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A Comprehensive Review on 1st-Generation Biodiesel Feedstock Palm Oil: Production, Engine Performance, and Exhaust Emissions

Digambar Singh[1] · **Dilip Sharma**[1] · **S. L. Soni**[1] · **Chandrapal Singh Inda**[2] · **Sumit Sharma**[1] · **Pushpendra Kumar Sharma**[1] · **Amit Jhalani**[1]

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Abstract

The rapid depletion of conventional fuel reserves and the increase in environmental pollution prompted the search for a sustainable energy solution. Biodiesel is one of the most promising energy substitutes with similar properties as conventional diesel fuel. Surplus availability of palm oil makes it suitable for biodiesel production. Due to the lack of availability of review articles that cover the entire process of palm biodiesel production and its optimum use in diesel engines, the authors were motivated to write this article. Cultivation parameters of palm trees, extraction of oil, and physicochemical properties of palm oil–based biodiesel are explained in this review. The production of palm biodiesel from raw oil can be done through pyrolysis, micro-emulsification, blending, hydro-esterification, and transesterification processes. For high biodiesel yield and less cost of operation, the transesterification method is adopted. The performance and emission parameters of diesel engines that operated on palm biodiesel and its blends are also explained. There is a decrease in brake thermal efficiency and an increase in brake-specific fuel consumption observed with the use of palm biodiesel in diesel engines. A reduction in CO and HC emissions and an increase in NOx emissions are found due to the oxygenating nature of palm biodiesel. This article provides the scientific approach to find out the optimum parameters for palm biodiesel production and its efficient use in compression ignition engines.

Keywords Edible oil feedstock · Palm biodiesel · Biodiesel standards · Physicochemical properties · Palm oil fatty acid profile

Nomenclature

ASTM	American Society for Testing and Materials
BTE	Brake thermal efficiency
CI	Compression ignition
CN	Cetane number
SVO	Straight vegetable oil
CPO	Crude palm oil
BX	Biodiesel blend level
BP	Brake power
EASAC	European Academies' Science Advisory Council
FFA	Free fatty acid
BSFC	Brake-specific fuel consumption
FAME	Fatty acid methyl ester
RPM	Rotation per minute
PM	Particulate matter
SIT	Self-ignition temperature
MW	Molecular weight
AN	Acid number
CP	Cloud point
SV	Saponification value
PP	Pour point
OSI	Oxidation stability index
FP	Flash point
MTBE	Methyl tert-butyl ether
IV	Iodine value
DI	Direct injection
HHV	Higher heating value
IDI	Indirect injection
WC	Water cooled
AC	Air cooled
S	Stroke

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✉ Digambar Singh
2017rme9033@mnit.ac.in

[1] Department of Mechanical Engineering, Malaviya National Institute of Technology Jaipur, Jaipur, Rajasthan, India

[2] Department of Mechanical Engineering, Faculty of Engineering, Jai Narain Vyas University, Jodhpur, Rajasthan, India

Introduction

The global energy structure relies heavily upon fossil fuels, and the use of these fuels is increasing rapidly. The reserves of petroleum will soon be exhausted because of its non-renewable nature. Petroleum-based fuel prices increase much higher because of the variation between supply and demand. The increase in environmental issues also stimulates the ongoing quest for new alternative sources of energy. To produce the fuels that could replace petroleum derivatives, researchers have concentrated on developing new basic sources of energy. In this search, biofuel is in the highest position because of its renewable energy nature, broad availability, and biodegradability [1]. In regard to the effects of emissions and global climate change and in line with the Kyoto Protocol, energy production should be modified to become more sustainable with lesser emissions [2–13]. The elimination of greenhouse gas pollution is never possible without environmentally sustainable renewable resources. Biofuels are a viable renewable fuel that can be combined with fossil fuels [14]. Two well-known biofuels are ethanol and biodiesel, which can be the substitute for petroleum gasoline and diesel fuel, respectively. Biodiesel, because it can minimize pollution, is a cleaner and more efficient alternative to conventional fuels [15, 16]. Several countries have established biodiesel regulations to cope with a range of concerns of fuel quality due to the characteristics of main fuel components, the fatty acid mono-alkyl esters, and minor contaminants [17]. The ASTM and EN standards act as guidelines for many biodiesel standards throughout the world. Blends of 6 to 20% biodiesel in biodiesel-diesel mixtures are specified by the ASTM D7467 [18]. ASTM D975 covers the specifications for a blend with less than 5% biodiesel [19]. ASTM D6751 specifications are for pure biodiesel, not for biodiesel blends [20]. No or low sulfur content, high flash point, absence of aromatic content, intrinsic lubricity, easy biodegradability, high miscibility with conventional diesel, and compliance with existing fuel delivery networks are the key advantages associated with biodiesel as fuel in compression ignition (CI) engines [21]. The technological issues with biodiesel are raising NOx emissions, less flowability in cold climatic conditions, and poor oxidation stability. NOx emission increases due to high oxygen content in the biodiesel. These emissions can be reduced by the addition of antioxidants in biodiesel, water-biodiesel emulsification, and employment of an exhaust gas recirculation system in CI engines. Biodiesel with a high content of saturated fatty acids has poor cold flowability. Blending and fractionation of oils are the effective methods to improve cold flow properties. The high oxygen content of the biodiesel is the main reason behind the poor oxidation stability. The oxidation stability of biodiesel can be improved with the addition of antioxidants in the oil. The biodegradability of biodiesel is sometimes pointed as a benefit, for instance, for environmental spills. It also implies that during the storage cycle, bacterial biodegradation expands and creates deposits that clog fuel supply lines [22, 23]. Methyl esters from vegetable oils are researched worldwide as substitutes for conventional diesel fuel. More than 350 types of plant-based feedstocks can be used for the production of biodiesel. As alternate fuels for diesel engines, various edible oils from soybeans, rapeseed, palm, etc., fall under first-generation feedstocks for biodiesel production [24]. Biodiesel produced from palm oil is considered as a promising alternate substitute for conventional diesel fuel [25]. The rate of heat release, combustion pressure and temperature, the timing of fuel injection, and the duration of combustion are the important combustion parameters [26]. When palm oil (straight vegetable oil, SVO) is used directly in CI engines, then less atomization due to the high-viscosity fuel has resulted in poor ignition performance. Methods such as the process of biodiesel production, better construction of engines, and fuel system have been suggested to solve issues that arise when SVO is used in engines. Different processes are used for the production of biodiesel from palm oil. Transesterification is one of the best processes for biodiesel production. Greenhouse gas emission levels, with the exception of NOx, are reduced when palm biodiesel is integrated into a blend of diesel-biodiesel [3, 27, 28].

Most of the review/research articles are available on either production of palm biodiesel or performance and emission analysis of diesel engines operated on palm biodiesel. The lack of availability of review articles that cover most of the details of palm biodiesel from cultivation to its optimum use in CI engines motivated the authors to write this article. The information reported in this article is collected from several authentic publication sources like Springer, Science Direct, Taylor and Francis, ACS, etc. Specific keywords like biodiesel, biodiesel generations, edible oil feedstocks, cultivation of palm tree, palm oil extraction, palm biodiesel production methods, biodiesel standards, and performance and emission analysis of CI engines operated on palm biodiesel are used in order to find out the research gaps of this study. The scrutinizing of the articles is done on the basis of relevance to the topic. Most recent articles of the years 2015 to 2020 are also included to enhance the quality of analysis with the current technical scenario of biodiesel as a fuel in diesel engines. Old research articles were also added due to their relevant information for some sections of this article. Various methods of palm biodiesel production from raw palm oil are included in this review. The study is not completed if the testing of palm biodiesel is not done on CI engines. A detailed performance and emission analysis of CI engines operated on palm biodiesel and its blends was done. This review article would enable researchers to get most of the details related to palm biodiesel such as fatty acid profile, physical and chemical characteristics, methods of biodiesel production, performance, and emission analysis in CI engines. Researchers can compare and analyze the best criteria for biodiesel production from palm oil and its optimum use in diesel engines.

Biodiesel

The best alternative for traditional petro-based diesel fuel is biodiesel (fatty acid alkyl ester). Biodiesel is a renewable fuel because it comes from diverse sources of animal fats and plant oils [29]. In comparison to petroleum-based fuels, this renewable fuel does not need to be taken from oil wells. Biodiesel is a non-toxic and biodegradable renewable fuel with fairly small combustion emissions (CO, HC, and PM), because it is free from carcinogenic materials and sulfur. In terms of safety, the higher flash point makes the handling, shipping, and storing of biodiesel easier [30]. Fuel consisting of alkyl esters with long-chain acids obtained from fats and oils is known as biodiesel (B100). The term biodiesel blend level (BX) refers to a blend of diesel and biodiesel fuels comprising $(100 - X)$ percent volume of diesel and $X\%$ volume of biodiesel. Biodiesel is classified into four generations based on the type of feedstock (EASAC report). Biodiesel is usually produced in the presence of the catalyst, creating mono alkali esters and glycerin as a by-product of reactions of oils or fats with alcohol [31]. The most adoptive method of biodiesel production is the transesterification method that is shown in the following equations.

$$\text{triglyceride} + \text{alcohol} \leftrightarrow \text{diglyceride} + \text{RCOOR}_1 \quad (1)$$

$$\text{diglyceride} + \text{alcohol} \leftrightarrow \text{monoglyceride} + \text{RCOOR}_2 \quad (2)$$

$$\text{monoglyceride} + \text{alcohol} \leftrightarrow \text{crude glycerol} + \text{RCOOR}_3 \quad (3)$$

The European Union is rated as the largest biodiesel production area across the globe, accounting for about 65% of the entire world's production [32]. The primary feedstock for the EU countries is rapeseed and corn; for the USA, it is soybean. Palm is considered as the primary feedstock in Asian countries like Malaysia and Indonesia for the production of biodiesel [33]. Most of the modern CI engines have direct-injection fuel systems, and such systems are more responsive than indirect injection systems in terms of standard fuel spraying characteristics. Hence, it requires fuel that has properties similar to conventional diesel fuel [34].

