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Review

Cottonseed Oil Biodiesel: Production, Properties, Engine Performance, Emissions, Tribological, and Life Cycle Assessment

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Abstract: The growing depletion of fossil fuel reserves and the environmental impacts of their use in internal combustion engines have accelerated the search for cleaner, renewable alternatives. Biodiesel has emerged as a promising candidate; however, many feedstocks still face challenges related to production methods, engine performance, emissions, and tribological compatibility. Cottonseed oil has attracted increasing attention as a sustainable and efficient biodiesel feedstock. This review highlights the major production techniques applicable to cottonseed oil biodiesel and evaluates its physicochemical properties, which conform to international American Society for Testing and Materials (ASTM) and European Norms (EN) standards. Studies have shown that cottonseed oil biodiesel blends offer improved environmental performance, with reduced emissions of Carbon monoxide (CO), Hydrocarbons (HC), and smoke opacity, although slightly elevated Nitrogen Oxide (NO_x) emissions are observed. Engine performance metrics such as Brake-Specific Fuel Consumption (BSFC) and Brake Thermal Efficiency (BTE) are analyzed and compared with those of petroleum diesel, revealing the potential for optimization. Moreover, the high content of unsaturated fatty acids in cottonseed oil contributes to enhanced tribological properties, which may extend the engine component life. In addition, studies indicate that Life Cycle Assessment (LCA) is a key tool for analyzing cottonseed biodiesel as a renewable energy source. Overall, cottonseed oil biodiesel has strong potential as a renewable, low-emission fuel with improved lubrication characteristics, making it a viable alternative for use in existing internal combustion engines.

***Keywords*:** cottonseed oil biodiesel, production, performance, emissions, tribology, internal combustion engine, Life Cycle Assessment (LCA)

1. Introduction

Fossil fuels remain the dominant source of energy production, with the automotive sector being one of their largest consumers (Pranta & Cho, 2025). In contrast, biofuels present a promising and sustainable alternative for use in the automotive sector (Selvam et al., 2025). Sourced from renewable feedstocks, biofuels can exist in liquid, gaseous, or

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solid forms (Arif et al., 2025). As a form of bioenergy, they offer significant potential to address future energy demands (Sathish et al., 2025).

Biofuels encompass a range of products, including biohydrogen, biogas, biodiesel, bioethanol, and biobutanol. Among these, bioethanol and biodiesel are especially promising substitutes for gasoline and diesel in the transportation sector (Aguilar-Aguilar et al., 2025). According to the literature, fossil fuels constitute approximately 80% of the world's total energy demand, whereas the transportation sector alone consumes nearly one-third of the global final energy (Dechamps, 2023). As such, integrating bioethanol and biodiesel into this sector presents a practical pathway for reducing fossil fuel dependence while increasing fuel availability and sustainability in transportation (Awogbemi & Desai, 2025).

Biodiesel serves as an effective alternative fuel for diesel engines (Abdelrahman & El-Khair, 2025). It is widely accessible, environmentally friendly, renewable, nontoxic, biodegradable, and easy to transport (Mboumboue & Njomo, 2018). According to the American Society for Testing and Materials (ASTM), biodiesel is defined as a fuel derived from biomass sources such as animal fats and vegetable oils, comprising long-chain monoalkyl esters (Laguitao et al., 2020). Biodiesel blends, typically ranging from B3 to B10, can be used in conventional internal combustion engines. Its physical and chemical characteristics are largely compatible with those of petroleum diesel. Furthermore, Indonesia has launched biodiesel blends, including B30, B35, and B40, whereas Malaysia has adopted the B20 blend.

Additionally, biodiesel can be blended with additives or fossil diesel to improve its combustion efficiency. One of the key environmental advantages of biodiesel is its potential to reduce greenhouse gas emissions. Compared with petroleum diesel, the combustion of biodiesel results in significantly lower levels of particulate matter, Carbon monoxide (CO), and unburned hydrocarbons. This is due to its higher oxygen content, which enhances the combustion efficiency and further reduces the environmental impact (Ortiz-Martínez et al., 2019). Biodiesel also has a higher flash point (423 K) than petroleum diesel does (350 K), making it safer to store, handle, and transport. The origin and source of the biodiesel are shown in Table 1.

Table 1. The origin and sources of biodiesel

Serial No.	Origin	Source	Reference
01	Oleaginous plants	Soybean, Rapeseed, sunflower, thistle seeds, jatropha curcas, castor African palm, etc.	Zheng and Cho, 2025
02	Used vegetable oils	Restaurants, households, and hotel industries	
03	Animal fat	Slaughterhouses	
04	Microalgae	Fresh water and marine systems	

Vegetable oil has a viscosity nearly ten times greater than that of conventional fossil fuels. This high viscosity leads to incomplete combustion, poor fuel atomization, and coking of fuel injectors when used directly in engines (Barnwal & Sharma, 2005). It also hinders smooth fuel flow within the combustion chamber and slows the air-fuel mixing process, resulting in delayed combustion and reduced brake power (Zhang et al., 2018). Therefore, vegetable oil must undergo chemical processing, such as transesterification, to make it suitable for engine use (Knothe, 2001).

The combustion of fossil fuels in internal combustion engines significantly contributes to greenhouse gas emissions, particularly those of carbon dioxide. This increase in atmospheric CO_2 is linked to approximately 150,000 additional deaths annually (Teske et al., 2007). One effective strategy to mitigate these emissions is the adoption of biomass-derived fuels for energy generation (Melamu & von Blottnitz, 2011; Mizsey & Racz, 2010). There is an urgent need to identify clean, sustainable energy sources, and biofuels offer a promising solution (Karakosta & Askounis, 2010). As they are derived from renewable biomass, biofuels contribute minimal net CO_2 emissions, maintaining a balance within the closed carbon cycle (Lal, 2005). This makes them environmentally friendly alternatives to fossil fuels capable of meeting energy demands without causing long-term harm to the planet, as shown in Figure 1.

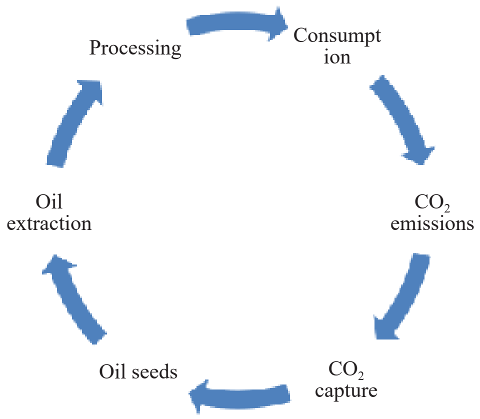

Figure 1. Closed carbon cycle of biodiesel

According to the United States Food and Agriculture Organization (FAO), only 11% of the global land area is utilized for food and agricultural production. In contrast, 45% are allocated to forestry, 3% to human settlements, 12% to protected areas, and 21% to various forms of economic development (Escobar et al., 2009). In biodiesel production, feedstock represents the most significant expense, accounting for approximately 75% of the total production cost (Knothe et al., 1997; Lim & Teong, 2010). A detailed cost breakdown of biodiesel production is illustrated in Figure 2.

