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RESEARCH ARTICLE

Techno-economic assessment of coconut biodiesel as a potential alternative fuel for compression ignition engines

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Abstract

Over the past years, there were dramatic improvements in identifying and assessing various feedstocks for the production of biodiesel fuels. To promote a particular feedstock as a renewable source of energy, it is important to analyze their energy, economic, and engine performance characteristics. The current work attempts to evaluate the net energy and economic indices for both fossil diesel and coconut-blended diesel (B20) considering the diesel consumption by the Indian railways. Further, we present the experimental results of a multi-cylinder diesel engine operated with neat coconut biodiesel (B100) and fossil diesel at various load and speed conditions. The engine experiments reveal that the coconut biodiesel exhibits leaner combustion and shorter ignition delay than fossil diesel. Lower amount of carbon monoxide, hydrocarbon, and smoke emission is observed in the case of coconut biodiesel, with higher levels of nitric oxide (14%) and fuel consumption than diesel. The coefficient of variation in indicated mean effective pressure is within the range of better driveability zone for both the fuels at all test conditions. Overall the engine performance, emission and combustion results with neat coconut biodiesel are favorable with a penalty in NO emission at high load conditions. The techno-economical study highlights higher production cost per liter of B20 than the cost of fossil diesel. However, the net energy ratio (NER) for B20 is 1.021, favoring higher output than diesel and thus lowers the dependency on crude oil.

Keywords Coconut biodiesel · Ignition delay · Combustion phasing · NOx emission · Net energy ratio · Land use efficiency · Economic assessment · Energy analysis

Introduction

Being a second populated country in the world, India requires a large amount of oil for domestic and transportation purposes. In India, the consumption ratio of diesel to gasoline fuel is 7:1, describing a critical situation (Murugesan et al. 2009). Hence, it is necessary to look for a sustainable and renewable alternative fuels to displace or substitute the fossil diesel. In this aspect, the processed form of vegetable oil (biodiesel) serves as a potential alternative for diesel engines. Government of India has introduced the national biodiesel mission plan I in 2003 which proposed blending of 5% biodiesel with diesel (National biodiesel mission plan 2003). In 2009, national biodiesel mission plan enhanced the blend concentration up to 20% (National biodiesel mission plan 2009). However, failure of such promising goals invoked further investigations in sustainability analysis to figure out the biodiesel crisis. Further, the sustainability analysis holds the key for a particular feedstock being successful in the market. Due to the availability of large arid land and plenty of oil-bearing crops (viz. karanja, jatropha, mahua, camelina and rice bran), the potential of cultivating biodiesel in India appears promising. Coconut biodiesel as an alternative to fossil diesel is significantly expanding in country like the Philippines (Kim et al. 2017). In India, the total production of coconut oil has more than doubled as

Highlights
- Demonstrated the potential of coconut biodiesel as an alternate energy source
- Coconut has a dominance of short chain saturated esters
- Ignition delay and combustion duration are lower with coconut biodiesel
- Coconut exhibits lower smoke and unburned hydrocarbon emissions
- B20 exhibits higher net energy ratio and energy productivity

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compared to the production in 1980s (Krishna et al. 2010). India ranks first in the global production of coconut in 2018 (Press Information Bureau, Government of India 2018), considering the average yield of nuts (10,199 nuts/ha) and yield of coconut oil (2869 kg oil/ha). Further, the ministry of agriculture and farmers welfare of the Indian government claims that 20.82 lakh hectares of land were used for coconut production in 2018. Most food manufacturers do not recommend high saturated oils like coconut (> 90% saturated fatty acids) and generally prefer hydrogenated polyunsaturated oils. Due to abundant amount of coconut oil left over in the country, there is a large potential to produce coconut biodiesel via transesterification process. Despite being productive, the coconut sector is faced with several constraints and challenges such as fluctuating productivity due to cultivation and distribution issues (Pricing policy of Copra 2017).

Generally, operating diesel engines with biodiesel fuels does not demand any prominent modification, since the properties of biodiesel are similar to diesel fuel (Canakci 2009). Similar to other feedstock, raw coconut oil has higher viscosity, lower volatility, and 12.8% of free fatty acid (FFA) which corresponds to an acid value of 25.5 mg KOH/g oil. Hence, by transesterifying the coconut oil to coconut biodiesel, the engine performance could be improved (Nakpong and Wootthikanokkhan 2010). Kalam et al. (2003) conducted an experiment in an indirect injection diesel engine to evaluate the characteristics of coconut oil of Malaysian origin. The authors pointed that the blend of 30% coconut oil with fossil diesel produces better performance with a net reduction in both the regulated and non-regulated exhaust emissions. However, when the concentration of coconut oil increased beyond 40%, the output power was reduced. Kinoshita et al. (2006) experimentally compared the performance characteristics of biodiesel fuels of different origin in a diesel engine. The authors concluded that coconut biodiesel and palm ethyl ester possess excellent fuel properties, good combustion characteristics, and low exhaust emissions. Similar observations were reported by Soma et al. (2007), in the case of coconut, tallow, and soybean biodiesel (refer to Table 1). However, it is to be noted that the hydrocarbon emissions are maximum in the case of coconut compared to other biodiesel fuels.

Liaquat et al. (2013) investigated the performance and emission characteristics of coconut-blended diesel (B5, B15) in an unmodified diesel engine. They observed a reduction in brake power and higher fuel consumption, CO_2 and NOx for the coconut blends compared to diesel fuel. Thus, the experimental investigations carried out by earlier researchers using coconut-blended diesel reveal that there is a significant loss of performance with a favor in lowering the emissions. However, there is a lack of unanimity about the extent of variations in the engine performance or exhaust emissions. It is also observed that most of the reported experimental results are based on tests conducted at a single speed under varying load conditions. Rarely, there are very few investigations providing the comprehensive effects of neat biodiesel-engine relationship along with the evaluation of the sustainability factors. The present work intends to fullfill this gap based on the following investigations viz. testing the coconut biodiesel of Indian origin in a four cylinder, turbocharged, diesel engine at different speed/load conditions and evaluation of the sustainability factors, considering the demand for Indian railway.

Table 1 Engine performance and emission characteristics

Parameters	Tallow	Soybean	Coconut
Brake mean effective pressure [MPa]	0.66	0.69	0.62
Hydrocarbon (ppm)	21.7	21.7	25.0
Smoke (%)	38	43	18.3

State of the art

By 2030, biomass consumption is expected to reach 20% of the renewable energy sources. As biofuels gain importance, it is crucial to examine their economic potential, which demands techno-economic analysis on the production method and refineries. Several research works have been carried out, utilizing software to evaluate and compare the technical and economic requirements of producing biodiesel fuels (Zhang et al. 2003a, b; Marchetti et al. 2008; Apostolakou et al. 2009). Majority of the studies emphasize the high cost of the source material for the biodiesel production and thus claim higher production cost of biodiesel than fossil diesel. With one exemption being waste cooking biodiesel, hence, the benefit to cost ratio of waste cooking oil is reported to be 2.081. The cost of biodiesel production, viz. cost capacity factor (CCF) is pivotal in defining the capacity of bio-refinery. For economic production of biodiesel, earlier research work has claimed the value of CCF to be in the range of 0.6 to 0.89. However, the economic benefits also rely on the capacity of biodiesel production (Amigun et al. 2008). Considering the higher consumption of fossil fuels, a hike from 0.0196 to 0.0224 $/L of B20 has been predicted by Kumar et al. (2012). Hence, it is necessary for the governmental organization to subsidize or exempt from excise taxes to promote biodiesel fuels. In this regard, energy and economic analysis are carried out for producing coconut biodiesel considering the Indian scenario.