Biodiesel Sources

Vegetable oils and fats that consist of triacylglycerols are sources of biodiesel. The source for the development of biodiesel is typically selected depending on its availability in the regions. More than 350 crops that carry oil are commonly considered as a possible substitute for diesel fuel. Among these crops, palm, sunflower, cotton, rapeseed, and peanut are regarded as the most promising first-generation biodiesel feedstocks [35, 36]. Throughout the processing of edible oil, European societies are self-dependent and also produce a surplus amount. Therefore, in European countries, edible oil like rapeseed is used for biodiesel production [37, 38]. Soybean is widely used in the USA as the source of biodiesel [39]. Coastal countries like Thailand, Indonesia, and Malaysia have a surplus amount of coconut oil as well as palm oil, which can be used as a biodiesel feedstock [40]. Some Asian countries do not have surplus supply of edible oils, so they move to non-edible sources for biodiesel production, e.g., karanja (*Pongamia pinnata*), jatropha (*Jatropha curcas*), etc. [41–43]. In Southeast Asia and India, karanja and jatropha are used as primary feedstocks for biodiesel production [44]. Palm oil can satisfy future requirements because of its fast rate of production and high oil yield. Approximately 75–80% of the total cost of biodiesel production is encountered by feedstock cost. The usage of commodity oils for biodiesel production influences the cost of foodstuffs. The cultivation of a fuel crop on agricultural land causes the reduction of the food crop cultivation area. Waste oil can be considered as a potential source of biodiesel production because it can be collected from waste streams like cooking operations, fish rendering operations, and food processing industries. Waste animal fats give dual benefits, i.e., waste stream reduction and side profit development. The expense of waste-based feedstock is effectively far less because only additional refining steps are required for impurities and water content in oil [45]. Animal fats contain more saturated fatty acids than vegetable oils, which contribute to additional processing requirements since the feedstock is generally in solid state, and there are also inadequate flow properties in cold climatic conditions of the resulting product [46]. Fish oils usually have significant quantities of unsaturated fatty acids, comparable to algae oils. However, most of them have a long chain so that the net result is still poor cold flowability [47].

Biodiesel's Advantages and Disadvantages

All sorts of fatty acid methyl esters are known as biodiesel, which is the green substitute of conventional diesel fuel and can be add directly in different blend ratios [48–52]. Transesterified edible oils have comparable properties as traditional diesel fuel [53–58]. CI engines can operate on a wide range of fuels. In addition to this fuel flexibility benefit, CI engines have higher brake thermal efficiency (BTE), lower brake specific fuel consumption (BSFC), and more durability in contrast to SI engines [59–61]. Some more advantages and disadvantages associated with the use of biodiesel in CI engines are given in Supplementary materials, Table S1.

Various Standards for Biodiesel

Biodiesel generally can be described as a local renewable fuel for CI engines such as palm, rapeseed, soybean, etc.-derived fuel that follows the EN 14214 or ASTM D6751 specifications. Various countries like Malaysia, India, South Africa, Brazil, Japan, etc. have developed their standards for biodiesel fuel. Biodiesel is a bright yellow amber substance with a diesel-like viscosity. European Union (EN 14214) and American (ASTM D6751) standards for biodiesel fuel are the internationally accepted standards for maintaining the quality of biodiesel [62]. The ASTM D6751 specification defines the conditions that follow pure biodiesel fuel (B100). As the production of palm oil is high in Malaysia, MS 2008:2008 standards are developed by Malaysia for biodiesel. The test methods and limiting values of biodiesel properties in all countries' standards are mostly adopted from ASTM and EN standards [63]. Various aspects affect the quality of biodiesel like nature of feedstock, composition of fatty acids, the types of production and extraction methods used, and the parameters related to post-production. The maximum density limit given is 880 kg/m^3, as per the ASTM standards, and it can be calculated by the ASTM D1298 or EN/ISO 3675 methods. The maximum acceptable viscosity value is given as 6.0 mm^2/s and measured by the ASTM D445 method. The viscosity controls the properties of the injection of fuel in the diesel engine. It is important to limit it to the acceptable value to avoid adverse effects on the performance of the fuel injector. Consequently, the proposed viscosity requirements are almost the same as those for diesel fuel. As per the standards, the limiting value of carbon residues is nearly the same. The minimum cetane number limit value is given as 47 by ASTM and is measured by the standard methods ASTM D613 or EN/ISO 5165. The acid value is measured with the ASTM D664 or EN 14104 methods. A maximum of 0.1% (m/m), 0.25% (m/m), and 0.25% (m/m), respectively, are the mono-, di-, and triglyceride amounts in accordance with the standards of ASTM [64]. The EN standard specifies the maximum allowable value of the cloud point. The ASTM D93, EN ISO3679, ISO 20846, ISO 20884, and IS P21 methods are used to measure the minimum limiting value of the flash point. Table 1 specifies the country-specific biodiesel standards for USA, EU, Malaysia, and India.

First Generation of Biodiesel Feedstocks (Edible Oils)

Biodiesels are categorized into four generations as per the report of the European Academies' Science Advisory Council. Sources of feedstocks are the prime factor for first to third generations of biodiesel, while synthetic biological technology is the main factor behind the fourth generation of biodiesel. Edible oils are the feedstocks for the first generation of biodiesel [65, 66]. At the beginning of a biodiesel era, the usage of edible feedstock for biodiesel production is prevalent. The critical advantage of first-generation feedstocks is crop availability. The crucial downside in the use of these feedstocks for biodiesel production causes an increase in the cost of food products that affect the food supply [67]. Further, barriers for the development of biodiesel from edible feedstocks are the adaptability to environmental factors, cost, and limited field of cultivation. Such disadvantages forced the users of biodiesel to turn to alternative sources [68].

Palm Oil as a Feedstock for Biodiesel Production

Crude palm oil (CPO) is derived from the palm tree. The oil is extracted from an inner shell of the fruit, and obtained oil is further processed in refineries. Refined palm oil is further treated with transesterification reaction to produce palm biodiesel. The complete process of production of palm biodiesel is shown in Fig. 1. CPO can also directly blend with diesel fuel, but some parameters like the viscosity of the blend reduce the performance of the engine. When a certain proportion of palm oil mixed with traditional diesel, then the mixture is referred to as Envo diesel. Palm biodiesel has high stability with lower exhaust emissions other than NOx in comparison with conventional diesel fuel.

There are various reasons associated with the use of palm oil for biodiesel production. These reasons are as follows:

- There is a large availability of vegetable palm oil in specific regions across the globe; those have an excess amount of oil apart from food use, which can be used for biodiesel production.
- Only under some local circumstances (e.g., in the USA, Malaysia, and some countries of the EU) can vegetable oil gain a significant share of the fuel industry.
- The low content of sulfur makes it suitable for biodiesel production.
- A high cetane number reduces the knocking tendency.
- High oil yield.
- High growth rate of palm trees.
- Continuous fluctuation in the price of palm oil creates the issues of availability and economic viability in comparison with diesel fuel [69].