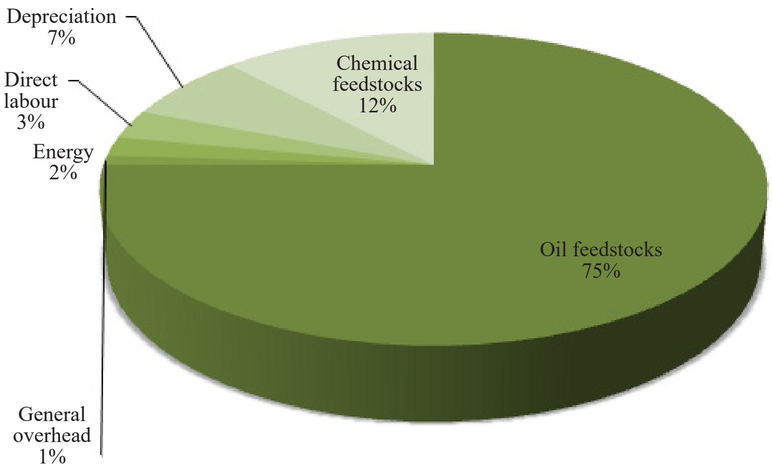

Figure 2. Breakdown of production costs for biodiesel

The global economy is significantly impacted by fluctuations in fossil fuel prices, including those of natural gas, coal, and oil. Increases in fuel prices often lead to increases in the costs of various commodities (Uihlein & Schebek, 2009). Cotton, a genetically engineered biotechnology crop with modified and identified Deoxyribonucleic Acid (DNA), has potential as a renewable and sustainable feedstock for biodiesel production (Elmore & Pearson, 2025). Several key properties of cottonseed crude oil, as analyzed by researchers, are presented in Table 2. Cotton crop production is largely driven by the needs of the textile industry, with cottonseed oil playing a minor role in biodiesel production. Traditionally, cotton crops have been used primarily for textiles, with cottonseed oil being a secondary product, which is used mainly in biodiesel and less so in cooking, thus having little effect on the food supply chain (Elmore & Pearson, 2025). Noted in their research on cottonseed oil biodiesel that the primary use of cotton crops has focused on the textile industry rather than on cottonseed oil for food and other uses. As the demand for biodiesel fuel increases, it is anticipated that cotton production will increase accordingly. This change could increase the use of cottonseed oil as a primary product for biodiesel, potentially benefiting the economic well-being of farmers and the agricultural sector. Nonetheless, significant research is needed to effectively manage the supply and demand of cottonseed oil for this purpose.

This review provides a comprehensive overview of the major production techniques used for cottonseed oil biodiesel, emphasizing key parameters such as catalyst type, solvent and cosolvent selection, reaction time, temperature, molar ratio, and the use of Supercritical Fluids (SCFs) that influence biodiesel yield. It critically analyzes previous research on biodiesel production via transesterification and further examines studies on the characterization, engine performance, emissions, tribological behavior, and Life Cycle Assessment (LCA) of cottonseed oil methyl ester. By consolidating these findings, this review identifies existing research gaps and outlines future directions to advance the development and optimization of cottonseed biodiesel.

Table 2. Properties of cottonseed oil

Density	Flash point	Acid value	Viscosity	Cloud point	Reference
At 20 °C			At 40 °C		
0.92 g/ml	289 °C	0.39 mg KOH/g	30.8 mm^2/s	+ 10 °C	Tefera et al., 2025

2. Biodiesel production through transesterification

Biodiesel is produced primarily through four main processing methods: pyrolysis, blending, microemulsion, and transesterification (Veličković et al., 2025). Among these methods, transesterification is the most commonly employed technique (Hu et al., 2025). Typical biodiesel feedstocks, such as vegetable oils or animal fats, consist of approximately 90-98% triglycerides and 1-5% free fatty acids, along with small amounts of diglycerides, monoglycerides, phosphatides, sulfur compounds, tocopherols, phospholipids, water traces, and carotenes (Mello et al., 2025). The renewable and environmentally friendly energy cycle of the cotton crop is illustrated in Figure 3.

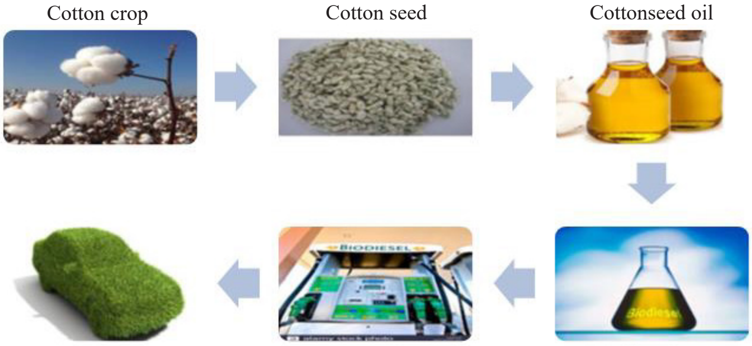

Figure 3. Process flow diagram depicting the conversion pathway from cotton crops to cottonseed oil, cottonseed oil, and biodiesel, demonstrating its integration as a renewable fuel within sustainable green transport systems

During the transesterification process, triglycerides are sequentially broken down into diglycerides, which are then converted into monoglycerides. These monoglycerides are ultimately transformed into esters (biodiesel), with glycerol generated as a byproduct (Mata et al., 2010). The transesterification reaction is represented by Eq. (1):

$$\text{Triglycerides} + \text{Alcohol} \rightleftarrows \text{Esters} + \text{Glycerol} \qquad (1)$$

Biodiesel is an alkyl ester formed through the thermochemical reaction of vegetable oils or animal fats with short-chain alcohols such as methanol or ethanol (Tefera et al., 2025). This transesterification reaction is typically carried out in the presence of catalysts such as sodium hydroxide (NaOH) or potassium hydroxide (KOH) to increase the reaction rate (Warabi et al., 2004). The process flow diagram for biodiesel production is shown in Figure 4. Biofuels derived from both edible and nonedible oils, as well as animal fats, via transesterification are suitable for use in internal combustion engines. These biofuels can also be blended with petroleum-based fuels for engine applications (Naik et al., 2010).

