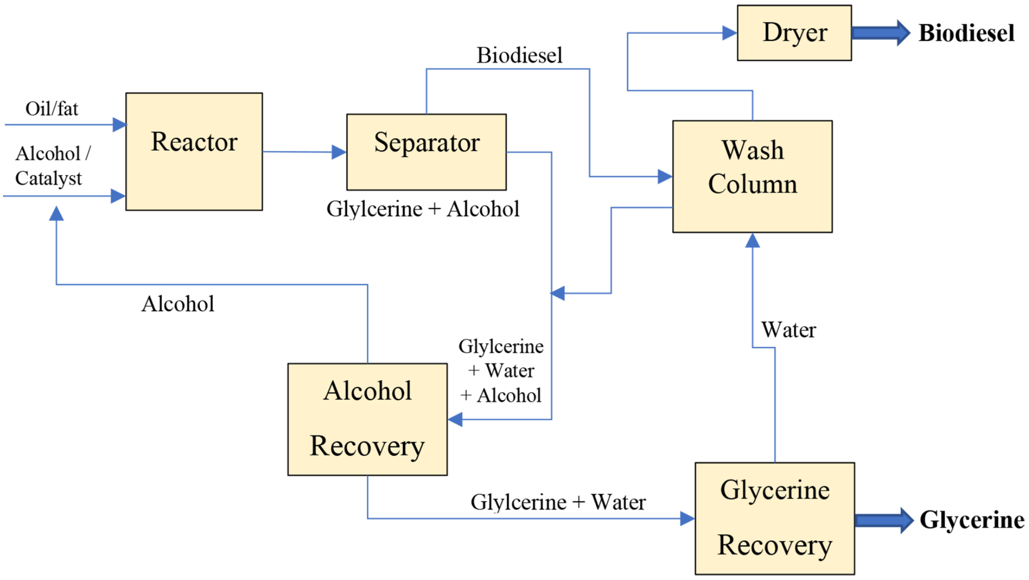

Figure 1. Flow diagram for conversion of oil to biodiesel

Acid-catalyzed transesterification

Acid catalysts, typically sulfuric acid (H_2SO_4), can convert high-FFA oils directly into biodiesel without soap formation. Although slower than base catalysis, acid esterification is crucial for pretreating waste oils and animal fats [5]. It also avoids catalyst deactivation caused by water in feedstocks, making it more flexible for diverse inputs.

Supercritical Methanol Process

The supercritical methanol process represents an advanced, catalyst-free approach in which methanol is pressurized (20–50 MPa) and heated to 250–300 °C to achieve near-instantaneous conversion of triglycerides into biodiesel [6]. This process tolerates high FFA and water content, eliminating the need for pretreatment. It also simplifies separation since biodiesel and glycerol naturally partition. Despite these advantages, the high energy demand and requirement for specialized reactors limit large-scale adoption.

Pyrolysis and thermochemical conversion

Pyrolysis, or thermal cracking, decomposes oils, fats, or biomass under oxygen-free conditions at temperatures above 400 °C. This process produces bio-oil (bio-crude) that can be upgraded to green diesel through catalytic hydrodeoxygenation (HDO) [18]. Unlike FAME biodiesel, green diesel consists of straight-chain hydrocarbons that closely resemble petroleum diesel, exhibiting superior cold flow properties and oxidation stability [3]. Commercial players such as Neste and ENI have developed renewable diesel refineries based on this route [6]. However, pyrolysis oil is highly oxygenated and acidic, requiring hydrotreating with metal catalysts (e.g., Ni–Mo, Co–Mo) to meet fuel standards [18].

Enzymatic transesterification

Enzymatic catalysis using lipases has been explored as a greener alternative. Enzymes function under mild conditions, tolerate water, and yield high-purity biodiesel and glycerol [17]. Immobilized lipases offer reusability and easier product separation. However, high enzyme costs and slower reaction kinetics currently prevent widespread commercialization.

Table 2 refers to the biodiesel production technologies. The involved algorithms for converting oil to biodiesel has been presented in Figure 2.

Equipment used in biodiesel production

The present work reviews the following equipment that are commonly used for biodiesel production.

Reactor systems

The reactor is the core unit of biodiesel production. Following is the list of reactors that may be used for biodiesel production.

