Feasibility of Coconut Testa oil and Coconut Waste Cooking oil as Potential Biodiesel Feedstocks

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Research Article

Keywords: Biodiesel, Coconut waste cooking oil, Coconut testa, Engine performance, Emission, Combustion

Posted Date: September 8th, 2021

DOI: <https://doi.org/10.21203/rs.3.rs-684031/v1>

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Abstract

It is well known that biodiesel from pure coconut oil is suited best for diesel engine operation. However, the commercialization of coconut oil biodiesel is unfeasible due to its higher cost and demand as a food material. In this study, biodiesels were produced from coconut testa oil and coconut waste cooking oil, two waste feedstock derivatives of coconut. Fatty acid composition and properties such as density, calorific value, kinematic viscosity, cloud and pour points, flash and fire points, Conradson carbon residue, and copper strip corrosion of these two biodiesels were determined and compared with those of fresh coconut oil biodiesel and the standard diesel. It was found that the properties and fatty acid profiles of all three biodiesels were similar. Furthermore, from the engine testing using B20 (diesel-biodiesel blend with 20% biodiesel) blends of prepared biodiesels, it was found that the engine performance, emission, and combustion characteristics were comparable for coconut testa oil and coconut waste cooking oil biodiesels with fresh coconut oil biodiesel. Thus the coconut testa oil and coconut waste cooking oil can be used as low-cost feedstocks for biodiesel production with all advantages of fresh coconut oil.

1. Introduction

Presently, the transportation and agricultural sectors are predominantly dependent on petroleum-based diesel fuels, which heavily contribute to environmental pollution. Biodiesel, which has emerged as a promising alternative fuel, is a cleaner fuel with a significant reduction in greenhouse gases, sulfur emissions, and particulate matter pollutants. It shows superior qualities such as low toxicity and biodegradable nature as compared to diesel (Lin and Lin 2006). Biodiesel is derived from either edible oils such as sunflower oil, palm oil, coconut oil, soybean oil, rapeseed oil (Can et al. 2016; Venu et al. 2019; Dueso et al. 2018; Raman et al. 2019; Prasad 2017), or non-edible oils such as pongamia, jatropha, castor, neem, rubber seed, linseed, mahua (Krishania et al. 2020; Dhanasekar et al. 2019; Ramadhas et al. 2005; Dhar et al. 2012; Kumar et al. 2018; Veinblat et al. 2018; Arunkumar et al. 2019). Biodiesel production from edible sources leads to food scarcity and thereby energy versus food competition. In most cases, the cultivation of non-edible oil crops requires land and irrigation, which leads to energy versus land competition. Also, the feedstock cost, which majorly contributes to the cost of biodiesel, is a significant hurdle in considering biodiesel as a promising alternative fuel.

Waste cooking oil (WCO) means the used vegetable oil remains after cooking or frying food. Usage of cooking oil repeatedly for the preparation of food is a common practice. During the heating process, vegetable oils undergo chemical reactions such as hydrolysis, thermal oxidation, and polymerization, which lead to the formation of a variety of deteriorating chemicals (Choe and Min 2007). Free radicals formed during the repeated heating process induce oxidative stress and stimulate damage at the cellular level. Histopathological observation of animals that consumed oil heated repeatedly for three times described considerable damage in the liver, jejunum, and colon (Venkata and Subramanyam 2016). Moreover, the WCO produced excessively from restaurants, cafeterias, and household kitchens (Sadaf et al. 2018) is discarded openly, leading to pollution of soil, water bodies, and sewerage system. Hence, instead of throwing away by degrading the environment, it could be used as a potential and cost-effective feedstock for biodiesel production as it is available in abundance. In this work, coconut WCO is recycled into biodiesel with the dual advantage of waste disposal and fuel production.

The coconut palm belongs to the family Arecaceae, and it is growing in many countries around the world commercially. The edible part of the coconut is used for making coconut oil, coconut milk, coconut cream, and desiccant coconut. (Appaiah et al. 2014). It is a well-known fact that biodiesel produced from pure coconut oil is best suited as diesel engine fuel due to its lower viscosity and density than other biodiesels and reduced engine emissions (Kalam et al. 2016; Liaquat et al. 2013; Woo et al. 2016; Zareh et al. 2017), but its high cost makes it unaffordable to be used as fuels for engines. Testa is the brown part covering the white meat, a byproduct of coconut processing industries, and is usually used as animal feed or discarded (Appaiah et al. 2014; Zhang et al. 2016), whereas testa oil is used in soap industries. In the prevailing research, testa oil is used as the second source for biodiesel production.

Encinar et al. (2015) studied the influence of reaction temperature, amount of methanol, and catalyst on biodiesel properties. The reaction temperature of 65°C, methanol to oil ratio of 6:1, and catalyst (KOH) concentration of 1% were reported as optimum. Niju et al. (2015) analyzed the emission and performance attributes of a diesel engine running with standard diesel and biodiesel blends at dissimilar loads. With the consumption of blended fuel, increment in brake specific fuel consumption (BSFC), decrement in brake thermal efficiency (BTE), fall off in unburnt hydrocarbons (HC) emission, carbon monoxide (CO) emission, and increment in oxides of nitrogen (NO_x) emission were observed for biodiesel blends in comparison with diesel. Wei et al. (2018) conducted the performance, emission, and combustion tests on a marine auxiliary diesel engine utilizing WCO biodiesel in three different blending percentages of 10%, 30%, and 50% with diesel. They observed increased BSFC, decreased BTE, NO_x emission, and peak heat release rate (HRR) by employing biodiesel-blended fuel. Ö Can (2014) produced biodiesel from WCO and studied performance, emission, and combustion attributes of a direct-injection diesel engine with diesel and two different biodiesel-diesel blends, with 5% and 10% of biodiesel. It was revealed that the incorporation of biodiesel consistently caused the advance in the start of combustion (SOC) with a combination of advanced injection timing and shorter ignition delay. For all engine loading conditions, increased combustion duration was observed with biodiesel addition. A slight decline in peak heat release rate was remarked with the biodiesel addition. A considerable change of maximum cylinder pressure was not observed with biodiesel addition. An elevated BSFC, diminished smoke and HC emissions, and raised NO_x emission were observed.