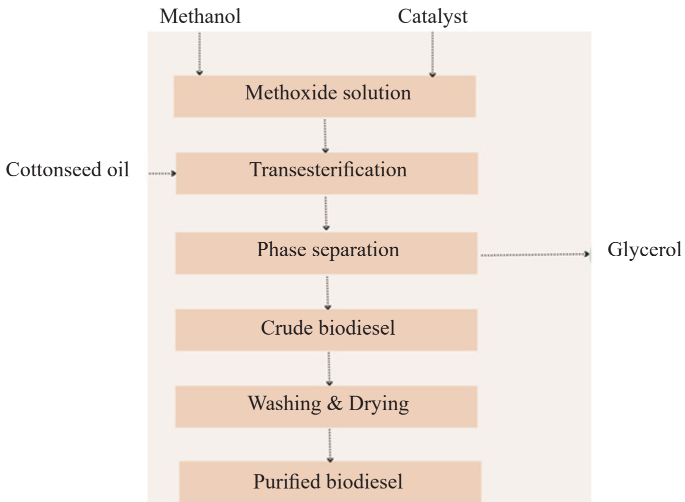

Figure 4. Process flow diagram for biodiesel production

3. Factors affecting the yield of biodiesel

3.1 *Catalyst*

Catalysts are typically used to accelerate the transesterification process (Yasvanthrajan et al., 2025). This method is generally classified into two main categories: catalytic transesterification and noncatalytic transesterification (Chouhan & Sarma, 2011). Catalytic transesterification can be further divided into homogeneous and heterogeneous processes (Hua et al., 2025). For homogeneous catalysis, both alkaline and acid catalysts are employed (Balat & Balat, 2010; Parawira, 2010). Common alkaline catalysts include sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium methoxide ($NaOCH_3$), and potassium methoxide ($KOCH_3$). These homogeneous alkali catalysts are widely used in industrial biodiesel production, typically within stirred reactors (Meher et al., 2006).

On the other hand, heterogeneous catalysts include a range of materials, such as enzymes, titanium silicates, alkaline earth metal oxides (e.g., SrO, MgO, and CaO), amorphous zirconia, titanium compounds, and potassium zirconia. Among these, potassium hydroxide and sodium hydroxide are the most frequently used materials by both researchers and manufacturers because of their effectiveness (Basha & Raja Gopal, 2012). Alkaline catalysts are preferred over acid catalysts because of their higher yield and faster reaction rates (Pramanik, 2003). Alhassan et al. (2014) reported that an optimal catalyst concentration of 0.75% (w/w) was effective across various cosolvents, regardless of their type or quantity.

Base-catalyzed transesterification is the most common approach in biodiesel research because of its low cost and high conversion efficiency. Typically, potassium or sodium hydroxide is dissolved in methanol, and the reaction is carried out at or near the boiling point of the alcohol to increase the reaction rate. An excess amount of alcohol is used to ensure the complete conversion of oil into biodiesel and glycerol, after which the alcohol is recovered by evaporation or distillation (Sharma et al., 2008). Owing to its high productivity and low operating costs, base-catalyzed transesterification can produce high-yield, high-quality biodiesel within 30-60 minutes (Marchetti et al., 2007). Acid catalysts such as phosphoric acid, hydrochloric acid, sulfuric acid, organic sulfonic acids, and ferric sulfate are generally more suitable for feedstocks with high Free Fatty Acid (FFA) contents. Some researchers have indicated that acid-catalyzed transesterification is more effective for these types of oils (Wang et al., 2025).

Enzymatic (lipase-based) catalysts have also shown promising results in biodiesel production (Yasvanthrajan et al., 2025). Diazomethane (CH_2N_2), for example, has proven effective in reducing the FFA content and performs better with long-chain fatty alcohols than with shorter chains. However, the high cost and relatively low reaction efficiency of lipase catalysts limit their large-scale industrial use. To address these challenges, advances such as solvent-tolerant lipases, immobilized enzyme systems, and multienzyme catalysts are being explored to develop more cost-effective enzymatic solutions for biodiesel production (Fukuda et al., 2001; Karmakar et al., 2010; Parawira, 2010).

3.2 *Solvent and cosolvent*

Researchers have explored the use of solvent-cosolvent systems comprising a hydrophobic solvent and a hydrophilic cosolvent in biodiesel production (Fu & Vasudevan, 2010). They reported that introducing a low concentration of cosolvent increased the biodiesel yield because of improved methanol diffusion. However, at higher cosolvent concentrations, lipase enzymes became deactivated, leading to a decline in biodiesel output. The polarity of the solvent-cosolvent mixture and the influence of the water content on lipase activity are critical factors affecting the efficiency of biodiesel synthesis.

Some studies suggest that the amount of cosolvent does not significantly impact the final methyl ester yield. For example, the use of hexane as a cosolvent in Supercritical Methanol (SCM) helps lower the oil viscosity, facilitating better reaction conditions (Sawangkeaw et al., 2007).

Additionally, researchers have carried out transesterification without a catalyst using SCM. They reported that the use of propane as a cosolvent allowed for reduced temperature and pressure requirements while still achieving high biodiesel yields. Propane also offers the advantage of being recyclable after suitable treatment, making the process more environmentally sustainable (Cao et al., 2005). Han et al. (2005) demonstrated that using carbon dioxide (CO_2) as a cosolvent significantly lowered the operating temperature and pressure of SCM, achieving a 98% ester yield under 14.3 MPa pressure maintained for 600 seconds. These findings indicate that cosolvents can effectively reduce both the reaction temperature and the required alcohol-to-oil molar ratio, contributing to a more efficient and sustainable biodiesel production process.

3.3 *Time*

The reaction time plays a crucial role in the efficiency of biodiesel production through transesterification. Researchers have noted that sufficient reaction time is required for a cosolvent solution to overcome the inter- and intramolecular forces within the solvent, which otherwise hinder mass transfer between reactants. At the initial stage of transesterification, the addition of the cosolvent to vegetable oil resulted in a cloudy mixture, indicating incomplete mixing (Alhassan et al., 2014).

To achieve full diffusion and optimal reaction conditions, adequate time must be allowed. However, the introduction of a cosolvent significantly reduced the required reaction time by up to five times without affecting the ester yield. The presence of a cosolvent accelerated the attainment of equilibrium, allowing up to 90% of the ester yield to be achieved within the first 10 minutes of the reaction. (Soriano et al., 2009). This faster reaction rate not only improves process efficiency but also makes biodiesel production more cost-effective and commercially viable.