Earlier studies have carried out the energy analysis using process simulation software (HYSYS) and reported that 75 to 80% of the cost is exhausted towards procuring the raw material (Marchetti et al. 2008). It has been remarked that the production plant, with capacity less than 40 kt/year, is at higher risk and hence such low capacity plants are not advisable. Other parameters such as energy productivity and energy intensiveness value were estimated and reported for a 2000 L plant with an area of 100 m^2 (Mohammadshirazi et al. 2014). Economic feasibilities of soya bean oil are studied with capacities of 8 kt, 30 kt, and 100 kt per year. Capacity of 100 kt/year seems to be economical but the capital cost involved in building such plant is prominent and occupies plenty of land (You et al. 2008). Nelson et al. (1994) carried out an economic study of the production plant (100 kt/year) using beef tallow. Noordam and Withers (1996) had done similar work using canola feedstock for a plant capacity of 7.8 kt/year. The unitary cost of biodiesel varies from 0.42 to 0.43 $ per liter based on the type of catalyst employed and considering the glycerol credits (Marchetti et al. 2008). The study conducted by Graboski and McCormick (1998) comprises of 38.8 million liters of biodiesel per year and accounted the credit benefits from glycerol to reduce the production cost of biodiesel. In this regard, it is important to evaluate and analyze the energy and economical requirement for producing biodiesel from coconut feedstock of Indian origin. Further for successful implementation of the biodiesel, the current work also attempts to test an automotive engine with neat coconut biodiesel under varying speed and load conditions.

Materials and methods

Fuel and engine experiments

Alcohol, catalyst concentration, FFA contents, reaction time, and temperature are the key factors affecting the transesterification process (Ma and Hanna 1999). If the oil contains higher FFA (> 1% *w*/*w*), it demands a two-step transesterification (Canakci and Gerpen 2001) or requires a higher amount of catalyst (Ghadge and Raheman 2005), else it would result in the soap formation. The measured FFA for coconut sample is 0.14 (% oleic acid), and thus single stage transesterification process was employed. The composition of coconut biodiesel is measured using a gas chromatography and engine-related properties such as density, viscosity, and surface tension are measured using hydrometer, viscometer, and tensiometer respectively. While other properties like iodine, saponification, acid, and peroxide values are measured by titration methods. Also, cetane number, long chain saturation factor, and unsaturation to saturation ratio (USR) are estimated from the measured compositional data. Table 2 provides the basis of estimation for the derived parameters related to fuel, engine combustion, and techno-economic analysis.

Engine measurements are conducted on a medium duty diesel engine equipped with a mechanical type distributor pump as shown in Fig. 1 and its specifications are provided in Table 3. The engine test setup is fitted with an eddy current dynamometer (Dynalec EB 150 HS), whereas the air and fuel flow rates are measured using a turbine flow meter and a burette-stop watch arrangement.

A solenoid changeover switch is utilized to shift the fuel input (diesel/biodiesel) to the engine. Piezo electric transducers are flush mounted on each cylinder for the pressure measurements. Whereas, piezo resistive transducers are used to measure the fuel line and manifold pressure histories. All the pressure signals are rendered to a combustion analyzer (KiBox) in conjunction with the crank angle signal (0.1 deg·CA). Pressure averaging is carried out using a MATLAB program for 100 consecutive cycles of the measured raw pressure data.

K-type thermocouples are equipped in the test setup to measure the temperature of exhaust gas, lube oil, cooling water, and inlet air. NO, smoke, HC, and CO emissions are determined using Chemiluminescent analyzer, AVL smoke meter, Emerson-flame ionization detector, and AVL di-gas analyzer respectively. Two fuel tanks are employed so that the engine will be started with diesel fuel and then switched over to biodiesel for the test operation. The engine test is conducted at steady state conditions for three different speeds, viz. 1000 rpm (low speed), 1400 rpm (maximum torque speed), and 2000 rpm (high speed) at three load conditions (46, 137, and 221 Nm). The set load corresponds to the brake mean effective pressure of 1.7, 5.2, and 8.4 bar, which are referred to as low, mid, and high load conditions respectively. The compositions and properties of coconut biodiesel and fossil diesel are included in Tables 4 and 5 respectively.

The test result reveals that the dominant ester present in coconut is methyl laurate and the estimated USR suggests that the coconut has major amount of saturated ester contents. Also, it is found that the oxygen content is higher (~ 14%) with coconut than other biodiesel fuels (~ 10%). The long chain saturated factor indicates that the coconut biodiesel has a dominance of short chain esters. It may be noted that the surface tension value of coconut is comparable to diesel and hence better spray characteristics are warranted (Ejim et al. 2007; Allen et al. 1999).

The experimental uncertainties are evaluated following Holman (2007) and are indicated in the corresponding figures. During experiments, ten repeated observations of parameters viz., engine speed, fuel flow rate, air flow rate, torque, NO, and smoke concentration are taken and corresponding standard deviations (σ) are estimated. According to normal distribution, the error was estimated based on 95% confidence interval.

Data evaluation methodology for energy and economic assessment

The data evaluation methodology for the production of B20 considers the diesel quantity of 2.793 billion liters utilized by the Indian railways for the period from 2016 to 2017. Energy and economic indices such as net energy ratio, energy productivity, energy intensity cost for both fossil diesel, and coconut-