Zareh et al. (2017) deliberated the performance and emission attributes of a turbocharged diesel engine at several loads and speeds with biodiesel-diesel blends from coconut oil, castor oil, and waste cooking oil with blending ratios of 5%, 10%, 20%, and 30%. The experimental results signify the best performance and emission characteristics for blended biodiesels from WCO and coconut oil. Biodiesel blends reduced brake power and particulate matter (PM) and continued to decline with the increase of biodiesel percentage. Coconut biodiesel blends showed the lowest NO_x change rate in the exhaust than diesel. Reduced CO emission was observed with blended fuel, and the highest reduction was related to coconut biodiesel. Krishania et al. (2020) conducted the performance, emission, and combustion analysis on a diesel engine at multiple compression ratios of 16.5, 17.5, and 18.5 with B20 blends of biodiesels produced from sources including coconut and waste cooking oil. A reduced brake thermal efficiency, exhaust gas temperature, ignition delay was observed

with B20 blends. A significant reduction of smoke, particulate matter, NO_x, and sulfur dioxide (SO₂) were observed with a compression ratio of 17.5. Thangaraja and Srinivasan (2019) explored the operation of a multi-cylinder diesel engine by utilizing coconut biodiesel and standard diesel at various load and speed conditions. Leaner combustion and concise ignition delay were reported for coconut biodiesel in contrast with diesel. Reduced emissions of smoke, CO, and HC were recorded with coconut biodiesel with higher NO_x emission.

Woo et al. (2015) reported a simultaneous decrement of emissions such as smoke and NO_x and enhanced brake power with a 10% blend of coconut biodiesel with diesel. Lower indicated mean effective pressure was observed with blended fuel by virtue of inferior calorific value. Kalam et al. (2016) evaluated the performance and emission characteristics of an indirect injection diesel engine functioning with coconut oil biodiesel. They have used biodiesel-diesel blends with 10%, 20%, 30%, 40%, and 50% biodiesel. It was reported that the fuel's calorific value decreased, and density increased with the supplement of coconut oil biodiesel in the biodiesel-diesel blend. Increased brake power output and increases in BSFC were observed for all blended fuels in contrast with diesel. Reduced emissions of HC, CO, smoke, NO_x, and benzene were observed with all blended fuels.

Chinnamma et al. (2015) compared the physicochemical properties of biodiesel extracted from coconut oil with diesel, and tests were executed on a diesel engine. They found that the properties of coconut biodiesel strongly support the functional similarity of coconut oil biodiesel with diesel. The engine tests showed similar torque, power, and improved mileage for biodiesel in contrast with diesel. Woo et al. (2016) conducted the performance and emission assessment of common-rail single-cylinder light-duty diesel engine, employing coconut biodiesel-diesel blends containing 10%, 25%, and 40% biodiesel. The engine speed was kept at 2000 rpm, and common rail pressure was maintained at 130 MPa for the test. Similar brake mean effective pressure was mentioned with biodiesel blends relative to diesel. Incremented BSFC, reduced smoke, CO, and NO_x emissions were remarked with blended fuel. Liaquat et al. (2013) compared performance and emissions attributes for a diesel engine consuming diesel and blends of coconut biodiesel B5 (diesel-biodiesel blend with 5% of biodiesel) and B15 (diesel-biodiesel blend with 15% of biodiesel). They have observed higher BSFC, lower emissions such as HC and CO, elevated carbon dioxide (CO₂), and NO_x emissions for both blends against diesel fuel.

It is observed from the literature that many investigations have been executed to evaluate the suitability and benefits of using biodiesel produced from coconut oil in diesel engines. The techno-economical study conducted by Thangaraja et al. (2019) reported that coconut biodiesel is a potential substitute fuel for standard diesel. However, its high cost and food versus energy issues are the barriers to commercialization as the feedstock cost is about 70–80% of the total biodiesel production cost (Gui et al. 2008).

Hence, by keeping the advantages of coconut oil in mind, two low-cost waste feedstocks derived from coconut, which are economically feasible for biodiesel production, are tried and tested. Biodiesels produced from two cheap and throwaway non-edible feedstocks, coconut testa oil and coconut waste (heated) cooking oil, were characterized and compared with the biodiesel derived from fresh coconut oil and the standard diesel. B20 blends of these three biodiesel samples were used to perform diesel engine testing. The performance, emission, and combustion characteristics of all three biodiesel blends were compared with diesel.

2. Materials And Methods

2.1 Preparation of waste cooking oil (WCO)

Pure coconut oil extracted from dried coconut by traditional method and coconut testa oil procured from the local market were used in this study. Since the normal frying temperature is between 150°C and 190°C (Choe and Min 2007), waste coconut oil was prepared by frying wheat dough for 1 hour by maintaining the temperature at 180°C and then cooled to room temperature. The above procedure was repeated thrice to prepare heated (waste) coconut oil.