3.4 *Temperature*

Two key variables that significantly affect biodiesel yield during transesterification are the reaction temperature and the molar ratio of alcohol to vegetable oil (Demirbas, 2008). In particular, the reaction temperature plays a crucial role in the transesterification of cottonseed oil for ester production (Mansourpoor & Shariati, 2012). Supercritical methods require elevated temperatures and pressures to achieve high ester yields (Revellame et al., 2010). Numerous studies have shown that the ester yield in homogeneous transesterification is highly sensitive to the reaction temperature. The chemical properties of the solvents used also greatly influence the reaction environment and overall efficiency (Talebian-Kiakalaieh et al., 2013).

However, excessive reaction temperatures, especially those exceeding the boiling point of methanol (64.7 °C), can lead to methanol evaporation, which reduces the biodiesel yield. The yield typically increases with increasing temperature up to the boiling point of methanol (Royon et al., 2007). Research has shown that the optimal reaction temperature for maximizing cottonseed oil biodiesel yield is approximately 65 °C (Okitsu et al., 2013). Maintaining the reaction temperature near the boiling point of methanol ensures optimal conversion efficiency and biodiesel yield.

3.5 *Molar ratio*

The molar ratio of methanol to oil is a critical parameter in the transesterification process (Agarwal et al., 2012). Owing to the reversible nature of the reaction, the use of excess methanol drives the reaction forward, increasing the biodiesel yield. Studies have shown that increasing the methanol-to-oil molar ratio generally leads to increased biodiesel production (Fadhil & Abdulahad, 2014). For cottonseed oil, the optimal molar ratio for maximum yield is 6 : 1 (Rashid et al., 2009). However, using methanol in excess can increase production costs, as more energy and time are required to separate and recover biodiesel from unreacted methanol.

3.6 *SCF*

SCF such as methanol or ethanol are used in the SCM process for biodiesel production. This method offers several advantages, including a rapid reaction time, high conversion efficiency, elimination of the need for a catalyst, and broad adaptability to various feedstocks. However, it also has notable drawbacks, such as the requirement for high temperatures and pressures, substantial energy consumption, and the high cost of specialized SCM equipment (Lin et al., 2011).

4. Production of biodiesel from cottonseed oil through transesterification

Researchers have previously conducted experiments and optimized various production parameters to increase the biodiesel yield from cottonseed oil through transesterification (Alhassan et al., 2014). This optimization involved adjusting factors such as the reaction temperature, stirring speed, and type of catalyst used.

4.1 *The effect of catalysts on biodiesel yield in the transesterification process*

Qing Shu et al. (2009) achieved a biodiesel yield of 89.93% using a methanol-to-oil molar ratio of 18.2 : 1, with the reaction carried out at 260 °C for 3 hours. Compared with sulfonated multiwalled carbon nanotubes, asphalt-based catalysts demonstrated greater activity, effectively reducing both energy consumption and waste generation during biodiesel production.

Rashid et al. (2009) optimized transesterification parameters for biodiesel production and identified sodium methoxide as the most effective catalyst among potassium hydroxide (KOH), sodium hydroxide (NaOH), and potassium methoxide ($KOCH_3$). The process yielded an average of 96.9% biodiesel, meeting the ASTM D6751 and EN14214 standards. The optimized conditions included a catalyst concentration of 0.75%, a methanol-to-oil molar ratio of 6 : 1, a stirring rate of 600 rpm, and a reaction temperature of 65 °C.

Mahdavi and Monajemi (2014) developed ethyl ester biodiesel via transesterification using a CaO-MgO (8 : 2)/Al_2O_3 solid catalyst. A 92.45% conversion rate was achieved at 95 °C with an ethanol-to-cottonseed oil molar ratio of 8.5 : 1.

Chattopadhyay et al. (2011) reported 80% biodiesel conversion via biocatalytic transesterification. A low-cost pancreatic lipase enzyme was employed as the catalyst in the presence of t-butanol as the organic solvent. The optimized reaction conditions included a temperature of 37 °C, pH of 7.0, a 1 : 15 oil-to-methanol molar ratio, 0.5% (w/w) enzyme concentration, and a reaction time of 4 hours.

4.2 *The effect of heating mode on cottonseed oil biodiesel yield*

Azcan and Danisman (2007) produced biodiesel from cottonseed oil via the transesterification process and compared conventional heating with microwave-assisted heating. The biodiesel yield ranged from 89.5% to 92.7%, with purity levels between 78.9% and 99.8%. Microwave irradiation significantly reduced the reaction time from 30 minutes to just 7 minutes, demonstrating that microwave heating can greatly accelerate the biodiesel production process.

4.3 *The effect of t-butanol as a solvent on cottonseed oil biodiesel yield*

Royon et al. (2007) achieved a 97% biodiesel yield from cottonseed oil using *t*-butanol as the solvent in the transesterification process. The reaction was conducted at 50 °C for 24 hours, with the mixture comprising 54% oil, 13.5% methanol, and 32.5% enzyme.

4.4 *The effect of noncatalytic supercritical fluids on cottonseed oil biodiesel*

Some researchers have produced biodiesel with a viscosity of 3.6-4.0 mm^2/s at 311 K, Higher Heating Values (HHVs) of approximately 40.5 MJ/kg, and flash points ranging from 435 to 445 K using noncatalytic supercritical fluids such as methanol and ethanol. They also emphasized that the reaction temperature and alcohol-to-oil molar ratio significantly influence the biodiesel yield (Demirbas, 2008). These findings indicate that cottonseed oil biodiesel can be effectively produced using supercritical fluids without the need for a catalyst. The resulting biodiesel meets the physicochemical property requirements specified by the ASTM D6751 standard.

4.5 *Effect of cosolvents on cottonseed oil biodiesel yield*

Alhassan et al. (2014) successfully produced biodiesel that met ASTM standards. They investigated the effects of three Cosolvents-dichlorobenzene (CBN), Diethyl Ether (DEE), and Acetone (ACT)-in combination with varying concentrations of Methanol (MeOH). The optimal reaction conditions were 55 °C for 10 min and a catalyst concentration of 0.75% (w/w). The highest biodiesel yield was achieved with a 10% (v/v) concentration of either acetone or dichlorobenzene. The study concluded that, in addition to the improvement in the caloric value, the proportion of cosolvents had a minimal effect on the overall fuel properties.