Table 2 Methodology of the derived properties/parameters of interest

Derived properties/parameter		Method of determination
Fuel-related	Cetane number (Bamgboye and Hansen 2008)	Calculated from the measured composition $CN = 61.1 + 0.08^{*}(C14:0) + 0.133^{*}(C16:0) + 0.152^{*}(C18:0) - 0.101^{*}(C16:1) - 0.0396^{*}(C18:1) - 0.243^{*}(C18:2) - 0.395^{*}(C18:3)$
	Long chain saturation factor (LCSF) (Ramos et al. 2009)	Calculated from the measured composition $LCSF = 0.1^{*}(C16:0) + 0.5^{*}(C18:0) + 1^{*}(C20:0) + 1.5^{*}(C22:0) + 2^{*}(C24:0)$
Engine-related	Dynamic start of injection	Deduced from the measured line pressure history, the moment at which the line pressure attains the nozzle opening pressure of 23 MPa
	Net heat release rates (Q_{net})	$\frac{dQ_{net}}{dt} = \frac{n}{n-1} P \frac{dV}{dt} + \frac{1}{n-1} V \frac{dp}{dt}$ *n* represents polytropic index, P and V are the instantaneous cylinder pressure and volume respectively.
	Start of combustion	Crank angle instant where a positive slope of energy release is attained
	Ignition delay	Time period from the start of injection to the start of combustion
	End of combustion	Crank angle instant where 90% energy release is observed in the cumulative energy release curve
	Combustion duration	Duration elapsed from the start of combustion to the end of combustion
	Combustion phasing	Crank angle instant where 50% energy release is observed in the cumulative energy release curve
Production of coconut biodiesel	Cost capacity factor (Amigun et al. 2008)	$C_1 = C_2 \times (Q_1/Q_2)^n$
	Cost per liter of biodiesel (Amigun et al. 2008)	$\ln C = 6.13 + 0.89 \ln Q$ *C* represents total cost of biodiesel production and *Q* is the capacity of biodiesel production in tonnes per annum
Economic and energy analysis	Net energy value (Ntihuga et al. 2013)	$NEV = \frac{Output\ Energy\ (MJ)}{Quantity\ of\ biodiesel\ produced\ (kg)}$
	Land use efficiency (Korres et al. 2013; Quaye et al. 2010)	$Land\ use\ efficiency\ (\eta_{land}) = \frac{yield\ of\ coconut\ biodiesel\ (Kg)}{Total\ land\ available\ (ha)}$
	Net energy ratio (Mohammadshirazi et al. 2014)	$NER = \frac{Output\ Energy\ (MJ)}{Input\ Energy\ (ha)}$
	Benefit to cost ratio (Mohammadshirazi et al. 2014)	$BC\ Ratio = \frac{Gross\ production\ value}{Total\ Production\ cost}$
	Fossil energy ratio (Mohammadshirazi et al. 2014)	$FER = \frac{Renewable\ Energy\ Output}{Fossil\ Energy\ Input}$

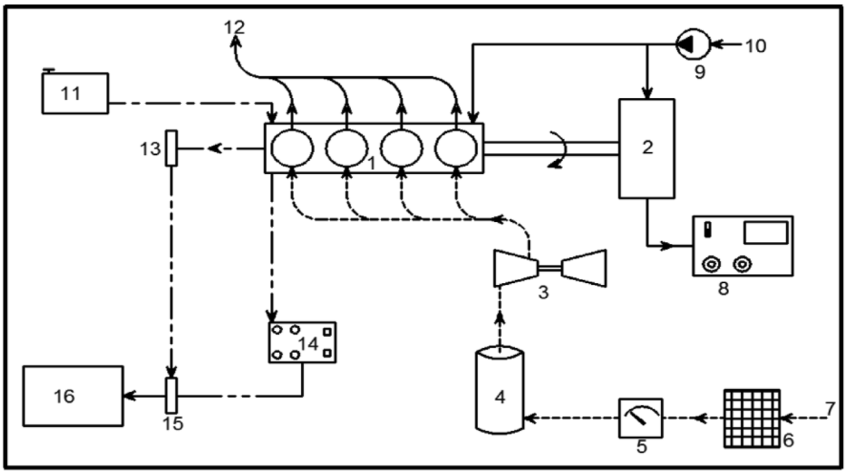


Fig. 1 Schematic layout of the test setup

[Legends: 1.Four cylinder engine 2.Eddy current dynamometer 3.Turbocharger 4.Surgetank 5.Turbine meter 6.Air filter 7.Air inlet 8.Dynamo controller 9.Water pump 10.Water inlet 11.Fuel tank 12.Exhaust-outlet/Turbine-inlet 13.Crank angle encoder 14.Signal conditioner 15.Data acquisition unit 16. PC]

Table 3 Test engine specifications

Number of cylinders	Four
Bore × stroke (mm)	100 × 105
Displacement volume (L)	3.298
Compression ratio	17.5:1
Maximum torque (N m)	285 @ 1400 rpm
Maximum power (kW)	70 @ 3200 rpm
Nozzle opening pressure	230 bar
Injector	5 hole, 0.209 mm diameter
Static injection timing	12 deg. CA bTDC
Cooling	Forced circulation

blended diesel (B20) are evaluated following Mohammadshirazi et al. (2014). As shown in Fig. 2, the quantity of diesel consumed by Indian railways is taken as the demand and the quantity of diesel to be displaced with coconut biodiesel is estimated following the National Biodiesel Mission Phase II (substitution of 20% diesel with biodiesel). Using the amount of coconut biodiesel required, the energy and economic analyses are carried out. Economic analysis involves the estimation of cost for procuring crude coconut oil, followed by the cost of electricity, transesterification cost, and fossil diesel spent during the transportation process. This analysis culminates with the estimation of cost per liter of coconut biodiesel. The energy analysis includes the evaluation of input and output energy involved for coconut biodiesel production and assessment of various energy parameters. The required data for the energy and economic analysis are provided in Tables 6 and 7 respectively. The pricing policy of copra provides the necessary details for the economic analysis (Pricing policy of Copra 2017). Whereas, the current market prices are considered for electricity, diesel, and other chemicals such as methanol, NaOH, and Glycerol. As shown in Fig. 3, the estimation of land use efficiency along with cost capacity factor is also a crucial parameter for sustainable way of biodiesel production.

Results and discussion

As shown in Fig. 4, coconut biodiesel exhibits an increase in brake thermal efficiency with a maximum increase of 3.4%

Table 4 Measured composition of coconut biodiesel

Saturated FAME		Unsaturated FAME	
Caprylic acid (C8:0)	8.97	Oleic acid (C18:1)	7.917
Capric acid (C10:0)	5.49	Linoleic acid (C18:2)	3.066
Lauric acid (C12:0)	41.92	Linolenic acid (C18:3)	0.089
Myristic acid (C14:0)	19.23	Unsaturation to saturation ratio (USR)	0.125
Palmitic acid (C16:0)	9.27	*Long chain saturated factor (LCSF)	2.612
Stearic acid (C18:0)	3.37		

*Estimated following (Ramos et al. 2009)

Table 5 Measured and estimated fuel properties of coconut biodiesel

Biodiesel characteristics	Diesel	Coconut	Test methods
Typical formula	$C_{12}H_{26}$	$C_{14.08}H_{27.87}O_{1.98}$	
Calorific value (MJ/kg)	42.49	36.56	ASTM D4868
Fuel bound oxygen	–	13.88	
Molecular mass	170	229	
Stoichiometric air-fuel ratio	14.9	12.02	
Cetane number	47	*63.45	
Density (kg/m^3) @ 40 °C	816	865	EN ISO 12185
Viscosity (cSt) @ 40 °C	2.43	3.62	EN ISO 3104
Surface tension (mN/m) @ 80 °C	22.04	24.15	
Saponification value	–	251.75	ASTM D5558
Iodine value	–	11.07	EN 14111
Peroxide value (milliequi./kg)	–	2.05	
Acid (as oleic acid %) value	–	0.14	EN 14104