- Batch stirred reactors are commonly used in laboratory and pilot-scale setups for their flexibility but are limited by throughput [1,2].

Table 2. Comparison of biodiesel production techniques

Method	Catalyst type	Operating conditions	Key benefits	Limitations
Base transesterification	NaOH, KOH	~60 °C, atmospheric pressure	Simple, widely adopted	Soap formation with high FFA feedstocks
Acid esterification	H_2SO_4	Pre-treatment step	Reduces FFAs before base transesterification	Corrosive, slower reaction
Supercritical methanol	None	250–300 °C, 20–50 MPa	Catalyst-free, works with wet/impure feedstocks	Energy intensive, costly reactor setup
Pyrolysis	None / metal catalysts	>400 °C, inert atmosphere	Produces green diesel, better cold performance	Needs further upgrading, expensive catalysts

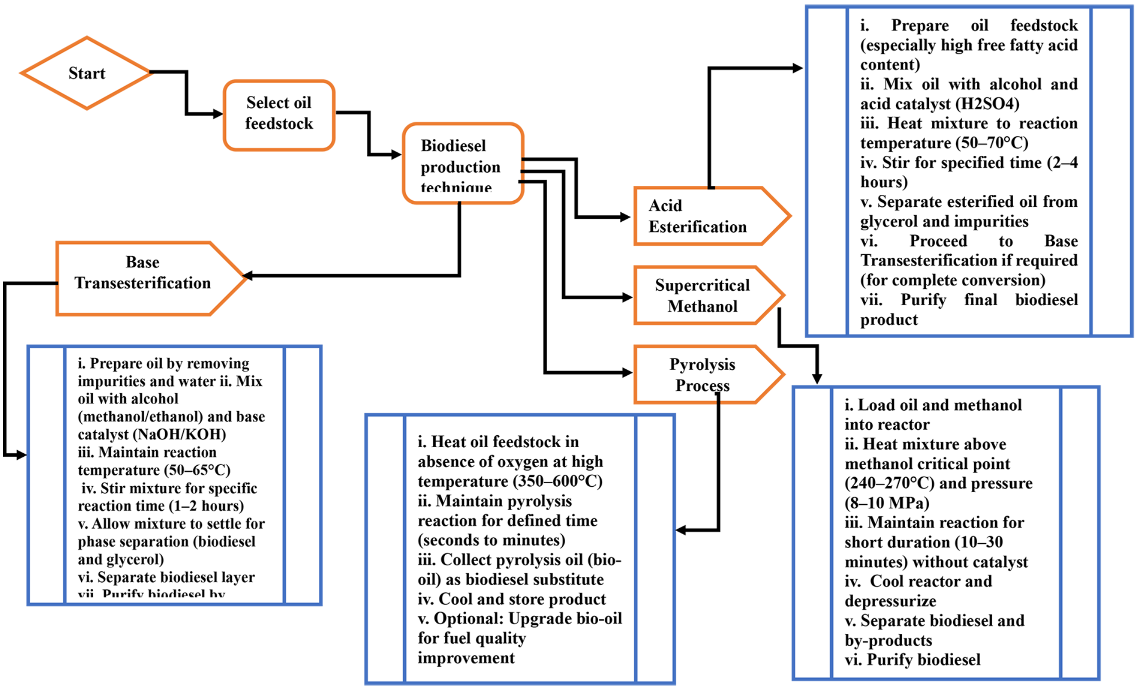

Figure 2. Flow diagram showing biodiesel production techniques with varying feedstocks

- Continuous stirred-tank reactors (CSTRs) and plug-flow reactors are widely adopted at industrial scale due to higher efficiency and consistent output [19].
- Fixed-bed reactors packed with heterogeneous catalysts allow continuous operation without downstream catalyst recovery, though they require clean, low-moisture feedstocks [6].
- Novel reactor designs such as microreactors, spinning disk reactors, ultrasonic reactors, and microwave reactors demonstrate reduced reaction times and enhanced mixing but are not yet industrially mainstream [19].

Separation and purification units

Following transesterification, separation and purification steps are necessary:

- Gravity settlers or centrifuges separate glycerol from biodiesel based on density differences. Centrifugation is preferred in industrial setups for faster throughput [3].
- Methanol recovery systems, usually distillation columns, recycle excess alcohol to improve economic and environmental sustainability [19].
- Washing and drying units remove residual soap, catalyst, and glycerol impurities, often through multi-stage water washing followed by vacuum drying or adsorption-based dry wash [1].
- Glycerol refining involves distillation and purification to upgrade crude glycerol (50–85% pure) to pharmaceutical or industrial grade (~99%) [19–21].