4.6 *The effects of methylic and ethylic routes on biodiesel production*

Table 3. Yields obtained from cottonseed oil feedstock by numerous researchers

Sr. No.	Production method for biodiesel	Feedstock for biodiesel	Yield (%)	Reference
01	Transesterification	Cottonseed oil	98.5-99.9%	Liang et al., 2010
02	Transesterification	Cottonseed oil	96.9%	Rashid et al., 2009
03	Transesterification	Cottonseed oil	96.85%	Alhassan et al., 2014
04	Transesterification	Cottonseed oil	91.5%	Fernandes et al., 2012
05	Transesterification	Cottonseed oil	92.45%	Mahdavi and Monajemi, 2014
06	Transesterification	Cottonseed oil	75-80%	Chattopadhyay et al., 2011
07	Transesterification (Authors' yield)	Cottonseed oil	98.3%	Jamshaid et al., 2019

Another researcher produced both methyl and ethyl biodiesel from cottonseed oil through transesterification, achieving yields of 91.5% and 88.5%, respectively, from triglycerides to esters. They reported that all the resulting biodiesel properties met the EN14214 standards, with the exception of oxidation stability. However, the oxidation stability was improved to over 6 hours by adding 33 mg of the antioxidant Tert-Butylhydroquinone (TBHQ) to the oil (Fernandes et al., 2012). These findings indicate that the methyl route yields higher biodiesel output than the ethyl route does. A summary of the cottonseed oil biodiesel yields obtained under various experimental conditions is presented in Table 3.

5. Characterization of cottonseed oil methyl ester

Biodiesel properties such as the Cold Filter Plugging Point (CFPP), pour point, Oxidation Stability Index (OSI), low-temperature flow behavior, and cloud point are significantly affected by climate conditions. To ensure optimal engine performance regardless of atmospheric parameter variations, these properties must be optimized for reliable use in internal combustion engines (Ong et al., 2013). The fatty acid composition of biodiesel varies depending on its feedstock, with over 350 oil-bearing crops from both agricultural and forest sources identified as potential biofuel sources (Jamieson, 1943; Kapilan et al., 2009). Biodiesel typically contains both saturated and unsaturated fatty acids (Li et al., 2011). Studies have shown that cottonseed biodiesel contains a greater proportion of unsaturated fatty acids than saturated biodiesel does (Rashid et al., 2009).

5.1 *OSI*

The OSI represents a fuel's resistance to degradation during storage. In the case of cottonseed oil methyl ester, the high content of polyunsaturated fatty acids such as linolenic (C18 : 3) and linoleic (C18 : 2) acids makes the double bond sites highly prone to oxidation, thereby lowering the overall oxidative stability of biodiesel (Yeneneh & Sufe, 2025). Therefore, extensive research efforts are needed to improve the oxidation stability of cottonseed oil biodiesel to comply with ASTM biodiesel standards. Several other factors, such as heat, light exposure, fatty acid composition, metal contaminants, and air, can influence the OSI (Vieira et al., 2025).

Researchers have reported that incorporating antioxidants can significantly increase the oxidation stability of cottonseed oil methyl ester. For example, the addition of 300 mg/kg TBHQ reportedly extends the OSI beyond six hours (Huerga et al., 2014; Ong et al., 2013).

5.2 *Pour point and cloud point*

When biodiesel is cooled, it begins to form wax crystals. The temperature at which these crystals first appear is called the cloud point. The pour point refers to the lowest temperature at which biodiesel remains capable of flowing (Demirbas, 2005; Fernando et al., 2007; Friday & Okano, 2006).

These properties can be measured via standards such as ASTM D2500, D97, and EN ISO 23015 (Fernando et al., 2006). According to the literature, the cloud point and pour point for cottonseed oil biodiesel are approximately -2 °C and -4 °C, respectively (Demirbas, 2005).

5.3 *CFPP*

The CFPP is the temperature at which biodiesel fails to pass through a standard test filter within a specified time under controlled conditions (Zuleta et al., 2012). At temperatures below the CFPP, biodiesel begins to form crystals or gel-like structures, leading to filter blockage (Meher et al., 2006; Moser & Vaughn, 2010; Sanford et al., 2009). This crystallization affects the performance of fuel systems in cold climates, potentially causing issues with injectors, fuel pumps, and fuel lines due to restricted fuel flow (Moser & Vaughn, 2010).

5.4 *Density*

Density plays a crucial role in the performance of biodiesel in internal combustion engines. According to several researchers, density and viscosity are influenced by the acid value of biodiesel; as the acid value increases, both the density and viscosity also increase. Cottonseed oil has a density ranging from 0.917 g/cm^3 to 0.933 g/cm^3. Generally, higher-density oils possess greater energy content than lower-density oils do (Schumacher et al., 1995). Density measurements are typically taken at standard temperatures of 15 °C or 20 °C. The density values of cottonseed oil biodiesel are presented in Table 4.

Table 4. Properties of cottonseed oil biodiesel

Property	Other researcher results of measured properties (Elmore and Pearson, 2025)	Author's Results of measured properties (Jamshaid et al., 2019)
Kinematic viscosity at 40 °C	3.89-7.91 cSt	4.15 mm^2/s
Density	0.855-0.9 g/ml at 25 °C	864 kg/m^3 at 40 °C
Cloud point	(-3)-17 °C	7
Pour point	(-15)-16 °C	6
Flash point	96-188 °C	> 160 °C
Calorific value	-	39.41 MJ/kg
Acid value	-	0.19 mg KOH/g

5.5 *Viscosity*

Kinematic viscosity is a critical property of biodiesel, as it directly influences fuel atomization during engine combustion (Alviso et al., 2020; Anwar et al., 2010). Although the type and quantity of cosolvent used have minimal effects on viscosity, it is highly sensitive to temperature changes (Murugesan et al., 2009). Research has shown that biodiesel typically has a higher viscosity than petroleum diesel does, primarily because of its larger molecular structure, which also causes it to solidify at lower temperatures (Shirazi et al., 2019). Elevated viscosity can negatively affect the fuel injection system and reduce the flow rate of biodiesel within the engine (Lin et al., 2009). The kinematic viscosity values for cottonseed oil biodiesel are presented in Table 4.

5.6 *Specific value*

The calorific value represents the amount of energy released upon burning a unit quantity of fuel. For biodiesel, this value is typically determined via the ASTM D4239 standard. The moisture content of fuel can significantly affect its calorific value (Filemon & Uriarte, 2010). The properties of cottonseed oil methyl ester, including its calorific value, are provided in Table 4.

6. Performance

6.1 *BTE*

Mangesha et al. (2025) reported that the addition of nanoparticles to cottonseed oil biodiesel led to reduced emissions and increased Brake Thermal Efficiency (BTE) in internal combustion engines. Multiple researchers have reported that preheating cottonseed oil methyl ester to 120 °C and 90 °C results in higher BTE than preheating at 30 °C and 60 °C. This improvement in BTE was attributed to a reduction in kinematic viscosity and specific gravity. During these tests, engine speeds ranged from 1,800 to 3,200 rpm, and fuel heating systems were incorporated (Karabektas et al., 2008).