Cultivation of Palm

The palm tree is known as *Elaeis guineensis* Jacq. (in Africa) or dendezeiro (in Portuguese). The Gulf of Guinea is considered as the place of origin of the palm tree. The life cycle of a palm tree is 20–30 years, and the product is obtained after 3.5 years of planting. A

Table 1 Biodiesel standards set by the USA, EU, Malaysia, and India [62–64]

Property	Units	ASTM D6751 (USA)		EN14214 (EU)		MS 2008:2008 (Malaysia)		IS 15067 (India)	
		Test method	Limits	Test method	Limits	Test method	Limit	Test method	Limits
Acid number or acid value	mg KOH/g	D 664	Max 0.50	EN 14104	Max 0.50	MS 2011	Max 0.50	P1	Max 0.50
Cetane number (CN)	–	D 613	Min 47	EN ISO 5165	Min 51	EN ISO 5165	Min 51	ISO 5156/P9	Min 51
Cloud point	°C	D 2500	− 3 to − 12	EN 116	Max − 4/3	EN 116	Max − 4/3	–	–
Copper strip corrosion (3 h, 50 °C)	Class	D 130	Max No. 3	EN ISO 2160	Max No. 1	MS 787	Max No. 1	ISO 2160/P15	Max No. 1
Density (15 °C)	kg/m^3	ASTM D 1298	Max 880	EN ISO 3675, EN ISO 12185	Max 900	ISO 3675, ISO 12185	Max 900	ISO 3675/P 32	Max 900
Flash point	°C	D 93	Min 130	EN ISO 3679	Min 120	ISO 20846, ISO 20884	Min 120	P21	Min 120
Iodine number or iodine value	g I/100 g	–	–	EN 14111	Max 120	EN 14111	Max 110	EN 14104	–
Kinematic viscosity (40 °C)	mm^2/s	D 445	Max 6.0	EN ISO 3104, ISO 3105	Max 5.0	MS 1831	Max 5.0	ISO 3104/P25	Max 6.0
Oxidation stability (110 °C)	Hours	–	Min 3.0	EN 14112	Min 6.0	EN 14112	Min 6.0	EN 14112	Min 6.0
Sulfur content	mg/kg	D 5453	Max 0.05 (% m/m)	EN ISO 20846, EN ISO 20884	Max 10.0	EN ISO 20846, EN ISO 20884	Max 10.0	D 5443/P83	Max 50
Monoglyceride content	% (m/m)	D 6584	Max 1.0	EN 14105	Max 0.80	EN 14105, ASTM S 6584	Max 0.80	–	–
Diglyceride content	% (m/m)	D 6584	Max 0.25	EN 14105	Max 0.20	EN 14105	Max 0.20	–	–
Triglyceride content	% (m/m)	D 6584	Max 0.25	EN 14105	Max 0.20	EN 14105	Max 0.20	–	–
Free glycerine	% (m/m)	D 6584	Max 0.02	EN 14105, EN 14106	Max 0.02	ASTM D 6584	Max 0.02	D 6584	Max 0.02
Total glycerine	% (m/m)	D 6584	Max 0.240	EN 14105	Max 0.25	EN 14105	Max 0.25	D 6584	Max 0.25

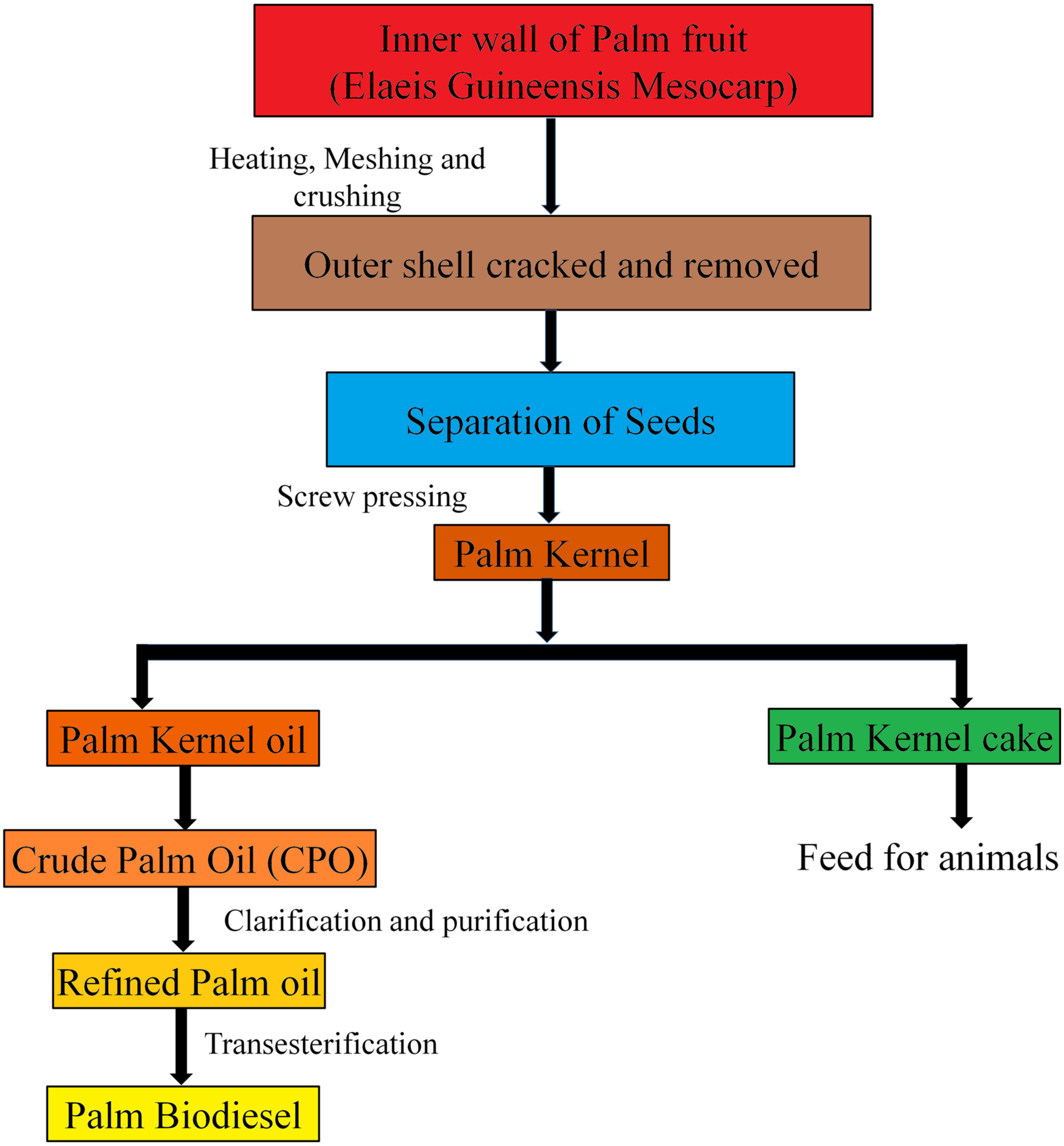


Fig. 1 Steps for biodiesel production from palm

palm tree requires deep soil, an average rainfall of 2000 mm/year, and moderate temperature conditions. It can also grow in acidic soil of pH 4–6. The slope of the planting ground should be less than 5% [70]. The palm tree has erected monoecious with separated female and male inflorescences. The weevil (*Elaeidobius kamerunicus* Faust) is the key pollination agent for cross-pollination in palm flower. Wind pollination is not as effective as pollination by weevil. The issue of a low level of pollination is resolved with assisted pollination. The product of the palm tree is the fruit, and an average of 8–15 fresh fruit bunches (FFB) with 15–25 kg weight is obtained from the palm tree [71].

Physicochemical Properties of Palm Oil

The physical and chemical characteristics of biodiesel vary with change in feedstock. The chemical characteristics of biodiesel depend on factors like fatty acid profile, free and total glycerin, and mono-, di-, and triacylglycerides. Viscosity, density, cloud and flash point, heating value, cetane number, etc. are the physical properties associated with biodiesel. The long-term storage ability of biodiesel is an important parameter. Palm oil has good oxidation stability, but poor low-temperature characteristics compared to oils from other feedstocks. The high amount of oxygen in biodiesel affects the various properties like viscosity, acid value, cloud and pour point, cetane number, peroxide value, and specific gravity [5, 55, 56, 60, 72–80]. Palm oil has an approximately similar amount of saturated and unsaturated fatty acids. Table 2 describes the different fatty acid profiles of palm oil. Different physicochemical properties of palm biodiesel are listed in Table 3.

Various properties associated with palm oil totally depend on the fatty acid profile. Different properties of palm oil are explained below in detail.

Cetane Number

The key indicator of diesel fuel quality is the cetane number (CN). It decides the delay of the ignition in the combustion chamber when fuel is injected. The higher amount of cetane allows a shorter ignition delay period, which contributes to lower noise in idling condition and easy cold starting of the engine. When the CN is low, then the ignition takes place late during the expansion stage, resulting in incomplete combustion, decreased power output, higher fuel consumption, and a rise in noise levels [60]. Alcohol additives always increase the CN of fuel. The cetane number for fuel and alcohol mixture is greatly improved by adding limited quantities of alcohol and ether, such as ethanol, methanol, and diethyl ether [54, 81–83]. The international methods like ASTM D613 (USA) and ISO 5165/P9 (India) are used to measure the CN of fuel [65]. MS 1895/ISO 5165 is the standard biodiesel test method set by Malaysia to measure the CN of biodiesel fuel [63]. The CN of biodiesel fuel with a more branched structure was found lower than that of a straight chain structure [84].The biodiesel CN should be minimum (47) as per ASTM D6751 or 51 as per EN 14214 [64]. In the case of determination of the CN of a biodiesel blend, the following equation is used:

$$\mathrm{CN_{blend}} = \Sigma\,(\%X_i \times \mathrm{CN}_i)$$

Here, $\mathrm{CN_{blend}}$ is the blend's CN, $\%X_i$ is the volume percentage of a particular fuel (in pure form), and CN_i is the CN of the respective fuel [85, 86]. A higher CN leads to high NOx formation. The engine technology and less pressure during injection are the factors that affect the engine emissions. Palm oil-derived biodiesel has a high cetane number (52) than traditional diesel fuel, so that it is responsible for high NOx emissions. As the biodiesel percentage in a biodiesel-diesel blend increases, then, due to an increase in the CN, the NOx emissions increase. The fatty acid structure also affects engine exhaust emissions [87].