Feedstock pre-treatment

Pre-treatment steps vary depending on feedstock type:

- Filtration and drying for used cooking oils and animal fats to remove particulates and water [2].
- Degumming for phospholipid-rich oils such as soybean or jatropha to prevent catalyst poisoning [3].
- Acid esterification for high-FFA feedstocks to reduce acid content [5].
- Oil extraction from solid feedstocks like oilseeds or microalgae via mechanical pressing or solvent extraction, sometimes followed by in-situ transesterification [6].

Quality testing and standardization

Ensuring biodiesel meets ASTM D6751 (USA) and EN 14214 (EU) standards is essential for market acceptance. A range of analytical methods is employed [1,3,19,20]:

- Gas chromatography (GC-FID) – determines ester content (>96.5%) and total glycerine (<0.24%).
- Viscosity (ASTM D445) – measured at 40 °C; biodiesel typically ranges between 4–5 cSt.
- Density (EN 14214) – specified between 0.86–0.90 g/cm^3 at 15 °C.
- Flash point (ASTM D93) – biodiesel has >130 °C, indicating safe handling post methanol removal.
- Cold flow properties – cloud point and pour point tests reveal operability limits, varying with feedstock (e.g., soy biodiesel ~1 °C vs. tallow biodiesel >10 °C).
- Acid number (ASTM D664) – should be <0.5 mg KOH/g to prevent corrosion.
- Water content (Karl Fischer titration) – ASTM limit <0.05%.
- Cetane number (ASTM D613) – typically, between 50–65, ensuring smooth combustion.
- Sulfur content (ASTM D7260) – biodiesel is naturally <15 ppm but requires confirmation to meet ultra-low sulfur diesel regulations.

These testing procedures ensure that biodiesel is chemically stable, compatible with engines, and environmentally safe, thereby securing consumer confidence and regulatory approval. Table 3 provides an overview of biodiesel production equipment and their functions and Table 4 standard fuel properties alongside their testing methodologies.

Assessment of production technologies

Transesterification

Conventional base-catalyzed transesterification remains the dominant industrial method due to its simplicity, relatively low operating conditions, and proven scalability [16]. However, the requirement for refined feedstocks restricts cost competitiveness. Pretreatment methods (e.g., acid esterification) have expanded the range of usable feedstocks but at added operational costs.

Supercritical methanol

The supercritical method achieves nearly complete conversion even with high-FFA or water-laden feedstocks, eliminating the need for catalysts and pretreatment [6]. Nevertheless, high energy demand and costly reactors limit large-scale feasibility. Research into energy integration (e.g., heat recovery systems) could improve its viability.

Pyrolysis and green diesel routes

Green diesel derived via catalytic hydrodeoxygenation offers superior performance properties compared to biodiesel, including better cold flow, oxidative stability, and compatibility with existing fuel infrastructure [6,18]. However, these processes require hydrogen and advanced catalysts,

Table 3. Key equipment in biodiesel production and their functions

Equipment	Function	Process phase
Stirred batch reactor	Mixes feedstock, alcohol, and catalyst	Transesterification
Continuous flow reactor	High-throughput production using serial reactors	Commercial-scale synthesis
Methanol recovery column	Recovers and recycles methanol	Purification
Water wash unit	Removes impurities like catalyst and soap	Biodiesel purification
Vacuum dryer	Removes moisture post-washing	Drying phase
Gas chromatograph (GC)	Tests ester/glycerin content	Quality analysis
Flash point tester	Ensures safety by verifying residual methanol removal	Fuel testing

Table 4. Standard fuel properties and testing methods for biodiesel

Property	Standard (ASTM/EN)	Typical value range	Testing method / instrument
Ester content	EN 14214: >96.5%	96.5–99%	GC-FID (EN 14103)
Total glycerin	ASTM D6751: <0.24%	<0.2%	GC (ASTM D6584)
Kinematic viscosity	ASTM D445: 1.9–6.0 cSt	4–5 cSt	U-tube or glass capillary viscometer
Density	EN 14214: 0.86–0.90 g/cm³	0.87–0.89 g/cm³	Oscillation-type densitometer
Flash point	ASTM D93: >130 °C	130–170 °C	Pensky-Martens closed cup
Water content	ASTM D6751: <0.05%	0.01–0.04%	Karl Fischer Coulometric Titration
Cetane number	ASTM D613: >47	50–65	Cetane Engine / Calculation methods

leading to higher capital and operational expenses. The emergence of commercial facilities by Neste and ENI underscores industrial interest in this pathway [18].