2.2 Biodiesel production from fresh coconut oil, waste (heated) coconut oil, and coconut testa oil

Prior to the transesterification process, the oil samples were made moisture-free by heating to 105°C and cooling to room temperature. Methoxide solution was generated by adding KOH (1 wt% of oil) to methanol (6:1 methanol to oil molar ratio) and was mixed with preheated oil. This reaction was performed in a batch reactor equipped with a magnetic stirrer and a heater, maintaining a reaction temperature of 60°C at ambient pressure for 1 hour. The product was then shifted into a separating funnel and enabled to segregate overnight. The bottom portion of glycerin was drained, and the upper layer of biodiesel (methyl esters) was washed 3–5 times using water at 50°C for removing residual catalyst and excess methanol. Biodiesel was then heated above 100°C to remove any moisture content for 20 minutes. The above procedure was followed to produce fresh coconut oil methyl ester (COME), heated coconut oil methyl ester (HCOME), and coconut testa oil methyl ester (CTOME).

The total cost of biodiesel counts on factors such as the size of the plant, annual production quantity, availability of materials, and the demand for byproducts. The total production cost of biodiesel includes fixed costs such as equipment cost, installation cost, piping cost, insulation and painting cost, electric and instrumentation cost, computer system cost, engineering and supervising cost, running costs such as human resources, transportation, material costs such as oil cost, alcohol cost, catalyst cost, and energy cost (Sakai et al. 2009). In the present study, biodiesel was produced at a laboratory scale. The estimated cost of production for 1 liter of biodiesel is shown in Table.1. The cost of WCO in the market is 15 to 30 rupees per liter, and that of coconut testa oil is 30 to 40 rupees per liter. This cost will vary with respect to local availability and transportation cost. The diesel cost varies from 67 to 85 rupees per liter in the last three years. The total income of the biodiesel plant can be improved by alcohol recovery and by selling byproducts such as glycerin, which is an ingredient in the soap industry.

Table 1

Production cost of biodiesel (Indian rupees per liter)

	COME	HCOME	CTOME
Oil cost	200	30	40
Alcohol and catalyst cost	35	35	35
Energy and labor cost	2	2	2
Total	237	67	77

2.3 Fatty acid profiles of biodiesel

The fatty acid profiles of the three biodiesels were obtained employing gas chromatography (GC) integrated with a flame ionization detector (FID). Detector and injector ports were held at 280°C and 260°C, respectively, and hydrogen was used as the carrier gas.

Table 2

Details of fuel property measuring instruments and corresponding ASTM standard

Sl. No.	Property	Instrument	ASTM Standard
1	Density	Portable digital density meter	D7777
2	Kinematic viscosity	Cannon Fenske viscometer	D446
3	Calorific value	Bomb calorimeter	D5865-13
4	Cloud and pour point	Cloud and pour point apparatus	D97-16
5	Flash and fire point	Pensky Marten flash and fire apparatus	D92
6	Copper strip corrosion	Copper strip corrosion apparatus	D130-12
7	Carbon residue	Conradson carbon residue apparatus	D189-06

2.4 Properties of Biodiesel fuel

The three biodiesel samples were characterized and compared using the instruments according to the ASTM standards shown in Table 2.

2.5 Diesel engine test setup for performance, combustion, and emission analysis

Performance, combustion, and emission attributes of a diesel engine, with specifications given in Table 3, were analyzed. Eddy current dynamometer loading system was utilized, and the exhaust gas was sampled from the exhaust line by diverting it without increasing the backpressure. Table 4 shows the range and resolution of the non-dispersive infrared analyzer (NDIR), AVL DiGas 444 five gas analyzer that measures CO, CO₂, HC, and NO_x. AVL 437C smoke meter was employed to determine smoke opacity. A piezo-resistive type cylinder pressure sensor and an incremental type encoder were used to analyze the combustion characteristics. The diagrammatic representation of the experimental arrangement is shown in Fig. 1.

Table 3

Specification of diesel engine test rig

Number of cylinders and strokes	1, 4 strokes
Cylinder bore / stroke	80 mm / 110 mm
Piston type	Bowl-in-piston
Rated power	3.73 kW
Speed	1500 rpm
Compression ratio	17.5 : 1
Injection pressure	200 bar
Injection timing	23 ° bTDC
Number of nozzle holes and diameter	3 and 0.25 mm
Dynamometer type	Eddy current
Dynamometer cooling	Air Cooled

Table 4

Species	Measuring Range	Resolution
HC	0-20000 ppm	$\leq 2000:1$ ppm
		$> 2000:10$ ppm
CO	0–10 % vol.	0.01 % vol.
CO ₂	0–20 % vol.	0.1 % vol.
O ₂	0–25 % vol.	0.01 % vol.
NO _x	0-5000 ppm	1 ppm
Smoke opacity	0–100 %	0.1 %

Before starting the engine, the fuel system was fully emptied, and the fuel filter was cleaned. After filling the fuel in the fuel line, without any air in it, the engine was started and then operated with the substitute fuel for about 15 min to remove any residue of the formerly examined fuel from the engine fuel delivery system. The engine test was performed at various loads at a steady speed of 1500 rpm. The engine supply performance parameters such as fuel consumption, torque, engine speed were noted and were utilized to compute brake power (BP), BSFC, and BTE.