*Estimated following Bamgboye and Hansen 2008

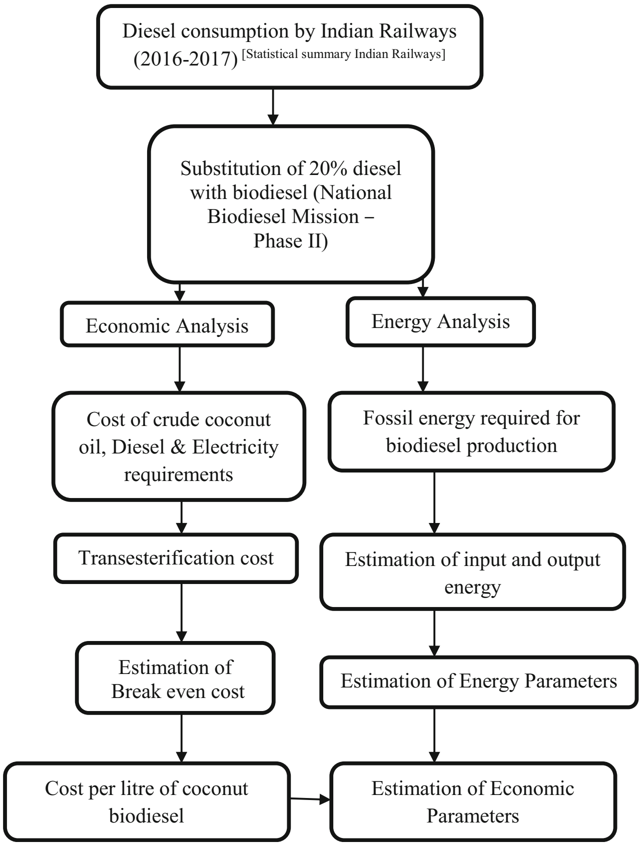


Fig. 2 Pathway for economic and energy analysis

than fossil diesel at full load and 1400 rpm. The observations concerning higher brake thermal efficiency for biodiesel conform to the investigations on sunflower (Kaplan et al. 2006) and neem methyl ester (Dhar et al. 2012). The presence of fuel bound oxygen is considered to be responsible for the improvement in the combustion efficiency. Also, the improvement in efficiency is caused by lower frictional losses due to better lubricity of biodiesel fuels (Lapuerta et al. 2008).

Due to the difference in heating value and density, the brake specific energy consumption (BSEC) is considered a more appropriate parameter than brake specific fuel consumption to compare performance of engine operated on different fuels (Sahoo et al. 2007). As seen in Fig. 5, BSEC is higher with diesel compared to biodiesel; hence, in terms of energy basis, biodiesel performs better compared to fossil diesel.

The general emission trend of replacing fossil diesel with neat coconut biodiesel (B100) is shown in Fig. 6 and clearly coconut biodiesel has lowered the CO, UBHC, and smoke emission significantly with an exemption in nitric oxide emission. In an aromatic and sulfur-free, oxygen-enriched combustion of biodiesel, a very low smoke concentration is as expected. The unburned hydrocarbon concentrations reduced considerably in biodiesel-fueled engine operation due to higher in-cylinder oxygen concentration and earlier start of combustion. The CO emissions are controlled primarily by the fuel/air equivalence ratio (Heywood 1988) and the reduction in CO emission with coconut biodiesel is attributed to the enhanced in-cylinder oxidation. Similar results are observed at all the tested conditions for CO, UBHC, and smoke emissions and hence for brevity, the representative plots are not presented here. However, the biodiesel-NO penalty is still prevalent in the case of highly saturated biodiesel like coconut and hence further analysis is attempted to explore the reason for the increase in NO emission.

Figure 7 shows the NO emissions at all the tested conditions and reveals that the low load conditions exhibit marginal differences, while at mid and high load conditions, substantial differences in the NO emissions were observed. Thangaraja et al. (2014) has opined that the bulk modulus of biodiesel fuels plays a major contributor to the NO emissions.

Table 6 Thermo physical property for energy analysis

Resources	Density (kg/L)	Calorific value (MJ/kg)
Crude coconut oil	0.909 (Jitputti et al. 2006)	33.2 (Stumpf and Mühlbauer 2002)
Coconut biodiesel	0.834 (Suryawanshi 2006)	36.56
Crude oil	0.828 (Corma et al. 2018)	43(World Nuclear Association 2016)
Diesel	0.840 (Kumar et al. 2012)	45.34(Kumar et al. 2012)
Sodium hydroxide	2.13 (CID 14798 NIH n.d.)	12.623(CID 14798 NIH)[a]
Methanol	0.792 (Bromberg and Cheng 2010)	20(Bromberg and Cheng 2010)
Petrol	0.741 (Staffell 2011)	43.93(CES IISC)[b]
Jet fuel	0.815 (1999, emergencies science and technologies division)	43.51(CES IISC)
LPG	0.533 (Staffell 2011)	45.18(CES IISC)
Heavy oil	0.96 (1999 fuel oil, emergencies science and technologies division)	43.09(CES IISC)
Fuel oil	0.959 (Staffell 2011)	40.16(CES IISC)
Glycerol	1.26 (CID 753 NIH n.d.)	19.00 (Eaton et al. 2014)

[a] Convert kJ/mol to MJ/kg

[b] Convert kcal/kg to MJ/kg

Table 7 Cost consideration for the economic analysis

Resources	Market price	Unit	References
Diesel	0.974	\$/L	Previous price of diesel, IOCL (2017)
Methanol	9.102	\$/kg	Merck & Sigma–Aldrich (2016–2017)
Sodium hydroxide	5.070	\$/kg	Merck & Sigma–Aldrich (2016–2017)
Glycerol	6.201	\$/kg	Merck & Sigma–Aldrich (2016–2017)
Crude coconut oil	1.098	\$/L	Pricing policy of Copra (2017)
Electricity	0.095	\$/kWh	Ministry of Power, Executive summary-01 (2016–2017)
Crude oil	0.362	\$/L	(Ministry of Petroleum and Natural Gas (2017)[a]

[a] Convert barrel to liters

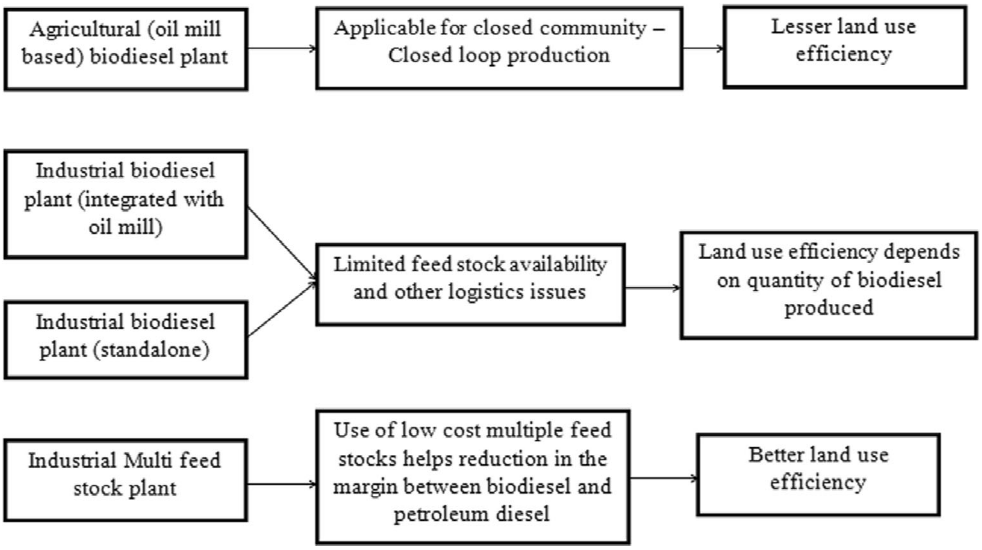


Fig. 3 Pathways of biodiesel production (Amigun et al. 2008)

To analyze the impact of bulk modulus of coconut, the difference in start of injection (SOI) at different operating condition for diesel and coconut biodiesel is shown in Fig. 8. An inadvertent advancement in the injection timing up to a maximum of 1.9 deg·CA is observed at high load conditions due to the higher bulk modulus of coconut biodiesel (1629.59 MPa), which has contributed to 10% increase in the NO emissions relative to fossil diesel (1386.25 MPa). Similar observations have also been reported by Monyem and Van Gerpen (2001) and Canacki and Van Gerpan (2003) in the context of soybean and yellow grease biodiesel fuels. The peak cylinder temperature occurs close to top dead center with advanced start of injection and thus permits a longer residence time for NO formation (Mishra et al. 2017). The difference in the maximum fuel line pressure for diesel and coconut biodiesel is also mentioned in Fig. 8.