Enzymatic approaches

Lipase-catalyzed biodiesel production has shown promise in producing high-purity FAME with minimal environmental impact [17]. Still, enzyme costs and lower reaction rates remain barriers. Advances in immobilization and genetically engineered lipases may accelerate industrial application. While base transesterification dominates today, the trajectory of innovation points toward more flexible, feedstock-tolerant technologies such as supercritical methanol and catalytic pyrolysis. Enzymatic methods may emerge in niche applications where high product purity is prioritized.

Technical challenges

Despite substantial progress, biodiesel faces several unresolved technical challenges:

- Cold flow performance – saturated fatty acid-based biodiesel (e.g., tallow, palm oil) exhibits high cloud and pour points, making it unsuitable for cold climates without blending or additives [3].
- Oxidative stability – unsaturated biodiesel (e.g., soybean oil-based) is prone to oxidation during storage, leading to polymerization and deposit formation in engines [2].
- Viscosity – although transesterification reduces viscosity, biodiesel remains higher than petroleum diesel, impacting fuel injection systems [3].
- Byproduct management – glycerol, which accounts for 10–20% of biodiesel output, requires downstream processing. Oversupply of crude glycerol has reduced its market value, challenging profitability [1].

Economic and policy considerations

Biodiesel's economic feasibility is strongly tied to feedstock costs, which account for 70–85% of total production expenses [2]. Waste oils and non-edible feedstocks reduce costs but require additional pretreatment infrastructure. The establishment of collection systems for WCO in countries like the UK and China demonstrates the importance of policy-supported logistics [3]. Government incentives, including blending mandates, subsidies, and carbon credits, play a decisive role in biodiesel adoption. For example, the European Union's Renewable Energy Directive (RED II) mandates renewable energy targets for transport fuels, with advanced feedstocks receiving double-counting credits [4]. Similarly, the U.S. Renewable Fuel Standard (RFS) and biodiesel tax credits have stimulated domestic production [1]. However, policy instability often leads to fluctuating investment confidence. Biodiesel expansion is not solely a technical issue but also a policy-driven process. Stable, long-term policy frameworks are essential to attract investment and support emerging feedstocks such as algae. Biodiesel is going to become new conventional fuel in years to come. The rising global temperature by 2 °C by 2050 is alarming avoiding of which will require increasing dependence on biofuel. Recent regulatory frameworks, including Intergovernmental Panel on Climate Change (IPCC), the European Union's RED III (2023) and updated U.S. RFS pathways are very relevant to understand this issue which emphasise on empowering biofuel use [22,23].

There is currently a lot of discussion about biodiesel production in Europe due to the planned increase in fossil fuel taxes. Multiple ways are being drafted word wide to promote biofuel over fossil energy. The ambitious 2009 Renewable Energies Directive (RED) aims to exogeneous increase in oil prices through increased tax on fossil fuel as a tax strategy. European countries like France are making a progress in this area. There are two aspects to promoting biodiesel production; one is boosting rural economy and the other is promoting low carbon emission [24].

Environmental impacts

Biodiesel combustion significantly reduces particulate matter, carbon monoxide, and unburned hydrocarbons compared to petroleum diesel [3]. Its near-zero sulfur content eliminates sulfur oxide emissions. Importantly, lifecycle analyses confirm that biodiesel can achieve 50–80% reductions in GHG emissions compared to fossil diesel, depending on feedstock type and cultivation practices [4].

Nevertheless, environmental trade-offs exist. The expansion of palm oil plantations for biodiesel in Southeast Asia has raised concerns about deforestation, biodiversity loss, and indirect land-use change (ILUC) [2]. Algae cultivation, while sustainable in theory, requires large amounts of water and nutrients, raising questions about environmental footprint unless integrated with wastewater treatment or flue gas utilization [6].