Emission readings such as smoke opacity, HC, CO₂, CO, and NO_x were recorded. A piezoelectric sensor attached to the cylinder head was employed to quantify cylinder pressure and recorded using a data acquisition system. The results for all the blended fuels were matched with the standard diesel operation.

2.6 Uncertainty analysis

To minimize the error from measuring instruments, the uncertainty analysis was performed. The percentage uncertainties of individual variables, such as BTE, BSFC, BP, HC, CO, CO₂, smoke, NO_x, cylinder pressure, and crank angle, are shown in Table 5.

The overall uncertainty of the experiments can be predicated as

Overall uncertainty = Square root of {(Uncertainty of BTE)² + (Uncertainty of BSFC)² + (Uncertainty of BP)² + (Uncertainty of CO)² + (Uncertainty of CO₂)² + (Uncertainty of HC)² + (Uncertainty of NO_x)² + (Uncertainty of smoke)² + (Uncertainty of cylinder pressure)² + (Uncertainty of crank angle)²}

$$= \sqrt{0.7^2 + 0.8^2 + 0.2^2 + 2.1^2 + 1.7^2 + 1.3^2 + 0.6^2 + 1.0^2 + 0.1^2 + 0.2^2} = \pm 3.40\%$$

Table 5

Percentage uncertainties of individual parameters

	Uncertainty (%)
BTE	± 0.7
BSFC	± 0.8
BP	± 0.2
CO	± 2.1
CO ₂	± 1.7
HC	± 1.3
NO _x	± 0.6
Smoke	± 1.0
Crank angle	± 0.2
Cylinder pressure	± 0.1
Total	± 3.40

3. Result And Discussion

3.1 Fatty acid profiles of biodiesel

Biodiesel is a combination of alkyl esters of various fatty acids of those in which the raw material is composed. Hence, the biodiesel properties depend on the concentration of each ester component. Biodiesel density increases with decreasing chain length and increasing unsaturation (Folayan et al. 2019). An extension in the chain length of fatty acids leads to increased random intermolecular interactions, which causes higher viscosity. Also, viscosity decreases with unsaturation because of the loosely packed and fluid-like structure of fatty acids with more double bonds (Folayan et al. 2019; Yalcin et al. 2012). Biodiesel calorific value increases with the increasing chain length (Folayan et al. 2019; Knothe 2005). Biodiesel fuels produced from fats or oils with considerable amounts of saturated compounds will exhibit higher cloud point and pour point temperatures because of the elevated melting point of saturated compounds (Knothe 2005). The difference in biodiesel properties will lead to changes in the performance, emission, and combustion characteristics during engine operation.

Table 6
Fatty acid profiles of different biodiesel samples

	COME	HCOME	CTOME
Caprylic acid (C8:0)	7.99	7.49	4.94
Capric acid (C10:0)	5.61	5.65	3.49
Lauric acid (C12:0)	45.04	45.77	33.02
Myristic acid (C14:0)	17.77	17.98	17.06
Palmitic acid (C16:0)	8.06	8.19	10.69
Palmitoleic acid (C16:1)	7.18	7.29	9.50
Stearic acid (C18:0)	1.70	1.90	1.42
Oleic acid (C18:1)	4.03	4.10	8.32
Linoleic acid (C18:2)	2.62	1.63	11.55
Saturated	86.17	86.98	70.63
Mono unsaturated	11.20	11.39	17.82
Poly unsaturated	2.62	1.63	11.55

The constituents of COME, HCOME, and CTOME are the fatty acids methyl esters with carbon chain lengths ranging from 8 to 18 with saturated, mono-unsaturated, and poly-unsaturated molecules. COME, HCOME, and CTOME consists of 45.04 %, 45.77 %, and 33.02 % of lauric acid (C12:0), which is the major component of all the three biodiesel samples, 86.17%, 86.98%, and 70.63% of saturated fatty acid, 11.20%, 11.39% and 17.82% of mono-unsaturated fatty acid, and 2.62%, 1.63% and 11.55% of poly-unsaturated fatty acids respectively. Linoleic acid methyl ester (C18:2) in CTOME was observed higher (11.55%) when compared to that of COME (2.62%) and HCOME (1.63%).

Table 7
Comparison of properties of the three biodiesel samples and diesel

Properties	Diesel	COME	HCOME	CTOME
Density (kg/m ³)	817.2 ± 0.1	864.5 ± 0.1	865.6 ± 0.2	865.9 ± 0.1
Kinematic viscosity @40°C (cSt)	2.38 ± 0.01	2.71 ± 0.01	2.81 ± 0.01	2.98 ± 0.01
Calorific value (MJ/kg)	43.49 ± 0.02	35.62 ± 0.03	36.68 ± 0.02	36.48 ± 0.01
Flash point (°C)	51 ± 1	105 ± 1	112 ± 1	114 ± 1
Fire point (°C)	58 ± 1	125 ± 1	127 ± 1	146 ± 1
Cloud point (°C)	-4 ± 1	2 ± 1	4 ± 0	4 ± 0
Pour point (°C)	-11 ± 1	-5 ± 0	-4 ± 1	-4 ± 0
Copper strip corrosion	1a	1a	1a	1a
Conradson carbon residue (%)	0.0295 ± 0.0001	0.0129 ± 0.0001	0.0130 ± 0.0002	0.0139 ± 0.0001

3.2 Comparison of fuel properties

Properties of the three biodiesel samples, such as density, calorific value, kinematic viscosity, cloud point, pour point, flash point, fire point, copper strip corrosion, and Conradson carbon residue, were determined and matched with that of standard diesel as demonstrated in Table 7. Properties of coconut-based biodiesels are also compared with other biodiesels, as reported in Table 8.