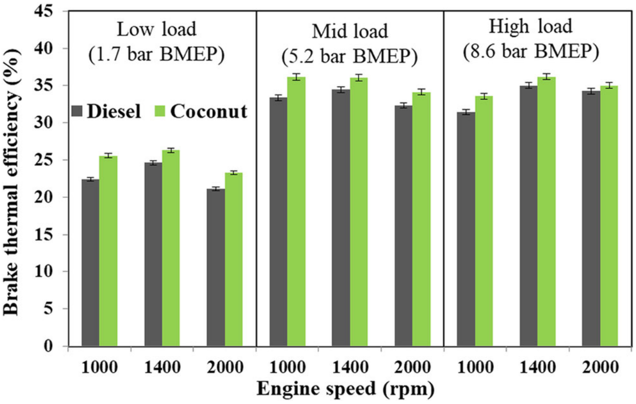


Fig. 4 Variation of brake thermal efficiency with diesel and coconut biodiesel

diesel and coconut biodiesel

However, at low load conditions, the difference in dynamic injection timing has retarded at 1000 and 2000 rpm and remains the same at 1400 rpm which has yielded in varying degree of NO emissions. Boehman et al. (2004) has highlighted the opposing trend of lower NOx to the retarded injection timing with fuels of lower bulk modulus of compressibility than fossil diesel. The lower fuel line pressure (FLP) at these conditions has nullified the bulk modulus effect, as the bulk modulus increase with increasing pressure. Hence, at 1000 and 1400 rpm (indicated in red color), the difference in FLP is negative for coconut biodiesel relative to diesel. Wherein at mid-load

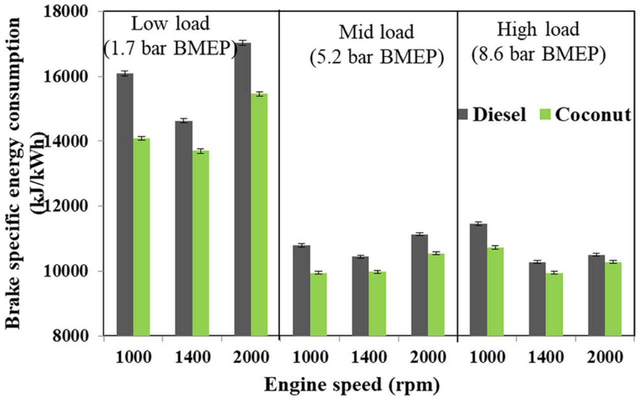


Fig. 5 Variation of brake specific energy consumption with diesel and coconut biodiesel

and high load condition, the difference in FLP is above 24 bar.

As observed in a typical fuel line pressure history at 1000 rpm, low load, and 2000 rpm, full load condition (refer to Fig. 9(a) and (b)). At high speed conditions to compensate for the higher fuel requirement, the fuel line pressure is relatively higher than low speed condition. The fuel line pressure is higher with coconut biodiesel compared to fossil diesel primarily due to higher density of biodiesel. This combines with the viscous effect and leads to lower leakage in the pump plunger. This fact corroborates with the observations of Tat and Van Gerpen (2003) in the context of soybean methyl ester.

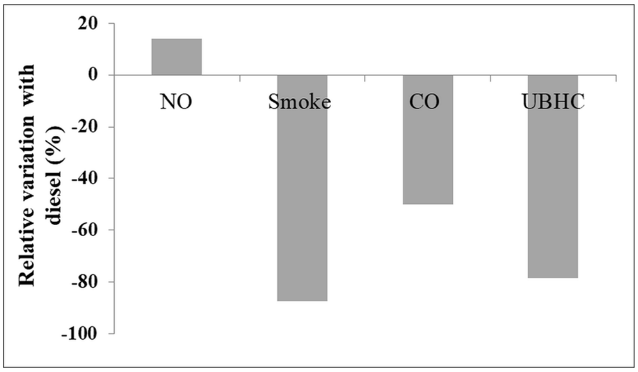


Fig. 6 Percent change in regulated emissions with coconut biodiesel relative to diesel

The comparison of in-cylinder pressure and heat release rate histories for coconut biodiesel and diesel fuel is shown in Fig. 10. As observed, biodiesel exhibits higher pressures than diesel fuel at high speed conditions. However, at low load and 1000 rpm conditions, both the pressure profiles overlap each other. The comparison of the energy release rates for full load at 2000 rpm is also included in Fig. 10 (b). A small dip in the energy release rate observed during the ignition delay period is primarily the absorption of in-cylinder thermal energy for the fuel vaporization process. As combustion proceeds, the slopes of energy release rates tend to become more positive with biodiesel operation than diesel. There is an early occurrence of energy release in the case of coconut compared to diesel and hence the peak energy release occurs in that order, as evident from Fig. 10 (b). In this context, it is important to reiterate that the dynamic start of injection has been inadvertently advanced for coconut biodiesel.

For the two fuels, the value of maximum cylinder pressure and combustion phasing at various loads is indicated in Table 8. Other than low load condition (1.7 bar), the peak pressure is higher for coconut biodiesel and a maximum difference of 5% is observed at 1400 rpm, high load condition. The presence of oxygen in the fuel molecule enhances the burn rate with coconut biodiesel as evident in Table 8. However, at low load and 2000 rpm, the difference is marginal and could be attributed to the dominance of premixed combustion owing to poor biodiesel spray vaporization characteristics. Mueller et al. (2009) opined that the faster combustion with the biodiesel fuels could play a role in their increased NOx emissions.