Calorific Value

In comparison with conventional diesel fuel, palm biodiesel has a lower calorific value. In the case of blending, as the palm biodiesel percentage increases, the overall calorific value (CV) of the blend reduces. The lower CV of biodiesel increases the brake-specific fuel consumption for palm biodiesel [88]. However, the density of palm biodiesel is higher than that of diesel fuel, which results in more energy inside the combustion chamber than diesel because the working of the injection pump is done on a volume basis. The average lower calorific value of palm biodiesel is 40.13 MJ/kg.

Acid Number

The amount of free fatty acid content of fuel is determined by the acid number (AN). AN is also referred to as the neutralization number. In comparison with traditional diesel fuel,

Table 2 Chemical structure and amount (%w/w) of different fatty acids present in palm oil [5, 55, 56, 60, 72–80]

Name	Structure	Chemical formula	Chemical name	Amount (%w/w)
Lauric acid	C_{12}	$C_{12}H_{24}O_2$	*Dodecanoic acid*	0.2
Myristic acid	C_{14}	$C_{14}H_{28}O_2$	*Tetradecanoic acid*	1.1
Palmitic acid	C_{16}	$C_{16}H_{32}O_2$ $\{CH_3(CH_2)_{14}COOH\}$	*Hexadecanoic acid*	44.0
Palmitolic acid	$C_{16:1}$	$C_{16}H_{30}O_2$ $\{CH_3(CH_2)_5CH_5CH{-}(CH_2)_7{-}COOH\}$	*Cis-9-hexadecanoic acid*	0.1
Stearic acid	C_{18}	$C_{18}H_{38}O_2$ $\{CH_3(CH_2)_{16}COOH\}$	*Octadecanoic acid*	4.5
Oleic acid	$C_{18:1}$	$C_{18}H_{34}O_2$ $\{CH_3(CH_2)_7CH_5CH(CH_2)_7COOH\}$	*Cis-9-octadecanoic acid*	39.2
Linoleic acid	$C_{18:2}$	$C_{18}H_{32}O_2$ $\{CH_3(CH_2)_4CH_5CH{-}CH_2{-}CH_5CH{-}(CH_2)_7COOH\}$	*Cis-9-cis-12-octadecadeneoic acid*	10.1
Linolenic acid	$C_{18:3}$	$C_{18}H_{30}O_2$ $\{CH_3(CH_2)_4$ $CH_5CH{-}CH_2{-}CH_5CH{-}CH_2{-}CH_5CH(CH_2)_4COOH\}$	*Cis-6-cis-9-cis-12-octadecatrienoic acid*	0.4
Arachidice acid	C_{20}	$C_{20}H_{40}O_2$ $\{CH_3{-}(CH_2)_{18}COOH\}$	*Eicosanoic acid*	0.4

Table 3 Different physical properties associated with palm biodiesel and traditional diesel fuel [5, 55, 56, 60, 72–80]

Properties	Unit	Palm biodiesel	Diesel fuel
Formula	–	–	$C_nH_{1.8n}$ (C_{10}–C_{22})
Average MW	kg/kmol	284.5	170
Cloud point (CP)	°C	16	–
Pour point (PP)	°C	14	6
Flash point (FP)	°C	175	70
Lower calorific value	MJ/kg	40.13	42.5
Higher calorific value	MJ/kg	41.30	44.8
Density at 15 °C	kg/m^3	880	833–881
Cetane number (CN)	–	52	40–55
Kinematic viscosity at 40 °C	g/cm s or cSt	4.50 cSt	(10–13 g/cm s)
Iodine value (IV)	g/100 g	55	–
Acid number (AN)	mg KOH/g	0.33	–
Sulfur (S)	%(w/w)	0.04	0.25
Conradson carbon residue	%(w/w)	0.07	–
Saponification value (SV)	–	169–174	–
A–F ratio (stoichiometric)	Mass basis	14.0	14.5
Limit of flammability	%(*v*/v)	–	0.6–5.5
Water amount	mg/kg	306	0.02
Ash amount	%(w/w)	0.0066	–
Monoglycerides	%(m/m)	0.390	–
Diglycerides	%(m/m)	0.090	–
Triglycerides	%(m/m)	0.020	–
Free glycerol	%(w/w)	0.011	–
Total glycerol	%(w/w)	0.124	–

biodiesel from palm oil has a high AN because of high free fatty acid content. According to EN 14214 and ASTM D 6751, the value of AN should not exceed 0.50 mg KOH/g. The measurement of the acid number is done with the D 664 (ASTM), EN 14104 (EN), and MS 2011 (MS 2008:2008) methods [63, 64]. The acid number of biodiesel should be as per standards specified by different countries. With an increase in biodiesel percentage in the blend of biodiesel-diesel, the acid number increases due to the increase in free fatty acid amount. The acid number for palm biodiesel is given as 0.33 mg KOH/g.

Kinematic Viscosity

Kinematic viscosity is the property that is primarily responsible for biodiesel production, and the explanation for this is the falling crude palm oil as a substitute for diesel fuel. Palm biodiesel has a smaller magnitude of viscosity in the form of methyl ester than parent crude palm oil. D 445 (ASTM), ISO 3104/3105 (EN), and MS 1831/686 (MS 2008:2008) are the methods used to determine the viscosity of biodiesel fuel [63, 64]. In the case of the mixing of different fuels, the overall kinematic viscosity of the blend can be determined by the following equation:

$$\nu_{\text{blend}} = \Sigma\left(\%X_i \times \nu C_i\right)$$

Here, ν_{blend} is the overall kinematic viscosity of the blend; X_i is the percentage amount (%w/w) of oil in a blend, and νC_i is the kinematic viscosity of the respective oil. From the above equation, it is observed that the final kinematic viscosity of the blend linearly depends on the blend ratio and kinematic viscosity of each fuel [89]. An issue is created regarding the compounds having a melting point greater than 40 °C. Normally, saturated fatty acids with chain length ≥C20 have a melting point of more than 40 °C. As per the standards, the kinematic viscosity is determined for temperature of more than 40 °C. So, in the case of a blend of two fuels in which one has a melting point < 40 °C, the kinematic viscosity cannot be determined directly. In such a condition, the polynomial equation is used to determine the overall viscosity of the blend. The polynomial equation is given as

$$\nu = 0.30487 + 0.0265 \times C + 0.0066 \times C^2 + 0.000491 \times C^3$$

Here, ν is the overall kinematic viscosity, and C is the number of carbon atoms. In general, the kinematic viscosity of palm biodiesel is obtained 4.50 cSt at 40 °C temperature.

Density

Density is the essential physical characteristic of biodiesel fuel. The density of fuel plays a vital role in the combustion process. It is the factor that creates the difference between palm biodiesel and crude palm oil. With an increase in heavier atoms or unsaturation, the density of biodiesel increases. The standard test method to find out the value of biodiesel density is given by ASTM D 1298, EN ISO 3675/EN ISO 12185, and ISO 3675/P32 [64]. The maximum permissible value of density is 900 kg/m^3 as per most countries' standards, while ASTM gives the lower value that is 880 kg/m^3. The calculation of the density of biodiesel blends is done through the following equation:

$$1/\rho_{\mathrm{blend}} = \Sigma\,(X_i/\rho_i)$$

Here, ρ_{blend} signifies the overall density of the biodiesel blend, X_i is the volume percentage of the different fuels in the biodiesel blend, and ρ_i is the density of the respective fuel [90].

Lubricity

With the increase in the demand for low sulfur fuel, the significance of lubricity increases. The fuel lubricity decreases or is removed with hydro-desulfurization, which ensures the proper working of injectors and fuel pumps in the engine [91–93]. Hydro-desulfurization also eliminates the nitrogen and oxygen compounds that are associated with inherent lubricity [93]. As per the EN 590 and ASTM D975, the maximum permissible wear scars are 460 μm and 520 μm, respectively [64]. Metallurgical microscopes are used to determine the average value of the wear scar. The benefit of biodiesel involves no requirement of additive in the case of biodiesel to reduce the sulfur content. The lubricity of oil also increases with chain length and availability of double bonds. From the study of various oxygenated C_{10} compounds, the order of lubricity is COOH > CHO > OH > $COOCH_3$ > C=O > C–O–C [94]. The lubricity of free fatty acids, glycerols, and monoacylglycerols is higher than that of biodiesel due to the presence of free OH groups [95]. High numbers of OH groups increase the lubricity of crude oils [96]. It is observed that the addition of pure palm oil in traditional diesel fuel increases the lubricity than the addition of methyl esters of palm oil.