3.2.1 Density

The densities of biodiesels produced were observed larger than that of diesel. Among the three biodiesel samples, the density of CTOME was highest, which may be due to the higher degree of unsaturation (Ramírez-Verduzco et al. 2012), and that of COME was the lowest. The higher density of biodiesel causes higher bulk modulus leading to advanced injection timing (Boehman et al. 2004). It is more exciting to point out that the densities of coconut-based biodiesels ($864.5 \text{ kg/m}^3 - 865.9 \text{ kg/m}^3$) were lower than biodiesels prepared from palm oil, soybean oil, sunflower oil, jatropha oil, rapeseed oil, pongamia oil, rubber seed oil, neem oil, linseed oil, mahua oil, and castor oil as shown in Table 8. Hence the coconut-based biodiesels are the best option among all other feedstocks.

3.2.2 Kinematic viscosity

The viscosities of COME, HCOME, and CTOME were observed higher than that of diesel by 14.01%, 18.27%, and 25.25%, respectively. A slightly higher viscosity observed for CTOME can be attributable to the existence of long-chain fatty acid methyl ester, as seen in Table 6. The viscosities of coconut-based biodiesels were found to be lower (2.376 cSt – 2.976 cSt) when compared to other biodiesels produced from soybean oil, palm oil, sunflower oil, jatropha oil, rubber seed oil, rapeseed oil, pongamia oil, neem oil, linseed oil, mahua oil, and castor oil as shown in Table 8. The lower viscosity may be due to the enormous amount of smaller molecular weight methyl esters, particularly methyl laurate and methyl myristate in coconut-based feedstocks (Nakpong and Wootthikanokkhan 2010). Thus, the problem of poor atomization of biodiesel fuel during the combustion process, due to higher viscosity, will be less for coconut-based biodiesels.

3.2.3 Calorific value

Calorific values (CV) of biodiesel samples were less compared to diesel fuel as diesel fuel is composed of various hydrocarbons containing oxygen lower than 0.3%, whereas biodiesel includes a considerable quantity of oxygen, about 9% (Ayeter et al. 2015). The calorific values of COME, HCOME, and CTOME were less than that of diesel by 18.09%, 15.65%, and 16.12%, respectively. The calorific value rises with an increase in molecular weight and reduces with the increased unsaturation (Ramírez-Verduzco et al. 2012). The slightly higher calorific values of HCOME and CTOME, compared to COME, could be due to the inclusion of fatty acid with large molecules. It was also seen that the calorific values of coconut-based biodiesels were found to be lower (35.62 MJ/kg – 36.68 MJ/kg) when compared to other biodiesels produced from soybean oil, palm oil, sunflower oil, jatropha oil, rubber seed oil, rapeseed oil, pongamia oil, neem oil, linseed oil, mahua oil, and castor oil as shown in Table 8. Lower CV coconut-based biodiesels may be because of the shorter chain length of fatty acid methyl esters.

Table 8

Comparison of properties of Coconut-based biodiesel with other biodiesels

Biodiesel	Density (kg/m ³)	Kinematic viscosity (cSt)	Calorific value (MJ/kg)	Flash point (°C)	Fire point (°C)	Cloud point (°C)	Pour point (°C)	Copper strip corrosion	Conradson carbon residue (%)
Coconut-based biodiesel	864.5 to 865.9	2.376 to 2.976	35.62 to 36.68	105 to 114	125 to 146	2 to 4	-5 to -4	1a	0.0129 to 0.0139
Palm oil	875 (Roschat et al. 2016)	4.5 (Mosarof et al. 2015)	38.1 (Soetaredjo et al. 2011)	186 (Roschat et al. 2016)	-	13 (Ali and Tay 2013)	17 (Ali and Tay 2013)	1a (Roschat et al. 2016)	0.0395 (Roschat et al. 2016)
Sunflower oil	885 (Saba et al. 2016)	4.47 (Dueso et al. 2018)	39.83 (Dueso et al. 2018)	161.2 (Sayed et al. 2020)	-	3 (Sayed et al. 2020)	0 (Sayed et al. 2020)	1a (Tomic et al. 2014)	-
Soybean oil	880 (Silva et al. 2008)	4.7 (Silva et al. 2008)	37.72 (Veinblat et al. 2018)	148 (Panchal et al. 2020)	-	4(Panchal et al. 2020)	1(Panchal et al. 2020)	1a (Panchal et al. 2020)	-
Rapeseed oil	882 (Koutsouki et al. 2016)	4.83 (Chong and Hochgreb 2014)	36.8 (Chong and Hochgreb 2014)	183 (Saravanan et al. 2020)	188 (Saravanan et al. 2020)	-3 (El-Enin et al. 2013)	-6 (El-Enin et al. 2013)	1a (Qian et al. 2013)	< 0.010 (Qian et al. 2013)
Jatropha oil	874.2 (Tan et al. 2012)	4.5 (Kathirvelu et al. 2017)	39.8 (Rahman et al. 2014)	185 (Kumar and Saluja 2020)	192 (Kumar and Saluja 2020)	5 (Rahman et al. 2014)	3 (Rahman et al. 2014)	1b (Tan et al. 2019)	-
Pongamia oil	895 (Perumal and Ilangkumaran 2018)	5.34 (Kumar et al. 2011)	39.32 (Perumal and Ilangkumaran 2018)	196 (Jaichandar and Annamalai 2012)	-	10.2 (Jaichandar and Annamalai 2012)	4.2 (Jaichandar and Annamalai 2012)	-	0.0035 (Jaichandar and Annamalai 2012)
Rubber seed oil	885 (Ahmad et al. 2014)	4.5 (Morshed et al. 2011)	39.7 (Ahmad et al. 2014)	152 (Ahmad et al. 2014)	-	3.2 (Ahmad et al. 2014)	-2 (Ahmad et al. 2014)	1a (Roschat et al. 2017)	-
Neem oil	890 (Balaji and Cheralathan 2015)	4.27 (Balaji and Cheralathan 2015)	40.67 (Balaji and Cheralathan 2015)	183.5 (Oni and Oluwatosin 2020)	-	9 (Oni and Oluwatosin 2020)	5 (Oni and Oluwatosin 2020)	-	0.032 (Shankar and Jambulingam 2017)
Mahua oil	869.8 (Aalam et al. 2016)	5.2 (Puhan et al. 2005)	36.9 (Puhan et al. 2005)	129 (Godiganur et al. 2009)	141 (Godiganur et al. 2009)	-	6 (Ghadge and Raheman 2005)	-	0.20 (Ghadge and Raheman 2005)
Linseed oil	887 (Guzatto et al. 2011)	5.21 (Veinblat et al. 2018)	37.6 (Veinblat et al. 2018)	151 (Kumar et al. 2013)	-	3.17 (Kumar et al. 2013)	-6.25 (Kumar et al. 2013)	1a (Guzatto et al. 2011)	0.018 (Kumar et al. 2013)
Castor oil	915 (Du et al. 2018)	11.2 (Du et al. 2018)	38 (Du et al. 2018)	146 (Attia et al. 2018)	-	-19 (Attia et al. 2018)	-15 (Attia et al. 2018)	-	-