Kumar and Manimaran (2013). noted that the BTE of cottonseed biodiesel blends declined due to increased fuel consumption. Similarly, Nabi et al. (2009) reported that BTE initially increased with engine speed but then began to decrease beyond a certain point. Diesel has a slightly greater BTE than biodiesel does, which is linked to its greater calorific value, since a higher energy content enhances engine efficiency (Shirazi et al., 2020).

Augustine et al. (2012) experimentally determined that injecting preheated cottonseed biodiesel at 100 °C into a single-cylinder, four-stroke compression ignition engine yielded a lower BTE than at 80 °C and was even lower than that of conventional diesel. Among the various preheating temperatures (20 °C, 40 °C, 60 °C, 80 °C, and 100 °C), 80 °C emerged as the optimal temperature for achieving the maximum BTE.

Other studies reported that preheated blends of cottonseed biodiesel presented greater BTE than did diesel. In particular, the B40 blend presented the highest BTE due to its enhanced combustion performance. The blends tested included B0, B20, B40, B60, and B100 (Verma & Singh, 2014). Kale and Prayagi (2012) used a single-cylinder, four-stroke Kirloskar vertical diesel engine at 1,500 rpm and reported greater BTE for cottonseed biodiesel than for diesel. In contrast, Kumar and Manimaran (2013) reported a lower BTE for B40 and B100 than for B5, B10, and B20, which was attributed to the higher calorific value of lower blends while maintaining a constant engine speed of 2,600 rpm.

6.2 *BSFC*

Brake Specific Fuel Consumption (BSFC) refers to the relationship between the amount of fuel consumed and the power output of an engine. Woldetensy et al. (2025) reported that blending cottonseed and castor oil biodiesel with conventional diesel resulted in an increase in BSFC. It is a critical parameter for assessing engine performance (Vellaiyan, 2025) and is typically expressed in kg/kWh. Kumar and Kumar (2012) examined BSFC relative to engine load and reported that as the load increased, the BSFC for cottonseed biodiesel blends decreased.

Aydin and Bayindir (2010) studied BSFC at full engine load and 2,000 rpm for cottonseed biodiesel blends B5 and B20. They reported BSFC values of 174 g/kWh for B5, 179 g/kWh for B20, and 168 g/kWh for diesel. For higher blends-B50, B75, and B100-the BSFC increased to 194 g/kWh, 198 g/kWh, and 205 g/kWh, respectively. This variation was attributed to the lower calorific value and higher viscosity of the biodiesel blends than those of conventional diesel. Interestingly, at full load and low engine speed, B20 displayed the lowest BSFC among all the tested blends and diesel, likely due to more complete combustion.

Chattopadhyay and Sen (2013) also confirmed experimentally that the BSFC decreased as the engine load increased. They recorded average BSFC values of 0.407 kg/kWh for diesel, 0.415 kg/kWh for B10, and 0.418 kg/kWh for B20. The slight differences in BSFCs with different blend ratios were attributed to the low calorific value and high viscosity of the biodiesel blends. Since viscosity is correlated with fuel density, more viscous fuels tend to have higher dynamic viscosity, resulting in reduced flow and poor atomization in the combustion chamber. Fuel blends with viscosities closer to those of diesel offer better atomization and combustion efficiency (Dahmen & Marquardt, 2016).

Nabi et al. (2009) conducted experiments using a single-cylinder, four-stroke, water-cooled, direct injection diesel engine with cottonseed biodiesel blends. Their findings indicated a reduction in BSFC with increasing torque for diesel. They also noted that BSFC values for pure biodiesel were generally higher than those for cottonseed biodiesel blends under identical loads. Verma and Singh (2014) reported a decrease in BSFC with increasing engine load for both cottonseed biodiesel blends and pure biodiesel. The BSFC values at full load for diesel, B0, B20, B40, B60, and B100 were 0.2762, 0.2728, 0.2559, 0.2786, and 0.3484 kg/kWh, respectively. They reported that at lower blend ratios, BSFC was actually lower than that for diesel, but it increased steadily as the biodiesel concentration rose from 0% to 100%.

Altun et al. (2011) used a Rainbow-186 engine (a four-stroke, single-cylinder, naturally aspirated, direct injection engine) and concluded that the BSFC decreased with increasing load for all cottonseed biodiesel blends and diesel. However, the BSFC remained higher for biodiesel blends than for diesel blends across all loads. Augustine et al. (2012) performed similar tests on a Kirloskar TV-1 diesel engine (660 cc displacement, compression ratio 17.5 : 1, water-cooled single-cylinder). Their results revealed higher BSFC values for biodiesel blends than for diesel. Specifically, the BSFC was reported to be 269 g/kWh for diesel and 345 g/kWh for 100% biodiesel. The increase was attributed to the lower calorific value, higher viscosity, and greater density of biodiesel than of diesel.

7. Emissions

Methyl and ethyl esters derived from various biodiesel feedstocks can be blended with petroleum diesel for use in internal combustion engines to increase fuel efficiency. In today's context, where air pollution poses a significant challenge globally, biodiesel stands out as a promising alternative for cleaner energy production. Compared with conventional diesel, it is a biodegradable, nontoxic fuel suitable for internal combustion engines and offers environmental benefits by significantly reducing the emissions of carbon monoxide, carbon dioxide, unburned hydrocarbons, polycyclic hydrocarbons, and sulfur.

7.1 *CO emissions*

Several researchers have investigated engine emissions via blends of cottonseed biodiesel and renewable diesel. Their studies revealed that CO emissions were lower for biodiesel blends than for conventional diesel fuel. Baluchamy et al. (2025) utilized cottonseed oil biodiesel in an internal combustion engine and reported a reduction in CO emissions compared with those of conventional diesel. This reduction is attributed to the higher oxygen content in biodiesel, which promotes more complete and cleaner combustion than petroleum diesel does (Von Wedel, 1999).

Experiments measuring CO emissions for various cottonseed oil methyl ester blends (B5, B20, B50, B75, and B100) across engine speeds ranging from 1,250 rpm to 2,500 rpm consistently revealed reduced CO levels compared with petroleum diesel (Aydin & Bayindir, 2010).

Notably, blends with higher biodiesel contents (B50, B75, and B100) resulted in greater reductions in CO emissions due to increased oxygen availability, facilitating better oxidation of CO into CO_2 (Pinto et al., 2005). Some studies reported up to a 33.3% decrease in CO emissions when biodiesel blends were used instead of diesel. The average measured CO emission values were 0.033% for B10, 0.029% for B20, and 0.046% for diesel, highlighting the improved combustion efficiency of biodiesel blends (Enweremadu & Rutto, 2010).

Additional experimental findings revealed that, compared with diesel, cottonseed biodiesel reduced CO emissions by 14.40% to 45.66%, especially when the biodiesel was preheated before injection (Chouhan & Sarma, 2011). Preheating lowers viscosity, enhances oxidation, and improves combustion due to the intrinsic oxygen content of biodiesel (Canakci, 2007).