Oxidative Stability

The major technical issue associated with biodiesel is its stability. There are three types of stability used for biodiesel, e.g., oxidation stability, storage stability, and thermal stability [97, 98]. Oxidation of the biodiesel takes place when it is stored for a prolonged period of time. There are some issues like microbial growth and water presence for long-time storage. The oxidative stability of the biodiesel depends on various external factors, i.e., heat supplied, availability of air and light, antioxidant presence, metal traces, peroxide presence, and the material of the storage container. In general, oxidation is induced by conditions such as air or light, high temperatures, and metals. As per several studies, it is found that metals or light presence increased the oxidation. According to the automated oil stability index (OSI), copper metal increases oxidation [99]. The effect of the fatty esters' structure on oxidation stability is even more than the above parameters [97]. The Rancimat method is used to evaluate the oxidative stability. In this method, air is bubbling through the samples at high temperature (110 °C), and the liquid effluent is continuously checked for conductivity. The maximum increase in conductivity is known as induction time. This induction time is the measure of oxidation stability. The minimum induction time for biodiesel fuel is 3 h and 6 h, respectively, as per ASTM and EN standards. The auto-oxidation of fuel can occur due to the presence of double bonds in FAMEs. The positions and number of double bonds are the factors behind the auto-oxidation of unsaturated fatty acids [100]. The allylic position in double bonds is more prone to oxidation. Bis-allylic positions are much more auto-oxidation prone than allytic positions in specific polyunsaturated fatty acids such as linolenic acid (double bonding at C_9, C_{12}, and C_{15} with two bis-alilylic at C_{11} and C_{14}) and linoleic acid (double bond at C_9 and C_{12}, while one bis-alilylic at C_{11}). The relative levels of oxidation reported are 98 in linolenates, 41 in linoleates, and 1 in oleate [100]. Antioxidant additives are used to increase the oxidation stability of biodiesel.

Cold Flowability

Biodiesel in both pure and blended forms has inferior low-temperature flow characteristics in comparison with traditional diesel fuel. Plugging of fuel filters and chocking of supply lines are caused by the rapid growth of solid crystals at low temperatures. So, the high cloud point and pour point are desirable for biodiesels. ASTM D2500 and ASTM D97 standards are provided for cloud point and pour point determination, respectively [64]. The cloud point and pour point for palm biodiesel are 16 and 14 °C, respectively. The cloud point is generally higher than the pour point temperature. Cloud point is the temperature at which cloudy appearance inside the fuel occurs due to the crystallization of fatty material. When the temperature is further dropped, then solid formation occurs, and the restriction of flow starts. This point is known as the pour point. The amount and nature of saturated fatty compounds affect the cloud point [101]. The cloud point and pour point of higher saturated fatty acid–content biodiesel is more than those of others. In comparison to the pour point, the cloud point is a more critical parameter for biodiesel [64, 102]. 2-Butyl, iso-butyl, and iso-propyl branched esters are more favorable than methyl esters for low-temperature operations of fuel [103].

Production of Biodiesel from Palm Oil

Production of palm biodiesel consists of two significant steps; the first step is the extraction of oil and, after that, the processing of oil to produce biodiesel. These two steps are explained here in detail.

Extraction of Oil

Processors of palm oil of all scales proceed through the operating processes of the unit. The variation in the degree of mechanization and the procedures for the movement of connecting materials render the system continuous or batch type. The size of activities differs from the concerning method and the quality assurance of goods that can be accomplished by the adopted system [104]. All the processes involved in the extraction of palm oil are as follows:

Reception of Bunch

As bunches or loose fruits, fresh fruit comes from the farm. Usually, the fresh fruit is emptied in wooden crates that are appropriate for measuring in a quantity such that fruits can be tested at the processing plant. Initially, the quality levels reached rely on the bunches' quality that enters the mill [105–107]. This quality cannot be changed by the mill, although it prevents or reduces further degradation. Genetics, tree age, agronomy, the technique of harvesting, handling, climatic condition, and transport are all factors that affect the composition and final quality of palm oil.

Separation of Fruit from Bunches

The new fruit bunch comprises fruit that develop on a central stem in spikelets. Manual threshing is achieved by removing the fruit-filled spikes with an ax and removing the fruit from the spikelets by hand. A revolving or fixed drum with revolving beater bars removes the fruit from the bunch and leaves the spikelets on the stem in a mechanized way [105–107]. The fruits are then boiled in water. Whole bunches that contain spikelets absorb water while boiling. To heat bunches without wasting any energy, high-pressure steam is more efficacious. So, several small operations thresh bunches before boiling the fruit, while high-pressure sterilization processes thresh bunches after boiling to loosen the fruit after heating.

Bunch Sterilization

The usage of high-temperature wet-heating procedures for loose fruits is the sterilization technique. Boiling typically requires hot water, while there is a requirement of pressurized steam for sterilization. There are various purposes associated with sterilization techniques. Oil splitting enzymes are removed with high temperatures and avoid autoxidation and hydrolysis. This process makes the removal of fruit from bunches easy. High heat softens the pulp structure and easily detaches fibrous material. Moreover, it is necessary to ensure that air is removed from the sterilizer during sterilization [104, 106]. Oil oxidation is significantly high at elevated temperatures; that is why the chance of oxidation is strong during sterilization.

Digestion of the Fruit

Digestion is the mechanism by which the palm oil is produced in the fruit through breakup or destruction of oil-bearing cells. The popular digester is made up of a steam-heated cylindrical structure equipped with a central revolving shaft holding multiple beating arms. The spinning wings of the beater hammer the fruit. Pounding or high-temperature digestion of the fruit decreases the viscosity of the oil, removes the exterior cover of the fruits (exocarp), and stops oil cell destruction that has already occurred during the sterilization step. Most of the small digesters do not provide steam injections or heat shielding to help preserve their contents at high temperatures during this process. It is due to the high price and complicated servicing procedure [105–107]. Iron degradation during digestion is more significant when the maximum amount of wear happens during the milling process. The chance for the onset of oil rancidity and oxidation tendency increases by iron contamination.

Palm Oil Extraction

The digested material is processed to extract oil in two ways. The first one is the dry method and uses a mechanical press arrangement. The second one is the wet method. In the wet method, hot water is used to extract the oil. Mechanical pressure is exerted upon the digested mash to remove the oil. Many specific styles of presses exist, but all of them have identical operating theories [104–107]. The presses can be equipped for batch or continuous processing.

Purification

Purification is the process of removing the impurities from the oil. Oil, cell debris, non-oily solids, and water are present in the fluid processes from the extraction step. The viscosity of this fluid is high. The addition of hot water ensures the settling of heavy solids in the bottom of the vessel. The ratio of oil to water is 1:3. Coarse fiber is removed with a screen. The heating of the mixture is done; water settles down due to more weight, and oil remains on top [104–107]. The clear oil is collected in a separate vessel. The water amount in the oil must be less than 0.15–0.25% to prevent the increase in FFA autocatalytic hydrolysis of oil.

Biodiesel Production from Palm Oil

Different techniques are available to produce biodiesel from crude palm oil. It is worth modifying crude oils so that the substance created has appropriate properties to use as fuels in the engine. Pyrolysis, blending, micro-emulsion, transesterification, and hydro-esterification are some common techniques used to produce biodiesel from palm oil [45, 73, 108–114]. The benefits and limitations associated with these techniques are given in supplementary material Table S2. Among all these techniques, transesterification is the most adoptive method to produce biodiesel from palm oil.

Pyrolysis

Pyrolysis is an anaerobic decomposition mechanism that happens at moderate temperature when the oil is heated in the absence of oxygen or air. It is used to transform raw oil into fuel with sufficient heat properties or by using a catalyst. For biodiesel production, the pyrolysis (thermal cracking) method can be used for vegetable oils, waste oils, algal-based oils, and animal fats [41]. The temperature during the thermal cracking process is the most crucial parameter. The biodiesel produced from palm oil with the thermal cracking process is of moderate yield.

Blending (SVO with Diesel)

The mixing of crude palm oil (SVO) directly to the diesel fuel is called blending or dilution. The viscosity of the blend is high in comparison with that of traditional diesel fuel. High viscosity causes various operational issues in diesel engines. A liming percentage (20%) of oil is blended with conventional diesel fuel due to high viscosity [108]. Formation of gum, chocking of injector nozzle, and high carbon deposition on piston heads are the effects associated with the use of highly viscous SVO directly in diesel engines.

Micro-Emulsification

Micro-emulsification is defined as a colloidal dispersion of optically isotropic fluid. The high viscosity of SVO can be reduced with the micro-emulsification process. The formation of explosive vapors increases the spray characteristic of fuel at a low boiling point [57]. Octanol, hexanol, butanol, ethanol, and methanol solvents are used to make the micro-emulsion to lower the viscosity of the fuel.

Hydro-Esterification

Hydro-esterification is the new approach to produce biodiesel from palm oil. Much research on catalyst type, reaction kinetics, multiple feedstocks, cost of production, and the set-up of hydro-esterification plants has been pursued [115–117]. This process consists of a reaction to the hydrolysis of triglycerides. It produces glycerol and fatty acids, followed by the esterification process of the fatty acids, and results in water and esters. The hydrolysis reaction raises feedstock acidity and removes unnecessary fatty acids. Vegetable oils, animal fats, waste cooking oils, acid sludge, etc. can be used in this process irrespective of their humidity and acidity. The feedstock utilization under these situations is far different than the conventional transesterification method that produces soap sand and complicates the distinction between glycerin and biodiesel [118]. The glycerol extracted during the esterification processes is entirely free from any contaminant. For example, animal fat is used in hydrolysis; the glycerol produced is nutritional with additional benefits. During the transesterification phase, glycerol cannot be obtained without any contaminant where the existence of salts and methanol is insignificant [119]. Water and biodiesel are produced from the hydrolysis process followed by esterification of fatty acids step. The produced water can be used again for the hydrolysis process. There is no requirement for the washing of biodiesel with this method. The separation of water from biodiesel is easy [119]. The complete process of biodiesel production using the hydro-esterification technique is shown in Fig. 2.