Biodiesel's environmental profile is generally positive, but feedstock sourcing and land-use impacts must be carefully managed to ensure genuine sustainability.

The comparative assessment of the above biodiesel producing technologies reveal distinctive features differentiating them in terms of relative maturity, scalability and influential trade-off favouring industrial applicability. Base transesterification is the most mature followed by less mature acid esterification and supercritical methanol process. The later supercritical methanol is progressively gaining attention due to process capability without catalysts. Pyrolysis is the least mature method among the four biodiesel production methods. In the context of scalability, base transesterification is highly scalable. Acid esterification is moderate and supercritical methanol is challenging due to high capital and operational expenditure. Pyrolysis scalability is attributed to handling of variable feedstocks and production upgradation flexibility. The trade-off point of view finds that base transesterification offers though high conversion efficiency with low catalysts but is sensitive to FFA and water content. Acid esterification overcomes this limitation but requires corrosion catalysts, careful waste handling and longer reaction time. Supercritical methanol is an advanced process and has no limitations of above nature but high energy consumption leads to higher costs and material degradation takes place due to extreme operating conditions. Pyrolysis can effectively upgrade bio-oil to bio-diesel but product quality is inconsistent, hence requires additional refining resulting in process complexity. Considering all, Base transesterification qualifies the benchmark for biodiesel production owing to its maturity and scalability. Acid esterification enables lower-quality feedstocks utility. Supercritical methanol faces economic and technical stability challenges. Pyrolysis is a versatile method but resulted in a less direct route to biodiesel.

FEEDSTOCKS

The selection of feedstock exerts the greatest influence on biodiesel economics, sustainability, and performance properties.

- Edible oils such as soybean, rapeseed, and palm offer high yields and low impurity levels, making them technically efficient for transesterification. However, their diversion to fuel production has intensified the global food-versus-fuel debate, raising concerns about food security and agricultural land allocation [2,5].
- Non-edible oils like jatropha and castor bean provide a promising alternative by utilizing marginal lands unsuitable for food crops. Nonetheless, their high free fatty acid (FFA) content requires acid esterification pretreatment, increasing complexity and costs [1].
- Animal fats deliver biodiesel with high cetane numbers due to their saturated fatty acid profile. Yet, their poor cold flow properties limit usage in colder climates unless blended with more unsaturated biodiesel or fossil diesel [3].
- Waste cooking oil (WCO) is increasingly favored for its low cost, sustainability, and contribution to waste management. In the European Union, WCO accounts for a growing share of biodiesel feedstock, supported by double-counting credits under the Renewable Energy Directive [4]. However, extensive pretreatment to remove water, FFAs, and impurities is mandatory [3].

- Algae represent the most futuristic feedstock, offering lipid yields up to 10–100 times greater than terrestrial crops while also sequestering CO_2 [6]. Despite these advantages, large-scale commercialization is hindered by energy-intensive harvesting and oil extraction processes [3].

While edible oils dominate current production, the transition toward non-edible oils, waste oils, and algae reflects a shift toward sustainable and circular economy principles. Feedstock diversification remains a key strategy for cost reduction and scalability.

FUTURE OPPORTUNITIES

Several avenues exist to enhance biodiesel's role in sustainable energy transitions:

- Feedstock diversification – expanding the use of non-edible oils, WCO, and algae can lower costs and improve sustainability.
- Catalyst innovation – development of solid, reusable catalysts and advanced enzymes may reduce processing costs and waste generation [17,19].
- Process intensification – integration of microwave, ultrasonic, and supercritical technologies can reduce reaction times and improve yields [19].
- Byproduct valorization – crude glycerol can be converted into value-added products such as bioplastics, solvents, and hydrogen, improving overall process economics [21].
- Integration with biorefineries – coupling biodiesel production with broader biorefinery concepts (e.g., co-production of bioethanol, biojet fuel, and chemicals) enhances resource efficiency.
- Policy support – stable regulatory frameworks and carbon pricing mechanisms remain central to scaling biodiesel technologies globally.