Martin and Prithviraj (2011) reported that preheated cottonseed biodiesel emitted less CO than unheated biodiesel did, indicating a higher combustion efficiency. Numerous researchers have also noted that introducing biodiesel into compression ignition engines lowers CO emissions, with greater reductions observed at higher biodiesel blending ratios, again owing to improved oxygen-driven combustion.(Altun et al., 2011).

7.2 *Nitrogen Oxide (NO_x) emissions*

NOx formation occurs through three primary mechanisms: thermal, prompt, and fuel NO_x. In the fuel NO_x mechanism, nitrogen compounds present in the fuel are oxidized to form NO_x. However, since the natural nitrogen content in both diesel and biodiesel is minimal, this mechanism is generally considered negligible. The prompt NO_x mechanism involves reactions between Hydrocarbon (HC) radicals (such as CH and CH_2) and atmospheric nitrogen (N_2) during combustion. These reactions form intermediate species containing carbon and nitrogen, which then react with oxygen to produce NO_x. Prompt NO_x is typically significant only under fuel-rich conditions, where sufficient hydrocarbon fragments are present to initiate these reactions. Thermal NO_x, which is considered the dominant mechanism, occurs when nitrogen (N_2) and oxygen (O_2) in air react at high temperatures through a series of chemical reactions known as the Zeldovich mechanism. This temperature-dependent process is the main contributor to total NO_x emissions in combustion systems (Fernando et al., 2006).

Wang et al. (2025) reported that biodiesel blends presented higher NO_x emissions than did conventional diesel. In terms of emissions, biodiesel generally produces higher NO_x levels than petroleum diesel does. Experimental studies reported NO_x emissions of 284.42 ppm for pure diesel (Aydin & Bayindir, 2010), whereas cottonseed biodiesel blends B10 and B20 produced 330.33 ppm and 336.67 ppm, respectively. This increase in NO_x emissions is attributed primarily to the higher oxygen content in biodiesel, which enhances combustion temperatures and promotes NO_x formation. Researchers have emphasized that the oxygen content in biodiesel plays a more significant role in NO_x generation than does the oxygen supplied by ambient air during combustion (Chattopadhyay & Sen, 2013).

7.3 *Sulfur dioxide (SO_2) emissions*

Sulfur emissions from biodiesel combustion in internal combustion engines are significantly lower than those from petroleum diesel. Studies have shown that, compared with conventional diesel, burning biodiesel blends results in a reduced percentage of Sulfur dioxide (SO_2) emissions. In fact, when 100% biodiesel is used, SO_2 emissions can be nearly nonexistent. This is primarily because biodiesel contains little to no sulfur, unlike conventional diesel fuel (Aydin & Bayindir, 2010). As a result, the absence of sulfur in biodiesel leads to much lower sulfur emissions during combustion.

7.4 *HC emissions*

Studies by various researchers have shown that unburned HC emissions result primarily from the incomplete combustion of fuel. HC emissions tend to rise with increasing engine load. The average HC emissions recorded for petroleum diesel, B10, and B20 were 96.25 ppm, 70.58 ppm, and 65.25 ppm, respectively. A consistent reduction in HC emissions was observed with higher biodiesel content in the fuel blends. Compared with pure petroleum diesel, biodiesel blends produce significantly lower HC emissions when used in internal combustion engines (Chattopadhyay & Sen, 2013).

7.5 *EGT*

The Exhaust Gas Temperature (EGT) is an important indicator used to assess the thermal output of burned fuel within an engine over a given time. Various researchers have reported EGT values for different blends of cottonseed oil methyl esters (B5, B20, B50, B75, and B100) in comparison to those of conventional petroleum diesel (Aydin & Bayindir, 2010). Preheating cottonseed oil biodiesel can lead to lower EGT values, primarily because of decreased fuel viscosity and more complete combustion (Martin & Prithviraj, 2011). A summary of previous studies on the performance and emission characteristics of cottonseed oil biodiesel blends is presented in Table 5.

Table 5. Summary of previous research regarding the performance of cottonseed oil biodiesel

Sr. No.	Variables	Engine type	Findings	Ref.
01	BTE BSFC *ISFC Viscosity	Kirloskar engines Ltd. Four-stroke single-cylinder, constant speed	BTE for B20 is higher than diesel. Smoke and emissions for COME is less as compared to pure diesel, The viscosity of B5 is less compared to B10, B15 & B20.	Kumar and Kumar, 2012
02	BSFC BTE EGT CO CO_2 NOx HC Smoke	Kirloskar diesel engine, four-stroke single-cylinder, water-cooled, 5HP, and 1,500 rpm speed	B10 and B20 showed reductions in CO, CO_2, and smoke emissions as compared to pure diesel.	Chattopadhyay and Sen, 2013
03	BSFC BTE	Diesel engine	BTE was more for preheated B20, B40, B60.	Verma and Singh, 2014
04	Compared Indicated thermal efficiency and BTE of COME blends	Kirloskar engine, Single cylinder, four-stroke, vertical diesel engine	At a constant speed of 1,500 rpm, the value of BTE and indicated thermal efficiency is more as compared with petroleum diesel.	Kale and Prayagi, 2012
05	*SFC CO BTE HC NOx CO	Greaves Engine, Single cylinder, speed 2,600 rpm	Specific fuel consumption depends on the load and brake power. Emissions were lower for biodiesel than petrol diesel.	Kumar and Manimaran, 2013
06	BTE Smoke EGT CO HC	Single cylinder, 4 stroke diesel engine, water-cooled	Preheated COME increase thermal efficiency, EGT decreased due to preheated COME Smoke was reduced by preheated COME.	Martin and Prithviraj, 2011

Table 5. (cont.)

Sr. No.	Variables	Engine type	Findings	Ref.
07	BSFC BTE NOx EGT HC CO smoke in exhaust	Rainbow-186, single-cylinder four-stroke compression ignition diesel engine and naturally aspirated, compression ratio 18 : 1	Fuel performance of B20 with the Addition of n-butanol performed better as compared to the biodiesel-diesel blend in single cylinder 4 stroke diesel engine.	Altun et al., 2011
08	BP BSFC BTE HC CO NOx Smoke opacity	Single-cylinder, 4-stroke, and the natural aspiration diesel engine were used for engine testing	All combined blended fuels have low BTE and emitted fewer hydrocarbons, carbon monoxide, and smoke opacity apart from nitrogen oxides compared with petroleum diesel fuel.	Author's results (Jamshaid et al., 2022)

*ISFC-Indicated Specific Fuel Consumption
*SFC-Specific Fuel Consumption

8. Tribological characteristics of biodiesels

Tribological properties are crucial in determining the overall quality of a fuel. These properties play a vital role in extending machine life and minimizing wear between moving components. By reducing friction at the contact surfaces of moving parts, energy consumption can also be significantly reduced (Tung & McMillan, 2004).