Transesterification

The transesterification technique for the production of biodiesel includes the addition of methanol or ethanol to triglycerides and the development of esters (methyl or ethyl). In the stoichiometric reaction, 3 mol of alcohol to 1 mol of triglyceride is used to produce 3 mol of esters and 1 mol of glycerin. In reality, excess alcohol is used to increase ester production performance [40]. Transesterification processes for the processing of biodiesel entail preparation of the feedstock, rate of reaction, the separation of phase, dehydration, recovery of alcohol, and purification of the ester and glycerin [120]. The processes involved in the transesterification of oils are shown in Fig. 3. The reactor is the main component of transesterification reaction (Fig. 4). The heating and mixing of oil with alcohol and catalyst take place in the reactor.

The preparation method is intended to decrease acidity and moisture content. Drying and dehumidifying processes are done after a neutralization operation. To accelerate the reaction, the transesterification process involves a catalyst; it can be acid, base, or enzyme catalyst. Sodium hydroxide and potassium hydroxide are the most widely used base catalysts. Hydrochloric acid, sulfuric acid, and phosphoric acids can be used as the acid catalyst and lipase as an enzyme catalyst. Alkaline catalysis is generally favored as the reaction is quicker and is carried out at a medium range of temperatures. Due to economic factors and easy availability, potassium hydroxide is a commonly used base catalyst [121]. It is advised to use an acid catalyst when oils have large amounts of FFA

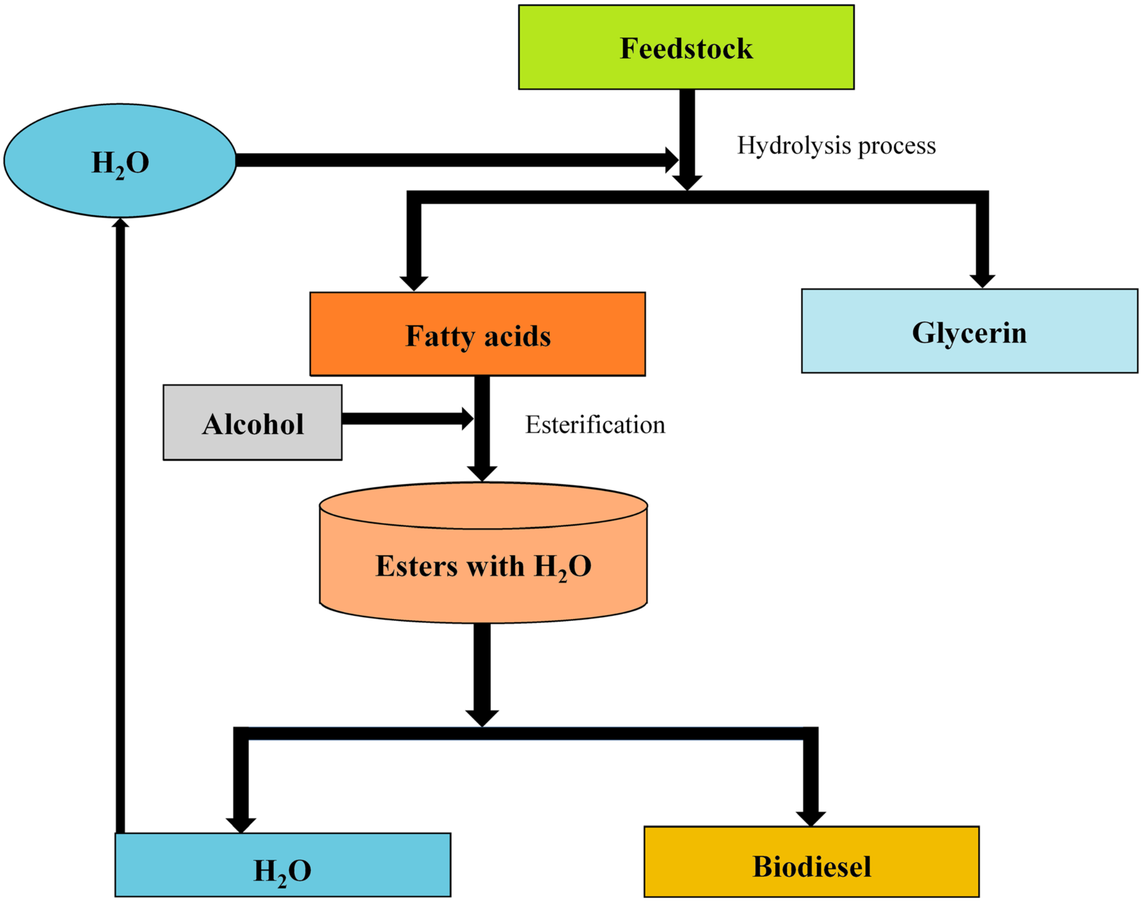


Fig. 2 Production of biodiesel from palm oil using the hydro-esterification method

and water [122]. Acid catalysts usually corrode machinery and facilitate the production of soap that also causes a rise in viscosity, reduces catalyst effectiveness, and causes difficulty in the separation of glycerol [123]. Because of the immense supply and low prices of methanol in the USA and Europe, it is the most commonly used alcohol for biodiesel production. Ethanol is used in Brazil, as it is exceptionally accessible at a low cost [122]. Due to a large amount of water found in the

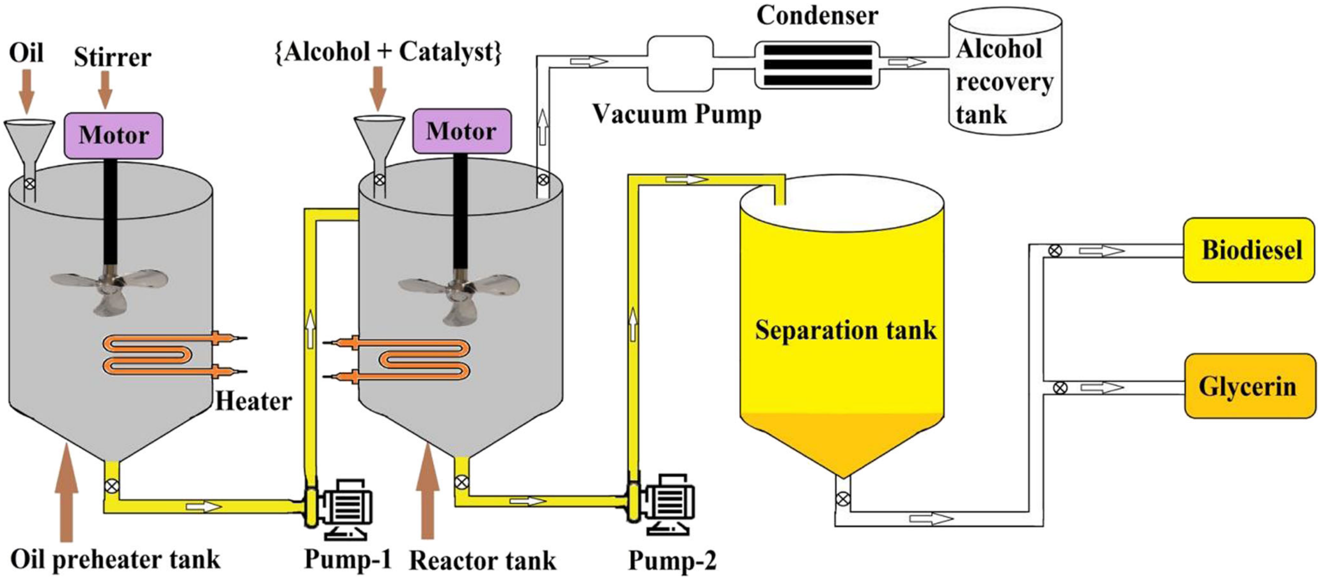
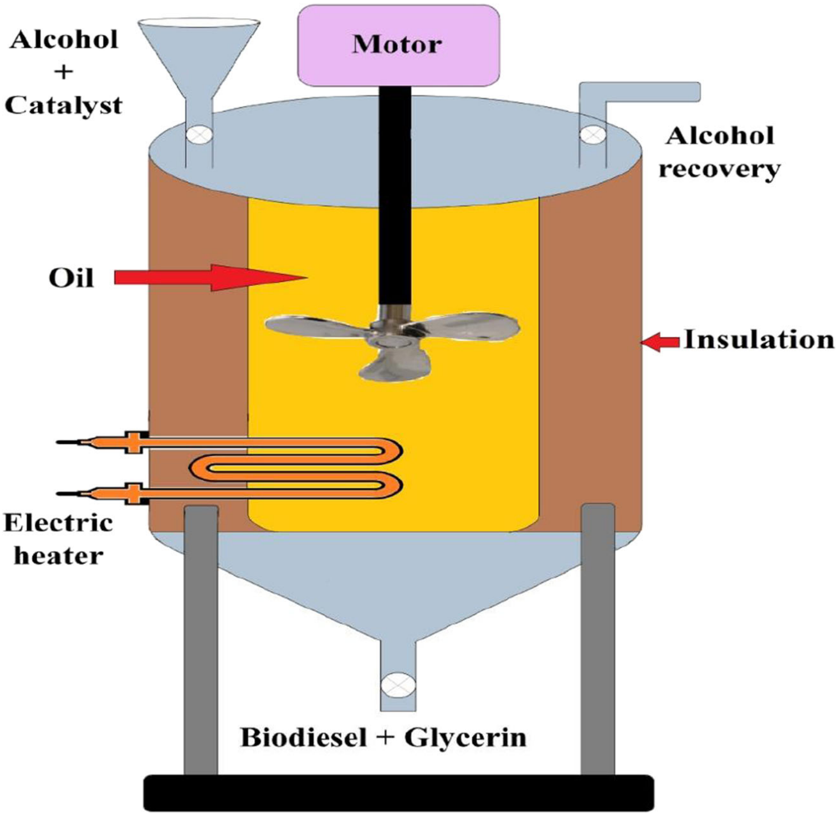