Several promising avenues prioritize their realistic potential for near-to-midterm deployment. The comparative assessment made with the biodiesel production technologies (base transesterification, acid esterification, supercritical methanol, and pyrolysis) suggest relevant future outlook. To achieve near-term biodiesel expansion, feedstock diversification is a highly realistic and impactful pathway. This approach will ensure inclusion of wide feedstock ranges (non-edible oils, waste oils, algae, and other biomass) that help reduce dependency on conventional oil crops and supply shortage issues. This strategy aligns well with two mature technologies (base transesterification and acid esterification) since feedstock diversification led to feasible scalability owing to increasing raw material availability and improves sustainability. For midterm deployment, cost effective, durable, and scalable catalyst innovation ensures overcoming limitations of high FFA and water presence. This will also address trade-offs observed in base and acid esterification. Process intensification integrated with catalyst innovation and feedstock diversification offer potential to overcome scalability challenges faced in supercritical methanol and pyrolysis process. Near-term deployment is feasible by valorizing byproducts which can offset production costs, making biodiesel competitive, and waste reduction. Biorefineries presents a strategic mid-term opportunity enabling co-production of biodiesel with fuels, chemicals, and materials from biomass. This pathway is highly relevant for emerging technologies like pyrolysis and supercritical methanol processes. Policy support across all avenues enables near term deployable and form a complementary roadmap for advancing biodiesel production beyond current technological constraints.

CONCLUSIONS

Biodiesel has evolved from a niche biofuel to an increasingly important component of global renewable energy strategies. As a renewable and biodegradable alternative to petroleum diesel, it offers significant environmental benefits, including reductions in greenhouse gas emissions, particulate matter, carbon monoxide, and sulfur oxides. With a high cetane number and favorable combustion properties, biodiesel is compatible with most diesel engines in blended forms such as B20, requiring minimal modification of existing infrastructure.

The findings of this review work emphasize three central themes shaping the biodiesel sector. First, feedstock diversification remains the most critical factor for ensuring economic viability and environmental sustainability. While edible oils like soybean, rapeseed, and palm still dominate, non-edible oils, waste cooking oils, animal fats, and microalgae represent the future of sustainable biodiesel production. Waste-derived oils in particular align with circular economy principles, reducing disposal issues while lowering production costs. Microalgae, though still in the pilot phase, hold long-term potential due to their high lipid productivity and ability to utilize CO_2 emissions.

Second, technological innovation in production methods continues to advance beyond conventional base-catalyzed transesterification. Emerging approaches such as the supercritical methanol process, catalytic pyrolysis for green diesel, and enzymatic transesterification expand the range of usable feedstocks while reducing environmental impacts. Reactor design innovations – including microreactors, spinning disk systems, and microwave-assisted processes – demonstrate the potential for process intensification, though their commercial readiness remains limited. Parallel advances in separation and purification technologies, as well as byproduct valorization strategies, will play an equally important role in improving economic competitiveness.

Third, policy frameworks and market incentives are indispensable drivers of biodiesel adoption. From the European Union's Renewable Energy Directive to the U.S. Renewable Fuel Standard, government mandates and subsidies shape the scale and direction of biodiesel deployment. However, policy instability can undermine investment confidence, highlighting the need for consistent, long-term regulatory support. Additionally, the sustainability of biodiesel expansion depends on avoiding indirect land-use change (ILUC) and ensuring that feedstock cultivation does not exacerbate deforestation, food insecurity, or water scarcity.

Looking ahead, biodiesel's role in the global energy transition will likely expand through its integration into broader biorefinery frameworks, where multiple renewable products – fuels, chemicals, and materials – are co-produced from diverse biomass sources. By coupling biodiesel production with advanced valorization pathways for glycerol and other byproducts, economic resilience can be strengthened. Furthermore, emerging research into genetic engineering of algae, advanced heterogeneous catalysts, and hybrid reactor systems promises to lower costs and improve scalability.

Biodiesel stands at a critical crossroads. It has proven its technical feasibility and environmental value but continues to face economic and sustainability challenges. Overcoming these barriers requires a combined approach: advancing process technologies, diversifying sustainable feedstocks, and maintaining strong policy support. With such measures, biodiesel can serve not only as a transitional renewable fuel but also as a cornerstone in the global effort to build resilient, low-carbon energy systems for the future. In addition, in recent time emerging of e-fuels are also putting positive impact on environment as it can compete as an alternative to costly fossil fuel. This has also proved to be non-toxic and environmentally friendly cost-effective alternative to fossil fuel dominance.

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