3.2.4 Flash and fire points

Flash and fire points, which measures flammability, of diesel are 51°C and 58°C, respectively, as compared to 105°C and 125°C for COME, 112°C, and 127°C for HCOME, 114°C and 146°C for CTOME, respectively. Flash and fire points of fuel are a reflection of the boiling point of the individual components. Diesel comprises lower molecular weight components with branches with a lower boiling point, which leads to diminished flash and fire points (Knothe 2010). Higher flash and fire points of biodiesel are an upper hand from the safety point of view. Flash and fire points of coconut-based biodiesels were lower than other biodiesels reported in the literature, as shown in Table 8.

3.2.5 Cloud and pour points

Generally, biodiesel exhibits elevated cloud and pour points compared to diesel (Ali and Tay 2013; Antolin et al. 2002; Sayed et al. 2020). Cloud point of diesel, COME, HCOME, and CTOME were observed as -4°C, 2°C, 4°C, and 4°C, respectively. Pour point of diesel, COME, HCOME, and CTOME were observed as -11°C, -5°C, -4°C, and - 4°C, respectively. The poor cold flow properties are a challenge to use biodiesel in cold weather (Verissimo 2011; Verma et al. 2016). Cloud and pour points of coconut biodiesels were found to be lower than biodiesels from palm oil, jatropha, pongamia, neem, mahua, soybean, rubber seed, and higher than biodiesels from sunflower, rapeseed, and linseed, as shown in Table 8.

3.2.6 Copper strip corrosion test

The outcome of the copper strip corrosion test demonstrates the corrosive nature of a liquid. From the results, it can be noticed that all the biodiesel samples have similar corrosive characteristics when compared to standard diesel. There will be no additional corrosive issue with biodiesel usage, and it does not affect engine parts.

3.2.7 Conradson carbon residue

This is a measure of the carbonaceous residue after evaporation and thermal degradation of fuel. Carbon residues of diesel, COME, HCOME, and CTOME were observed as 0.0295%, 0.0129%, 0.0130%, and 0.0139%, respectively. Compared to diesel, the carbon residues of all three biodiesel samples were found to be lower. This can be attributable to the presence of short-chain and saturated fatty acid methyl ester in coconut-based biodiesels.

3.3. Comparison of properties of biodiesel-diesel blends B20

It is commonly agreed that biodiesel blending in diesel up to 20% in volume, namely B20 (20% biodiesel + 80% diesel), do not need any alteration in the prevailing diesel engines (Caresana 2011), and some of the engine manufacturers approved the 20% blending of biodiesel in diesel (Can 2014). Hence, B20 blends were prepared for further testing in the diesel engine, using the three biodiesel samples COMEB20 (coconut oil methyl ester B20), HCOMEB20 (heated coconut oil methyl ester B20), and CTOMEB20 (coconut testa oil methyl ester B20). Property comparison of biodiesel blends with diesel is shown in Table 9. The densities of COMEB20, HCOMEB20, and CTOMEB20 were found to be 1.14%, 1.17%, and 1.21% higher than diesel. Kinematic viscosities of COMEB20, HCOMEB20, and CTOMEB20 were 1.97%, 2.35%, and 2.65% higher than diesel. The calorific values of COMEB20, HCOMEB20, and CTOMEB20 were 3.63%, 3.12%, and 3.40% lower than diesel.