Fig. 3 Transesterification process

Fig. 4 Reactor used in transesterification reaction



ethanol (approximately 7000 ppm) than methanol (50 to 100 ppm), ethanol resulted in low biodiesel yield due to more saponification. Two phases are separated by centrifugation after the transesterification reaction. Being lightweight, esters remain on top and glycerin settled down. Alcohol recovery from glycerin and esters is achieved by evaporating, condensing, and dehydrating the water by distilling series. The dehydrating process is favorable if methanol is employed because if ethanol was used, then the azeotropic water-ethanol mixture is formed [120].

Vacuum distillation purifies pure glycerin, which eliminates the reaction impurities contributing to a limpid and transparent liquid, commonly named distilled glycerin. Finally, through centrifugation and dehumidification, ethyl or methyl esters are refined to produce biodiesel and comply with the requirements of defined technical standards [120]. The biodiesel can be used as a pure form or as a blended form in CI engines without major modifications. Various critical parameters influence the yield of produced biodiesel in the transesterification reaction [124]. The optimum value of each parameter results in a high yield of the end product. These parameters are as follows:

- Catalyst type
- Amount of water and FFA in oil
- Temperature of reaction
- Catalyst amount
- Alcohol type
- Alcohol to oil molar ratio
- Time of reaction
- Co-solvent use
- Mixing speed (RPM)

Ninety-seven percent of biodiesel yield is obtained from palm oil, when 40:1 alcohol to oil molar ratio with 5% by weight of H_2SO_4 catalyst is used during transesterification reaction at 95 °C temperature for 540 min [125]. The two-step transesterification process is used when the FFA content of palm oil is more than 1%. In the first step, acid catalyst (H_2SO_4) is used for esterification with 1% of the weight of oil and 6:1 ethanol to oil molar ratio for 60 min. The esterification step reduces the FFA content, and the base-catalyzed transesterification process is followed after esterification. During transesterification, KOH base catalyst with 1.5% (w/w of oil) is used with an ethanol to oil molar ratio of 8.5:1 for 5 min. The yield of palm biodiesel obtained is 85% in this process [126]. The various parameters associated with the transesterification reaction are given in Table 4.

Several studies reported the use of heterogeneous acid and alkaline catalysts for the production of biodiesel from palm oil [127–134]. Higher temperature (140 to 170 °C) is required for transesterification reaction using acid catalysts. With the help of these catalysts, the biodiesel yield achieved is more than 90% with a high molar alcohol to oil ratio [127–129]. When

Table 4 Various parameters associated with transesterification reaction

Catalyst	Alcohol type	Molar alcohol to oil ratio	Concentration of catalyst (%w/w)	Reaction duration (min)	Reaction temperature (°C)	Yield of biodiesel (%)
Homogenous H_2SO_4 [125]	Methanol	40:1	5	540	95	97.00
Homogenous KOH [126]	Ethanol	8.5:1	1.5	4.8	–	85.00
Heterogeneous montmorillonite KSF [127]	Methanol	8:1	3	180	190	79.60
Heterogeneous alum [128]	Methanol	18:1	7.09	720	170	92.50
Heterogeneous Ar SBA15 [129]	Methanol	20:1	6	240	140	90.00
Heterogeneous KF/Ca-Al [130]	Methanol	12:1	–	180	65	99.70
Heterogeneous KF/ZnO [131]	Methanol	11.43:1	5.52	583.2	65	89.23
Heterogeneous Mg-Al [132]	Methanol	30:1	7	360	100	86.60
Heterogeneous KOH/Al_2O_3 [133]	Methanol	15:1	–	120	60	91.07
Heterogeneous BaO [134]	Methanol	9:1	2.8	60	65	95.20
Heterogeneous SrO [134]	Methanol	9:1	2.8	60	65	65.20
Heterogeneous CaO [134]	Methanol	9:1	2.8	60	65	77.30
Enzyme Novoz. 435 [135]	Methanol	3:1	–	1440	40	92.00
Super critical [136]	Ethanol	30:1	–	28.98	349	79.20
Super critical [136]	Methanol	40:1	–	16.02	372	81.50

methanol is used in the molar ratio of 8:1 (methanol to oil) with 3% (w/w) of montmorillonite KSF catalyst, then 79.60% biodiesel yield is achieved at 190 °C in 180 min [127]. A biodiesel yield of 92.50% is obtained with heterogeneous catalyst alum in 720 min [128]. Very high biodiesel yield (99.70%) is achieved while using heterogeneous KF/Ca-Al catalyst [130]. A high alcohol to oil molar ratio is required (30:1) during transesterification reaction using a heterogeneous Mg-Al catalyst [132]. When a heterogeneous KOH/Al_2O_3 catalyst is used, then a 15:1 M ratio of alcohol to oil is required with 60 °C temperature. The palm biodiesel yield obtained with this catalyst is 91.07% in 120 min [133]. While using BaO, SrO, and CaO heterogeneous catalysts, the highest biodiesel yield (95.20%) is obtained using the BaO catalyst [134]. Novos 435 produced a biodiesel yield of 92% in 1440 min and a methanol to oil molar ratio of 3:1 [135]. High reaction time, no reusability of catalysts, difficulty in separation of catalysts, and high sensibility with FFA and water causing saponification are some limitations associated with use of catalysts in transesterification reaction [137]. These issues can be resolved using alternate option–supercritical transesterification techniques. The rate of reaction is very fast in this technique. High temperature and pressure are required during this reaction. The pretreatment of oil is not required in this supercritical transesterification method [138, 139]. As no catalyst is used in this reaction, so there is no issue regarding saponification. Elimination of water and FFA contributes to the reduction of the cost of biodiesel production. However, high pressure and temperature are responsible for more price of equipment, and high alcohol to oil molar ratio also enhances the price of biodiesel production [140]. Methanol is the best alcohol type in this process due to low cost and easy availability. When ethanol is used in this process, then less biodiesel yield (79.2%) has resulted in 28.98 min at 349 °C temperature [136]. The requirement of alcohol to oil molar ratio and temperature of the reaction is high with the supercritical methanol method.

The transesterification reaction rate is profoundly affected by FFA and water content. Significant research efforts are required to improve the processing of biodiesel production. Some process improvement approaches are given below:

- Microwave irradiation
- Direct contact of oil with alcohol
- Equilibrium with early product removal
- Minimal effects of mass transfer

Performance and Emission Parameters of the Engine Using Palm Biodiesel

Research and development on the production of fuel from palm oil got started in the 1980s. There are various methods suggested to produce methyl esters from crude palm oil [141]. Most of the researches suggested that palm biodiesel is a promising alternative to conventional diesel fuel with fewer emissions [88, 142–144]. The detailed information on various performance and emission parameters of palm oil, palm biodiesel, and its blends is listed in Table 5 and Table 6, respectively.

Table 5 Performance parameters of a CI engine fuelled with palm oil, palm biodiesel, and its blends

Engine specifications	Input parameters	Performance parameters		Ref.
		BTE (%)	BSFC (g/kWh)	
Kirloskar TV 1, 4S, WC, 5.2 kW max. Power, 1500 RPM	Fuels: Diesel, B25, B50, B75, B100 (palm biodiesel); Load variation: 20–100%	30.89, 30.56, 29.22, 29.58, 28.65	Increases 2.59% (B25), 8.93% (B50), 9.25% (B75), 12.70% (B100)	[25]
Mitsubishi Pajero (4D56T), multi-cylinder, 4S max power 78 kW at 4200 RPM, radiator cooling, IDI	Fuels: B5, B10 (palm biodiesel) RPM range, 1000–4000	–	Lower than diesel fuel and increases with increases in palm biodiesel percentage in blend	[145]
Bharat stage III and IV engines	Fuels: B10, B20, B50, B100 (palm biodiesel) Variation in speed and brake power	Lower than diesel fuel	Increases with speed and BP; increases with increase in palm biodiesel percentage in blend	[146]
Lister 8/1 VA, single cylinder	Fuels: Palm kernel oil (PKO); RPM range, 1200–2100	–	Higher than diesel fuel, minimum 10% increase at 1800 RPM	[147]
Single cylinder, 4S, radiator cooled, maximum power 7.7 kW and maximum RPM 2400	Fuels: Diesel, B20 (palm biodiesel) Range of operating hours, 0–160	–	Higher than diesel fuel	[148]
4 inline cylinders, 4S, maximum power 55 kW at 3000 RPM, maximum torque 142 Nm at 2000 RPM	Fuels: Diesel, B5, B10, and B20 (palm biodiesel)	–	Higher than diesel fuel and increases with increase in palm biodiesel percentage in blend	[143]