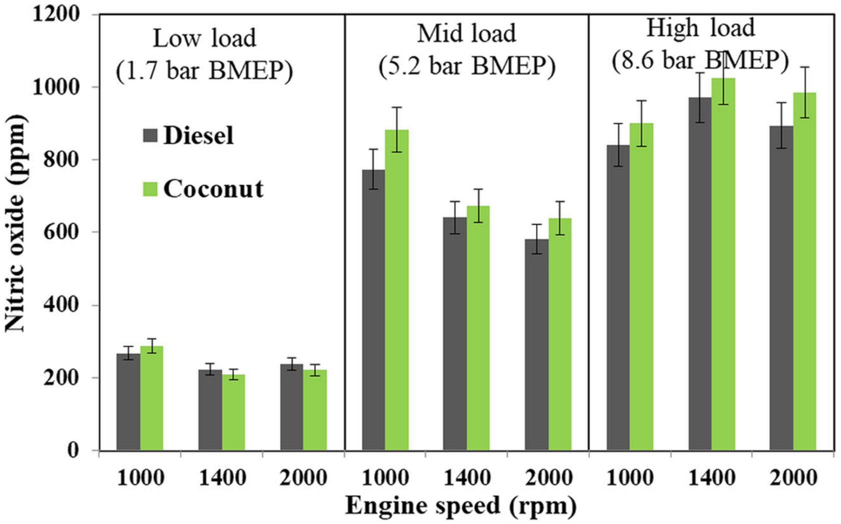
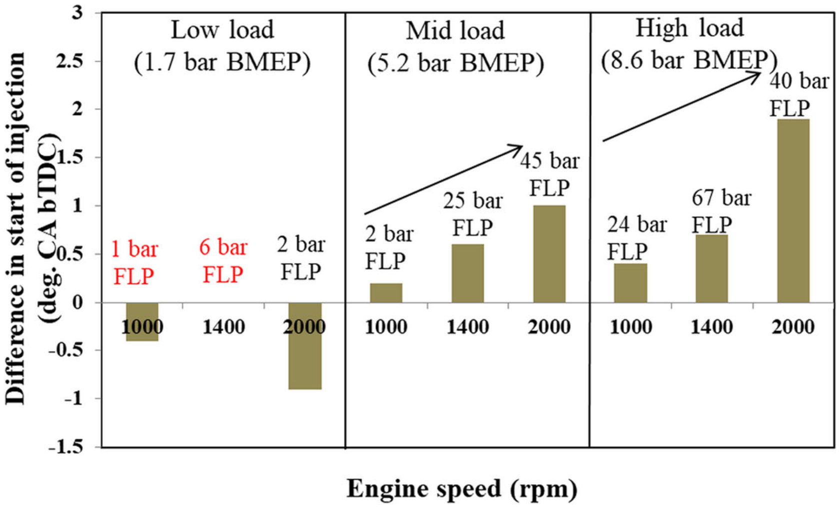


Fig. 7 Variation of nitric oxide emissions with diesel and coconut biodiesel

Fig. 8 Difference in start of injection and maximum fuel line pressure for



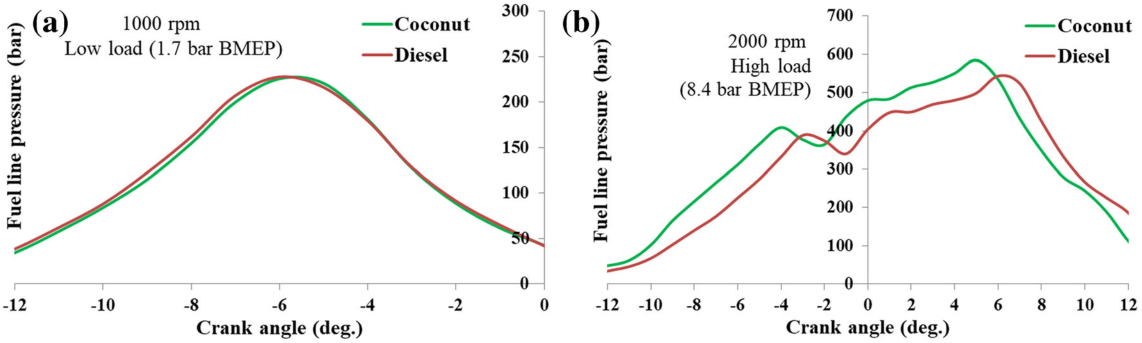


Fig. 9 Fuel line pressure histories at 1000 rpm (**a**), low load, and 2000 rpm (**b**), full load condition

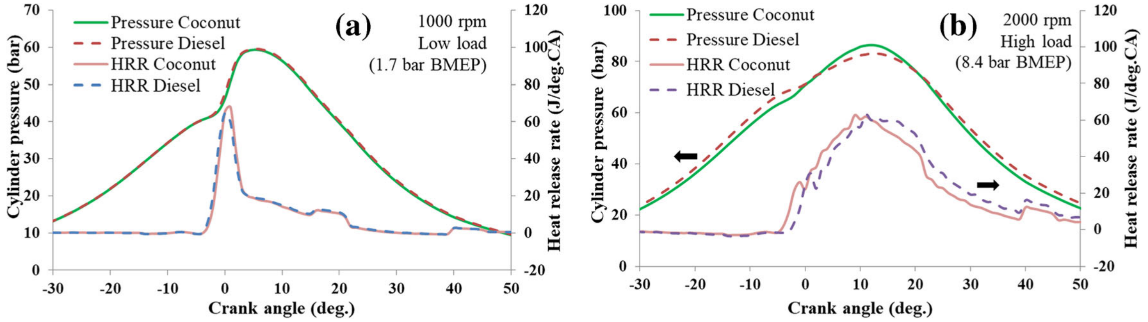


Fig. 10 In-cylinder pressure and heat release rate at 1000 rpm (a), low load, and 2000 rpm (b), full load condition

Table 8 Variation in peak cylinder pressure and combustion phasing for the test fuels

Operating conditions		Maximum pressure (bar)		Combustion phasing (deg·CA)	
Speed (rpm)	BMEP (bar)	Diesel	Coconut	Diesel	Coconut
1000	1.7	59.6	59.3	4.3	4
1400	1.7	58.5	59.1	6.2	5.6
2000	1.7	63	62	8.8	9.4
1000	5.2	70.5	71.8	8.1	7.6
1400	5.2	68	71.4	11.2	9.7
2000	5.2	74	76	13.7	12.2
1000	8.4	86.5	87.1	10.2	9.7
1400	8.4	78	81.9	13.7	11.8
2000	8.4	83	86	17.2	14.3

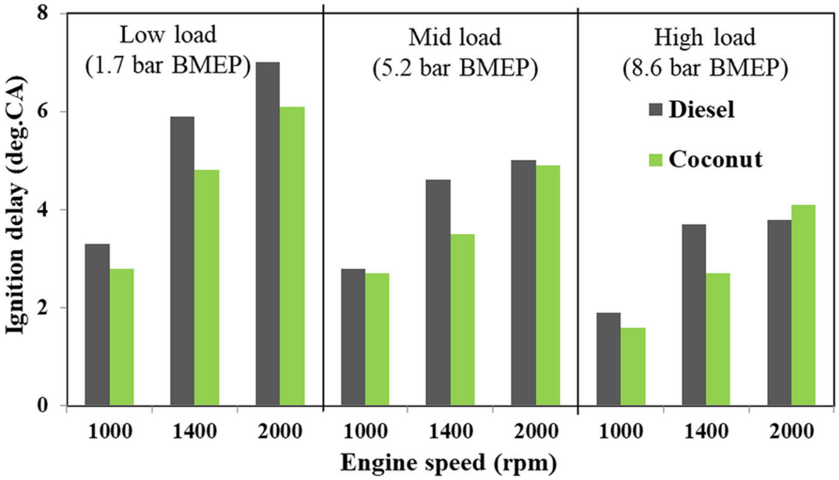


Fig. 11 Variation in ignition delay for the test fuels

As shown in Fig. 11, higher cetane number (CN) of coconut (~63) biodiesel has yielded in shorter ignition delay than fossil diesel (~47) except at high load and 2000 rpm conditions. In a recent article by Aldhaidhawi et al. (2017), the effect of rapeseed biodiesel on ignition delay was thoroughly reviewed and concluded that the ignition delay decreases with increasing percentage of biodiesel blends. As shown in Fig. 12, the combustion durations for coconut biodiesel is