Table 9

Comparison of properties of the three biodiesel blends (B20) and diesel

Properties	Diesel	COMEB20	HCOMEB20	CTOMEB20
Density (kg/m ³)	817.2 ± 0.1	826.5 ± 0.2	826.8 ± 0.1	827.1 ± 0.1
Kinematic viscosity @40°C (cSt)	2.37 ± 0.01	2.42 ± 0.01	2.43 ± 0.01	2.44 ± 0.01
Calorific value (MJ/kg)	43.49 ± 0.02	41.91 ± 0.02	42.13 ± 0.01	42.01 ± 0.02

3.4 Performance, combustion, and emission analysis of the engine

Performance parameters such as BTE and BSFC are expressed in Fig. 2. In-cylinder pressure variation, HRR, and the SOC at maximum load are shown in Fig. 3 to Fig. 5. Various exhaust emissions measured such as HC, CO, CO₂, Smoke, and NO_x are shown in Fig. 6 to Fig. 8.

3.4.1 BTE and BSFC

Performance characteristics such as BTE and BSFC indicate the applicability of fuel in engines. Figure 2 shows that at the maximum load of 3.73 kW, the BTE of the engine were 32.7%, 32.37%, 32.19%, and 32.08% with diesel, COMEB20, HCOMEB20, and CTOMEB20 as fuels, respectively. All blended fuels indicated elevated BSFC in contrast to standard diesel. At the maximum load, the engine had a BSFC of 0.2531 kg/kWh, 0.2653 kg/kWh, 0.2654 kg/kWh, and 0.2671 kg/kWh with diesel, COMEB20, HCOMEB20, and CTOMEB20, respectively. Even though biodiesel contains elevated oxygen content, promoting improved combustion, reduced BTE, and higher BSFC can be attributed to its lower CV (Ramadhas et al. 2005; Muralidharan et al. 2011; Yatish et al. 2018), higher density, and viscosity leading to inadequate atomization and mixture formation (Kannan and Anand 2012) as compared to diesel. Lower BTE of HCOMEB20 and CTOMEB20 compared to COMEB20 may be due to slightly higher viscosity even though they have high CV compared to COMEB20.

3.4.2 In-cylinder Pressure

Cylinder pressure versus crank angle records of the engine operating cycle reveals information on the progress of combustion. Figure 3 expresses in-cylinder pressure variation, averaged for 100 consecutive combustion cycles, against the crank angle at the maximum load for different fuels. Pressure rise was observed earlier, and the peak cylinder pressure was detected lower for biodiesel blends in contrast with diesel. Maximum in-cylinder pressure of 65.42 bar, 64.77 bar, 64.88 bar, and 64.94 bar was observed with diesel, COMEB20, HCOMEB20, and CTOMEB20, respectively. The reduced maximum cylinder pressure with blended fuels can be described by the lower calorific value, high viscosity, and low volatility (Muralidharan et al. 2011).

3.4.3 Heat release rate (HRR)

The heat release rate represents the transformation rate of chemical energy into heat energy in the fuel through the engine combustion process. The heat release rate curves of blended fuels and diesel at maximum load, as shown in Fig. 4, indicate that the heat release with biodiesel blends starts before diesel. Maximum HRR was found to be 86.26 J/°CA for diesel when compared to 79.88 J/°CA, 79.71 J/°CA, and 80.60 J/°CA for COMEB20, HCOMEB20, and CTOMEB20, respectively. The decrease in maximum HRR with biodiesel blends could be caused by the poor energy content of the fuel (Zhang et al. 2016), higher viscosity, and poor spray formation (Muralidharan et al. 2011).

3.4.4 Start of combustion (SOC)

The start of combustion is the point of the first distinguishable hike in-cylinder pressure owing to exothermic energy discharge within the combustible mixture and can be fixed from the curve of cumulative heat release rate, the respective point where the cumulative heat release rate switches from zero to positive (Lata and Misra 2011). SOC for diesel, COMEB20, HCOMEB20, and CTOMEB20 were derived from the cumulative heat release curve as 4.52 °, 4.66 °, 4.80 °, and 4.89 ° before TDC (top dead center), respectively. A lower heat release rate with a similar start of combustion leads to lower NO_x emission with blended biodiesel fuels. Biodiesel blends with higher bulk modulus and viscosity induce quicker transmission of pressure waves from the pump to the nozzle due to higher sound velocity. Also, higher viscosity reduces pump leakage. These lead to faster and advanced needle opening and advanced injection timing than diesel fuel (Caresana 2011).

3.4.5 CO and CO₂ emissions

Air fuel ratio, inadequate mixing of air and fuel, on-the-spot rich zone in the combustion chamber, and shortage of time and oxygen for the post-oxidation process are the circumstances leading to incomplete combustion resulting in increased CO emission (Sanli et al. 2015). At higher load, all blends showed reduced CO emissions than diesel caused by the oxygenated nature of biodiesel, which improves the combustion process. At maximum load, CO emission with COMEB20, HCOMEB20, and CTOMEB20 was 0.05 % vol. contrary to 0.06 % vol. for diesel. However, CO emission was observed lower for diesel fuel compared to blended fuels at lower loads. The oxygenated nature of biodiesel is not an advantage at lower load with leaner combustion. However, the higher kinematic viscosity of blended fuels causes inadequate atomization and mixing, leading to imperfect combustion and higher CO emissions (An et al. 2013).

At maximum load CO₂ emission was observed as 5.8%, 5.9%, 5.9%, and 6.0%, respectively for diesel, COMEB20, HCOMEB20, and CTOMEB20, respectively. Even though the carbon to hydrogen ratio of biodiesel fuel is less than that of diesel, CO₂ emissions with blended biodiesel fuels were observed higher. This may be owing to the inferior CV of biodiesel blends, thereby higher BSFC (Can 2014; Xue 2013). Improved combustion of blended fuel resulting from fuel-bound oxygen may be another reason for increased CO₂ emission (Xue 2013; Almeida et al. 2017). Also, reduced ignition delay results in the early start of combustion, which enhances the CO oxidation with the biodiesel blended fuels (Can 2014).