Engine Performance Parameters

The storage ability of palm biodiesel makes it a safer fuel than traditional diesel fuel. The flash point of palm biodiesel is high when it is stored for about a year. Other properties like iodine number, pour point, cloud point, and acid number remain the same for that duration [149]. There is a decrement in the induction period reported when palm biodiesel is stored for more than 3 months [150]. The high storage ability of biodiesel makes it suitable to be used in CI engines for a longer duration. Low-power CI engines produce fewer emissions with high brake-specific fuel consumption (BSFC) when palm biodiesel is used as a fuel [151]. A 4S diesel engine (Kirloskar TV-1) is operated on diesel fuel and blends of palm biodiesel at various loads. The engine is operated on a constant 1500 RPM with load variation from 20 to 100%. The maximum power of the engine is 5.2 kW. Different palm biodiesel blends B25, B50, B75, and B100 are tested, and brake thermal efficiency (BTE) is observed 30.56%, 29.22%, 29.58%, and 28.65%, respectively. The increase in BSFC reported is 2.59%, 8.93%, 9.25%, and 12.70% for B25, B50, B75, and B100 palm biodiesel blends, respectively [25]. The higher BSFC is observed for Mitsubishi Pajero (4D56T) multi-cylinder engine compared to diesel fuel, and with the increase in blend percentage, the BSFC increases [145]. When palm biodiesel blends (B10, B20, B50, and B100) are used in Bharat stage III and IV engines, then the BTE is found lower than diesel and as palm biodiesel percentage the BTE also decreases. The increase in BSFC is recorded with an increase in speed and brake power [146]. During an experiment on a Lister 8/1 VA single-cylinder CI engine, the BSFC was found to be more for PKO than petroleum diesel [147]. The viscosity of palm kernel oil (PKO) is more than that of diesel fuel, which causes choking of the injector nozzle. Some engines' deteriorating effects like corrosion filter plugging and fuel supply line choking are caused by less oxidation stability [152].

The average brake power is observed almost similar to biodiesel blends and diesel fuel. An increase in BSFC is found when a single-cylinder engine of 7.7 kW power is operated on the B20 palm biodiesel blend [148]. When a 55-kW powered four-cylinder engine is operated on palm biodiesel blends (B5, B10, and B20), then there is an increase in BSFC reported, and this BSFC also increases with an increase in blend percentage [143]. From these experimental results, it is observed that the BTE of CI engines is reduced with the use of palm biodiesel due to the lower calorific value of fuel, and BSFC is observed higher than conventional diesel fuel.

Table 6 Emissions parameters of CI engine fuelled with palm oil, palm biodiesel, and its blends

Engine specifications	Input parameters	Emission parameters					Ref.
		HC	CO	NOx	CO_2	Smoke opacity	
Kirloskar TV 1, 4S, WC, 5.2 kW max. power, 1500 RPM	Fuels: Diesel, B25, B50, B75, B100 (palm biodiesel); load variation, 20–100%	Lower than diesel for B75 and B100; higher than diesel for B25 and B50	Lower than diesel and decreases with increase in palm biodiesel percentage in blend	Lower than diesel fuel	–	Lower than diesel for B50, B75, and B100; higher than diesel for B25	[25]
Mitsubishi Pajero (4D56T), multi-cylinder, 4S max power 78 kW at 4200 RPM, radiator cooling, IDI	Fuels: B5, B10 (palm biodiesel) RPM range, 1000–4000	Lower than diesel fuel, decreases at all RPMs and decreases with increase in palm biodiesel percentage in blend	Lower than diesel for all blends and decreases with increase in palm biodiesel percentage in blend	Higher than diesel fuel, increases at all RPMs and increases with increase in palm biodiesel percentage in blend	Higher than diesel fuel, increases at all RPMs and increases with increase in palm biodiesel percentage in blend	–	[145]
Bharat Stage III and IV engines	Fuels: B10, B20, B50, B100 (palm biodiesel) Variation in speed and brake power	Higher than diesel fuel	–	Higher than diesel fuel	–	–	[146]
Single cylinder, 4S, radiator cooled, maximum power 7.7 kW and maximum RPM 2400	Fuels: Diesel, B20 (palm biodiesel); Range of operating hours: 0–160	11.71% lower than diesel	Lower than diesel	Higher than diesel fuel and increases with an increase in operating hours	–	–	[148]
4 inline cylinders, 4S, maximum power 55 kW at 3000 RPM, maximum torque 142 Nm at 2000 RPM	Fuels: Diesel, B5, B10, and B20 (palm biodiesel)	Lower than diesel for all blends and decreases with increase in palm biodiesel percentage in blend	Lower than diesel for all blends and decreases with increase in palm biodiesel percentage in blend	Lower than diesel	–	–	[143]

Engine Emission Parameters

The diesel engines are more prone to NOx emissions due to lean-burn nature. With the use of palm oil biodiesel as an alternate fuel, emissions like CO, HC, and PM are reduced. CO, PM, and HC emissions are more harmful to human health than other emissions. Experimental investigation on four strokes Kirloskar TV-1 diesel engine shows lower HC emissions for B75 and B100, and higher for B25 and B50 blends than conventional diesel fuel. CO emissions were reduced with the increase in blend percentage. In this study, NOx emissions are higher than diesel fuel. Smoke opacity is observed lower for B50, B75, and B100 palm biodiesel blends and higher for B25 blend [25]. The same trend of emissions is observed with a multi-cylinder Mitsubishi Pajero (4D56T) engine except for CO_2 emissions. CO_2 emissions are increased with the increase in blend percentage at all RPMs [145]. When B10, B20, B50, and B100 palm biodiesel are used in Bharat stage III and IV engines, then both HC and NOx emissions are reported higher in comparison with traditional diesel fuel [146]. An 11.71% decrease in HC emissions was observed with the use of a B20 palm biodiesel blend than diesel fuel [148]. There is a decrease in HC, CO, and NOx emissions observed with B5, B10, and B20 blends of palm biodiesel than diesel fuel [143].

From all these results, it is observed that NOx emissions are higher for palm biodiesel than diesel fuel, and these emissions also increase with an increase in the percentage of palm biodiesel in blend. The main reason behind these emissions is higher oxygen content in palm biodiesel than diesel. The main parameters for high NOx formation are high temperature, availability of oxygen, and combustion duration. Emissions like carbon monoxide (CO), unburnt hydrocarbon (HC), particulate matter (PM 2.5 and PM 10), and carbon dioxide (CO_2) also associated with CI engines with a lower amount than SI engines [153]. HC emissions decreased due to more oxygen content of palm biodiesel than diesel fuel which results in complete combustion. CO_2 emissions are increasing due to the high availability of oxygen; CO gets converted to CO_2 at high temperatures. The use of the antioxidant additives in palm biodiesel reduces the NOx emissions in CI engines.

Scope of Future Work

Continuous biodiesel production and improvement in the production of cleaner fuel, with a much lower environmental impact and cost than fossil fuels, are essential. Advance research is required in the area of reduction in the cost of biodiesel production and increase in the yield of biodiesel. The research in the area of blending of vegetable oils or animal fats with waste oils should be explored. The research should also be focused in the area of developing cost-effective emission reduction techniques. The development of a technique to increase the photon-to-fuel conversion efficiency for different-generation feedstocks is an emerging area of research.

Conclusion

The physicochemical properties of oil decide the quality of biodiesel produced. Variations in these properties finally affect the performance and emissions of CI engines operated on biodiesel. Transesterification is the most suitable method among the various methods of biodiesel production with high biodiesel yield with low cost of production. High palm biodiesel yield (99.70%) is obtained using a heterogeneous KF/Ca-Al catalyst with 12:1 methanol to oil molar ratio in 180 min at 65 °C temperature. When palm biodiesel is used in the CI engine, there is a decrease in BTE, and an increase in BSFC observed due to the low calorific value of the fuel. With the rise in palm biodiesel percentage in blend, BTE decreases and BSFC increases. The emissions like HC, CO, and smoke opacity decrease with the use of palm biodiesel. Due to more oxygen content in palm biodiesel than diesel fuel, higher NOx is produced, and CO gets converted to CO_2 at high temperatures. CI engines are more prone to NOx emissions due to lean-burn nature, so antioxidant additives are required to reduce these emissions. The blending of palm biodiesel with diesel fuel up to 20% is suggested for optimum performance and emission results in CI engines.

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Authors' Contributions Digambar Singh: writing—original draft, writing—review and editing, conceptualization, formal analysis
Dilip Sharma: supervision
S. L. Soni: supervision
Chandrapal Singh Inda: validation, data curation, resources
Sumit Sharma: resources
Pushpendra Kumar Sharma: formal analysis
Amit Jhalani: visualization

Compliance with Ethical Standards

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