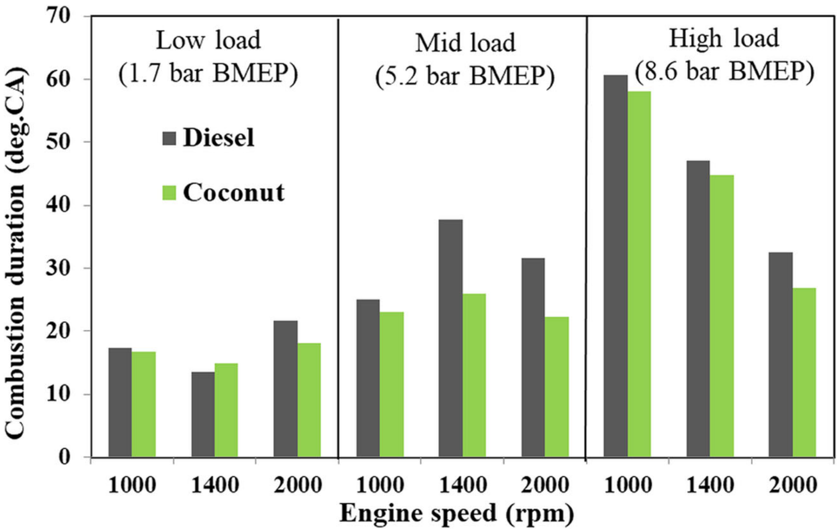


Fig. 12 Variation in combustion duration for the test fuels

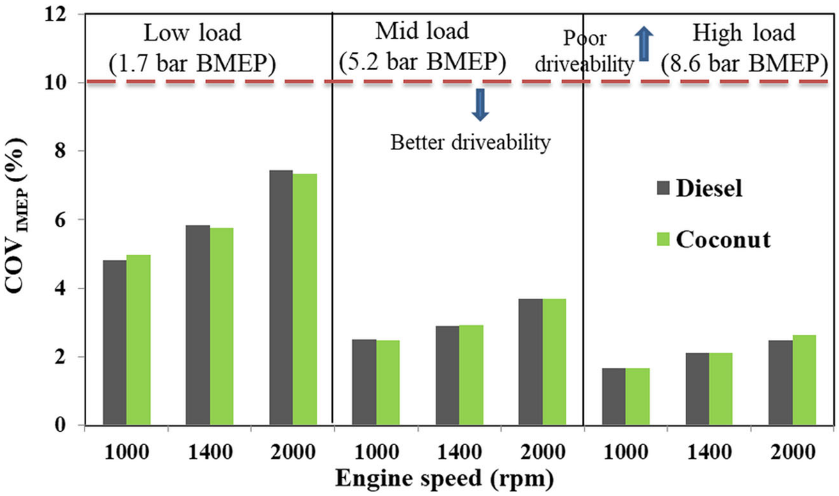


Fig. 13 Variation of COV_{IMEP} for diesel and coconut biodiesel

observed to be slightly lower than diesel and primarily attributed to its faster burning rate. The higher combustion duration with load is simply a result of increased fuel quantity.

The coefficient of variation in indicated mean effective pressure ($\mathrm{COV_{IMEP}}$) for 10 consecutive cycles was estimated following Heywood (1988)

$$\mathrm{COV_{IMEP}} = \frac{\sigma_{\mathrm{IMEP}}}{\mathrm{IMEP}} * 100 \tag{1}$$

As shown in Fig. 13, the $\mathrm{COV_{IMEP}}$ is within the range of better driveability zone for diesel and coconut biodiesel at all load conditions. However, at low load condition, the $\mathrm{COV_{IMEP}}$ is significantly prominent than mid and high load conditions for both fuels. Overall the engine performance, emission and combustion results with neat coconut biodiesel are favorable with a penalty in NO emission at high load condition, which could be compensated by controlling the start of injection. However, the associated energy and economic analysis need to be evaluated for their practical implications. Thus, the net energy ratio and cost analysis for achieving the set target of National Biodiesel Policy–II (B20) were carried out and their results are discussed in the following section, considering the demand for Indian railway sector.

Table 9 Economic analysis of coconut biodiesel

Cost	Particulars	Required quantity		Rate	Unit	Total cost	Unit
Direct operating cost	Crude coconut oil	603,934,531	kg	68.67	Rs/kg	1,027,152,727	$
	Methanol	166,098.61	kg	606.826	Rs/kg	562,781.608	$
	NaOH	99,659.164	kg	338.028	Rs/kg	379,781.14	$
	Operating labour[a]					96,248.95	$
	Supervisor[a]					14,437.343	$
	Utilities						
	Low pressure steam[a]					5119.625	$
	High pressure steam[a]					10,239.25	$
	Electricity	901,311,894	kWh	6.35	Rs/kWh	126,814,584	$
	Cooling water[a]					853.262	$
	Liquid[a]					1535.886	$
	Solid[a]					682.616	$
	Maintenance and repairs[a]					11,945.789	$
	Operating and suppliers[a]					1791.868	$
	Laboratory charges[a]					9624.895	$
	Patents and royalties[a]					35,325.412	$
	Direct operating cost					707,732,493	$
Indirect operating cost	Overhead, packaging, and storage[a]					73,579.249	$
	Fixed capital cost[a]					204,785	$
	Local taxes[a]					3071.775	$
	Insurance[a]					1023.925	$
	Indirect operating cost					77,674.949	$
	Depreciation[a]					20,478.5	$
General expenses	Administrative costs[a]					18,394.812	$
	Distribution and selling cost[a]					1177.866	$
	Research and development[a]					588.933	$
	General expenses					20,161.612	$
	Total production cost					707,850,808	$
	Glycerine credit	215,928,187.7	kg	413.45	Rs/kg	1,134,469,424	$
Net total	Production cost of biodiesel					5,068,000,000	$
	Operational expenses					510,904.96	$
	By-products credit					2,828,000,000	$
	Cost per liter of biodiesel in US $					0.859	$/L
	Cost per liter of biodiesel in INR					57.30	Rs/L

[a] Values interpolated from 8000 tonnes to 1694 tonnes (Amigun et al. 2008)