3.4.6 Unburnt Hydrocarbon (HC)

The HC emission was determined less with blended fuel than with diesel at higher loads. At the maximum load of the engine, HC emissions of 66 ppm, 51 ppm, 54 ppm, and 54 ppm were observed for diesel, COMEB20, HCOMEB20, and CTOMEB20, respectively. The oxygen-enriched biodiesel blends enhance hydrocarbon oxidation, which diminishes the HC emission (Niju et al. 2015). As discussed earlier, at lower load conditions, the oxygenated quality of biodiesel is not a benefit, and higher viscosity induces inadequate atomization and, thereby, ineffective combustion. This may be the cause for augmented HC emission at lower load conditions.

3.4.7 Smoke opacity and NO_x emission

NO_x and smoke are inherent to diesel engines and have been of great distress owing to their environmental impact. An increasing trend of smoke opacity was observed with increasing load for every fuel caused by augmented fuel injection at elevated loads. At the maximum load, a smoke opacity of 62% was found with diesel in contrast to 55.1, 56.3, and 56.3 for HCOMEB20, COMEB20, and CTOMEB20, respectively. The decreased smoke opacity of biodiesel blends could be attributable to fuel-bound oxygen, which leads to better combustion (Kannan and Anand 2012).

Incrementing NO_x emission was observed with respect to load for all the fuels by virtue of additional fuel injected into the cylinder resulting in higher cylinder pressure and temperature. At maximum load, NO_x emissions of 631 ppm, 640 ppm, and 651 ppm were observed for COMEB20, HCOMEB20, and CTOMEB20, respectively, compared to 676 ppm for diesel. The reason for reduced NO_x emission with coconut oil-based biodiesels may be the presence of highly saturated and shorter carbon chain length molecules which causes the diminished flame temperature (Zareh et al. 2017; Boehman et al. 2004).

4. Conclusion

Biodiesels produced from two waste feedstocks, coconut waste cooking oil (HCOME) and coconut testa oil (CTOME), were compared with the fresh coconut oil biodiesel (COME) and diesel. Properties were found similar for HCOME and CTOME compared to COME. Hence HCOME and CTOME can be used in diesel engines with all advantages of COME with reduced cost. Then, the respective biodiesel blends B20 (COMEB20, HCOMEB20, and CTOMEB20) of the three biodiesels were used in the single-cylinder constant speed diesel engine to conduct performance, combustion, and emission analysis, and significant findings are summarized as below:

- At maximum load, BTE of the engine with COMEB20, HCOMEB20, and CTOMEB20 were lower by 0.33%, 0.51%, and 0.61%, whereas the BSFC were higher by 0.0122 kg/kWh, 0.0123 kg/kWh, and 0.0139 kg/kWh, respectively when compared to diesel, which may be due to lesser CV, increased density, and elevated viscosity.
- At maximum load, the maximum in-cylinder pressure with COMEB20, HCOMEB20, and CTOMEB20 were lower by 0.65 bar, 0.54 bar, and 0.48 bar, and the maximum HRR of the engine were lower by 6.38 J/°CA, 6.55 J/°CA, and 5.66 J/°CA, respectively, when compared to diesel due to inferior CV.
- At maximum load, compared with diesel, the SOC of the engine with COMEB20, HCOMEB20, and CTOMEB20 were advanced by 0.14°CA, 0.28°CA, and 0.37°CA, respectively, because of elevated viscosity and density.
- Even though brake thermal efficiency slightly decreased, being oxygenated fuel, all the three blended fuels showed reduced CO, HC, and smoke with respect to diesel operation. Moreover, the most relevant advantage of tested waste coconut-based fuels is the decreased NO_x emission analogous to that of diesel, which can be attributable to the reduced flame temperature and lower maximum HRR with similar SOC, as a result of the short and saturated carbon chain, when compared to that of diesel.

Thus, CTOME and HCOME are best suited and cost-effective alternative fuels for diesel engines without any engine alterations, with the advantages of COME such as lower viscosity and density with reduced NO_x and smoke emissions simultaneously.

5. Declarations

Ethics approval and consent to participate

Not applicable

Consent for publication

Not applicable

Availability of data and materials

Not applicable

Competing interests

"The authors declare that they have no competing interests"

Funding

No funding was received for conducting this study.

Authors' contributions

"MN did conceptualization, investigation, formulated the methodology, validation, and written original draft. AS did supervision, reviewed & edited the manuscript. All authors read and approved the final manuscript."

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Figures

1. Engine	5. Fuel tank	9. Fuel injector	13. Smoke meter	17. Fuel line
2. Dynamometer	6. Air Box	10. Intake manifold	14. DAC system	18. Crank case vent
3. Load Variac	7. Head	11. Exhaust manifold	15. Computer	19. Timing gear case
4. Fuel metering	8. Fuel filter	12. 5 gas analyser	16. Coolant line	

Figure 1

Schematic diagram of engine test rig

Figure 2

BTE (a) and BSFC (b) at different loads

Figure 3
Pressure V/S crank angle diagram at maximum load

Figure 4
Heat release rate at maximum load

Figure 5

Start of combustion for different fuels

Figure 6

CO (a) and CO₂ (b) emission at different loads

Figure 7

Hydrocarbon emission at different loads

Figure 8

Smoke opacity (a) and NOx (b) emission at different loads