In internal combustion engines, fuel acts as a lubricant for key components such as fuel injectors, pumps, valve systems, and cylinder liners. Therefore, the fuel must possess adequate tribological properties to protect these parts, especially since fuel temperatures at the engine inlet typically exceed 60 °C (Knothe & Steidley, 2005; Serrano et al., 2012). Elevated temperatures can impact the lubricating behavior of fuel, particularly in injectors and pumps (Nwafor, 2003).

Compared with conventional petroleum diesel, biodiesel offers several technological benefits, including biodegradability, a higher flash point, and lower engine emissions (Fazal et al., 2011; Kannan et al., 2012; Ozsezen & Canakci, 2011). One notable advantage of biodiesel is its superior lubricity (Haseeb et al., 2010a), which is attributed to the presence of unsaturated fatty acid components (Geller & Goodrum, 2004). However, biodiesel also presents several limitations, such as potential clogging of filtration systems and injector fouling. These drawbacks can hinder its broader application, despite its environmental and technological advantages (Fazal et al., 2011). Cottonseed oil biodiesel possesses relatively low oxidation stability, which can result in injector choking, deposit formation, and reduced engine durability. Therefore, further research is needed to explore the use of antioxidants to increase their oxidative stability, ensuring better engine performance, longer service life, and improved fuel efficiency in future applications (Amran et al., 2022). While various studies have examined the friction and wear characteristics of biodiesel, further investigations are needed to assess the effects of different biodiesel types and blends on specific engine components, such as cylinder liners, valves, and fuel injectors (Habibullah et al., 2015; Hamdan et al., 2017; Haseeb et al., 2010). Jamshaid et al. (2022) experimentally determined the Coefficient of Friction (COF) and wear coefficient of all B20 blends and petroleum diesel fuel via a HFRR and reported that both values were lower for blends than for petroleum diesel. The unsaturated fatty acids present in cottonseed biodiesel significantly enhance its tribological performance, helping to reduce friction and wear in automotive mating components, particularly in systems where the fuel itself provides lubrication, such as the piston, piston ring, cylinder liner, fuel pump, fuel injector, fuel tank, and fuel lines.

9. LCA of cottonseed oil biodiesel

LCA is used to evaluate the environmental impacts of cottonseed oil biodiesel production, from processing to final disposal. As outlined in the ISO (2006) framework, LCA includes four phases: goal and scope, Life Cycle Inventory (LCI), Life Cycle Impact Assessment (LCIA), and critical analysis. Studies on biodiesel LCA highlight the need for improvements to make the process more environmentally sustainable (Hosseinzadeh-Bandbafha et al., 2022).

Studies across various countries have shown that biodiesel reduces environmental impacts. Compared with those of diesel, the LCA results for algae and jatropha biodiesel yield 36-40% lower greenhouse gas emissions and 10-25% less fossil energy use (Ajayebi et al., 2013). Similar reductions in CO_2 emissions were observed with the use of cooking oil biodiesel (Sajid et al., 2016).

Garraín et al. (2014) reported that applying industrial symbiosis can enhance the environmental performance of biofuels, although benefits vary by impact category and depend on allocation methods and energy systems. Similarly, Amouri et al. (2017) reported that second-generation biodiesel from Ricinus communis in Algeria is a promising energy-efficient alternative.

LCA studies on cottonseed oil biodiesel have shown various key impact stages. Lima et al. (2017) identified agriculture, mainly fertilizer and pesticide use, as the largest contributor across impact categories, whereas Saleh et al. (2025) reported that cotton ginning, oil extraction, and refinement had the greatest impacts, with transesterification contributing the least.

Biodiesel production demands significant material and energy inputs and releases emissions to air and water, making all production stages important to consider, as shown in Table 6. Thus, LCA serves as an effective tool to assess renewable energy options and guide policymakers in selecting suitable sources.

Table 6. LCA studies of various biodiesel feedstocks with their boundaries and findings

Serial No.	LCA study's boundary	Findings	feedstock	Reference
1	• Cotton cultivation • Cotton ginning • Oil extraction • Oil refinement • transesterification	Cotton ginning, oil extraction and oil refinement shared the highest environmental and transesterification shared the least	cotton	Saleh et al., 2025
2	• Agriculture • Processing (ginning) • Oil extraction • Oil refinement • transesterification	Agriculture phase shared most environmental impact with mainly due to the application of pesticides and fertilizers	cotton	Lima et al., 2017
3	• Seed production • Oil extraction • Biodiesel production	Fertilizers and energy use shared the most environmental impact	tobacco	Carvalho et al., 2019
4	• Plantation • Seed harvest and separation • Oil extraction • Biodiesel production • Byproduction application • Biodiesel transportation • Biodiesel utilization	Fertilizer application, combustion of jatropha sells, and methanol production affected the environment with NOx and dust emissions	Jatropha	Liu et al., 2024
5	• Respective raw materials • Their production • Harvesting, transportation, oil extraction (for jatropha oil) • Biodiesel production • Biodiesel end use	Crops growing and cultivation showed higher environmental impact compared to waste cooking oil process	Jatropha and waste cooking oil	Sajid et al., 2016

10. Conclusions

Biotech cotton crops hold significant potential as renewable energy sources for internal combustion engines. The alkaline transesterification process has proven to be a cost-effective method for large-scale biodiesel production. Studies have shown that the physicochemical characteristics of cottonseed oil biodiesel meet the required ASTM and EN fuel standards. However, the BTE of cottonseed biodiesel remains lower than that of conventional petroleum diesel across all tested engine speeds. Cottonseed oil biodiesel possesses relatively low oxidation stability, which can result in injector choking, deposit formation, and reduced engine durability. Therefore, further research is needed to explore the use of antioxidants to increase their oxidative stability, ensuring better engine performance, longer service life, and improved fuel efficiency in future applications.

Cottonseed biodiesel offers environmental benefits because of its sulfur-free composition and inherent oxygen content, which enhances combustion and helps reduce harmful exhaust emissions. From a tribological perspective, however, biodiesel fuels often face compatibility challenges with various engine components, such as fuel injectors, pumps, valve systems, and cylinder liners. The presence of unsaturated fatty acids in biodiesel, particularly in cottonseed oil, contributes positively to its lubricating properties. Research studies indicate that LCA is a valuable tool for evaluating renewable energy alternatives and assisting policymakers in identifying appropriate options.

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Conflict of interest

The authors declare that he has no competing interests.

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