Economic section consists of expenses incurred during the production of coconut biodiesel. To calculate the price of coconut biodiesel per liter, CCF value remains pivotal in predicting the capacity of bio-refinery. The expenses include fixed cost, variable cost, administrative cost, depreciation cost, and miscellaneous cost (refer to Table 9). The economics behind the three reference concepts discussed by Amigun et al. (2008) is attempted in the current study for the production of coconut biodiesel. The first method is cultivating the coconut in a farm and transforming it to biodiesel. The second method involves purchasing of coconuts from the coconut farms and converting it to biodiesel. The third method involves purchasing of crude coconut oil and transesterifying it to biodiesel. The last method is considered to be economically viable, as the cultivation method incurs cost of cultivation, land, fertilizers, etc. To be an economical plant, Amigun et al. (2008) has claimed that the cost capacity factor (CCF) value should lie within 0.6 to 0.89. In the current study, the estimated CCF value is 0.94, indicating that the production cost of B20 is marginally higher than the economical indices. Through interpolation, the biodiesel production requirement for Indian railways demand is found to be 1.694 kt/year of biodiesel, where the feedstock to the industrial plant is in the form of raw coconut oil. This is considered to be a minor plant, compared to the existing capacity (10–50 kt/year) in other countries (Apostolakou et al. 2009). Further sensitivity analysis from Marchetti et al. (2008) observed that the cost per liter of biodiesel ranges from $0.405 to $0.48. From the current study, the estimated cost per liter of biodiesel is 0.859 $/L which justifies the twofold increase of biodiesel cost. Considering 7500 h per annum of operation per plant, India requires 274 such smaller capacity plants to meet the diesel demand for Indian Railways. However, scaling of plants can be done at the rate of 0.6% per annum and it is expected that the diesel demand will also increase.

Further, the estimation of land use efficiency and net energy value is made on the basis of energy and economic characteristics of coconut biodiesel. To analyze the land requirement for the production of coconut, data provided by the pricing policy of copra 2017 is considered. Taking into account of 9784.66 nuts per hectare, land utilized for the production of coconut is 7.90 lakh hectares. The Government of India claims 20.9 lakh hectares that were utilized for coconut production in 2017. As per the requirements of Indian railways, it is found that 38% of total land could be spared for producing coconut biodiesel. Hence, being one of the leading coconut-producing countries in 2017, the future land availability for coconut production is not a major concern. Further, the land use efficiency of coconut biodiesel is 11,611.26 MJ/ha. In terms of count, 8.066 billon coconuts are sufficient for producing coconut biodiesel in accordance with the requirements of Indian Railways. Hence, coconut oil stands out as promising source for biodiesel fuel for Indian Railways. Various energy indicators like net energy ratio and energy productivity for fossil diesel and coconut-blended diesel (B20) are presented in Table 10. Net energy ratio (NER) is a primary parameter, which indicates the efficiency of biodiesel production. NER for coconut biodiesel is 1.021 and thus favors higher output in comparison with fossil diesel. The production of diesel demands higher input energy due to its energy productivity (0.0061 kg/MJ). Specific energy pertains to the amount of energy which can be extracted per unit kilogram of fuel. From Table 10, it can be inferred that the coconut biodiesel possesses marginally lower specific energy which clearly indicates that the energy obtained from fossil diesel is higher. Total energy cost is

Table 10 Evaluation of energy and economic parameters

Parameters	Unit	Coconut biodiesel–blended diesel (B20)	Fossil diesel
Energy input	MJ/L	148.516	136.413
Energy output	MJ/L	151.634	118.779
Net energy ratio	–	1.021	0.870
Specific energy	MJ/kg	43.024	44.224
Energy productivity	kg/MJ	0.0061	0.0061
Fossil energy ratio	–	6.859	–
Energy intensiveness	MJ/$[a]	73.500	76.823
Energy intensity cost	$/kg	2.330	1.775
Energy intensiveness value	MJ/$	6.326	265.109
Energy ratio cost	–	1.830	1.365
Gross production value	$/L	41.472	50.66
Total production cost	$/L	1.954	1.775
Benefit to cost ratio	–	0.758	0.141
Productivity	kg/$	1.26	0.473
Cost per liter	$/L	0.859	0.842[Previous price of diesel, IOCL 2017]

[a] Convert Indian Rupees (INR) to US Dollar ($)[Reserve Bank of India n.d.]

estimated by replacing the input energy required for biodiesel production to equivalent of US Dollars ($). Fossil energy ratio for biodiesel is 6.859 and thus the displacement of 20% diesel will lower the dependency on crude oil. Nogueira (2011) opined that the rationality of biodiesel production depends on the choice of an effective productive system. To summarize, the energy utilized for biodiesel production is lower when compared with fossil diesel. However, the cost of biodiesel production is higher than diesel with and without considering their by-products.

Conclusions

The study conducted to explore the effect of coconut biodiesel on engine performance, energy and economic assessment, reveals the following:

- The lower content of FFA in coconut aids single stage transesterification process and the performance of coconut biodiesel is rated better compared to fossil diesel in terms of specific energy consumption.
- Coconut biodiesel emits lower smoke, CO, and unburned hydrocarbon emissions, with an increase in NO concentration relative to fossil diesel. Coconut biodiesel provides a significant reduction in smoke emission (87%) relative to diesel under high load operation.
- The fuel line pressure and bulk modulus play a major role in altering the dynamic injection timing and thus the biodiesel-NO emissions.
- Coconut biodiesel exhibits shorter ignition delay, higher peak cylinder pressure and faster burn rate than fossil diesel.
- The coefficient of variation in indicated mean effective pressure is within the range of better driveability zone for both the fuels at all test conditions
- The cost per liter of B20 is marginally higher (0.017 $) than the cost of fossil diesel. The net energy ratio for B20 is 1.021, favoring higher output than diesel and thus lower the dependency on crude oil.

Hence, this study recommends coconut biodiesel as a potential alternative for compression ignition engine. However, to attain biodiesel-NOx neutrality, modified injection strategies need to be adapted.

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Appendix

Nomenclature and abbreviations

bTDC	before top dead center
B100	coconut biodiesel
B20	20% coconut biodiesel blended with 80% diesel
B15	15% coconut biodiesel blended with 85% diesel
B5	5 % coconut biodiesel blended with 95% diesel
BC	benefit to cost ratio
BSEC	brake specific energy consumption
BMEP	brake mean effective pressure
FER	fossil energy ratio
FFA	free fatty acid
FLP	fuel line pressure
CCF	cost capacity factor
CN	cetane number
CO	carbon monoxide
COV_{IMEP}	coefficient of variation in indicated mean effective pressure
LCSF	long chain saturation factor
NER	net energy ratio
NEV	net energy value
Q_{net}	net heat release rates
SOI	start of injection
UBHC	unburnt hydrocarbon
USR	unsaturation to saturation ratio
$/l	US dollars per liter
$/kg	US dollars per kilogram
kcal/kg	kilocalories per kilogram
kg oil/ha	kilograms of oil per hectare
kg/L	kilograms per liter
kg/$	kilograms per US dollar
kg/MJ	kilograms per megajoule
kt	kilotonnes
kt/year	kiloton per year
kJ/mol	kilojoules per mole
kJ/kWh	kilojoules per kilo Watt hour
mg/m^3	milligrams per cubic meter
MJ/L	megajoules per liter
MJ/ha	megajoules per hectare
MJ/FU	megajoules per functional unit
MJ/kg	megajoules per kilogram
MJ/$	megajoules per US dollar
Nuts/ha	coconuts per hectare

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