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A techno-economic assessment of waste oil biodiesel blends for automotive applications in urban areas: Case of India

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ABSTRACT

The effects of greenhouse gas emissions, urban air pollution, and rising transport fuel prices, on the low-income capita in India, necessitate appropriate measures to ensure commodities are sustainably available. This paper presents a study whereby biodiesel blends produced from waste cooking oil are optimised for use in urban medium-duty commercial vehicles, accounting for factors of production capacity, economics, and approximated engine characteristics. An artificial neural network model, trained with experimental data, is used to predict performance, combustion, and emission parameters. The results for various biodiesel blends are applied to a standard driving cycle to obtain variations in key factors. A multi objective optimisation is carried out with engine operation parameters to arrive at optimised biodiesel blends varying between 25% and 81% based on different criteria such as minimising fuel cost, enhancing engine efficiency, and reducing emissions. Considerations when choosing blend concentration are discussed in light of different governmental targets.

1. Introduction

Biofuel production has largely occurred in Brazil, the European Union (EU), and the United States (U.S.), but several other countries have also articulated large biofuel targets [1]. Among them, China and India stand out with their large populations, and a prominent food versus fuel debate [2]. Biofuel production generally requires governmental intervention for uptake because of issues associated with cost and NO_x [3]. Countries that continue to rely on fossil energy sources will be required to make significant efforts to achieve decarbonisation objectives and comply with the Paris Agreement targets [4]. In response to the requirements of the transport sector, environmentally friendly and cost-competitive fuels must be further integrated as an energy resource.

Diesel accounts for the highest share of petroleum fuels used in India (> 40%), with 88 billion litres consumed in 2020 compared to 37 billion litres of gasoline in the same year, with the largest portion of 53 billion litres being used on-road [5]. Even though CO_2 emissions from the power sector is the highest emitter of carbon dioxide, transport alone contributes to 337 Mt CO_2 emissions in India [6]. The Indian Ministry of Petroleum and Natural Gas has reported a massive consumption of 90 million litres of high-speed diesel (HSD) between 2021 and 2022 [7]. In comparison to the previous year, the HSD consumption rate has increased steadily by 5.47% post the COVID-19 restrictions [7]. To limit the dependency of India on its primary energy source (fossil-fuel), sustainable and cost-effective fuels must be further introduced into the energy mix. Such fuels would preferably be produced through the recovery and recycling of waste, rather than using farmland which only complicates the existing water-energy nexus.

A major share (87%) of diesel is utilised by the transport sector and the northern part of India consumes a large amount of diesel in comparison to other regions [8]. Hence, a prominent contribution of road transport drives diesel demand and as shown in Table 1, the trucks segment, both heavy-duty vehicles (HDV) and light-duty vehicles (LDV), account for the lion's share of diesel in the country [8]. Diesel has also been widely used in agriculture pumping and stationary power generation. In lieu of this steady and broader consumption of diesel, its retail price is increasing significantly in the country. Biodiesel has been a topic of interest and various governments are promoting the utilisation of higher concentrations of renewable energy resources. In the aim of deterring the continuous dependence of the transport sector on fossil fuel,

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Table 1
Total share of diesel consumption in India [8].

Diesel: Transport share [%]		Diesel: Non-transport share [%]	
Commercial (taxis)	3.4	Agriculture	4.7
Private cars	14.2	Power generation	1.6
Three-wheelers	1.4	Industry	2.6
Trucks (HDV & LDV)	64.2	Mobile towers	0.4
Busses	4.1	Other	3.4
Total transport	87.3	Total non-transport	12.7

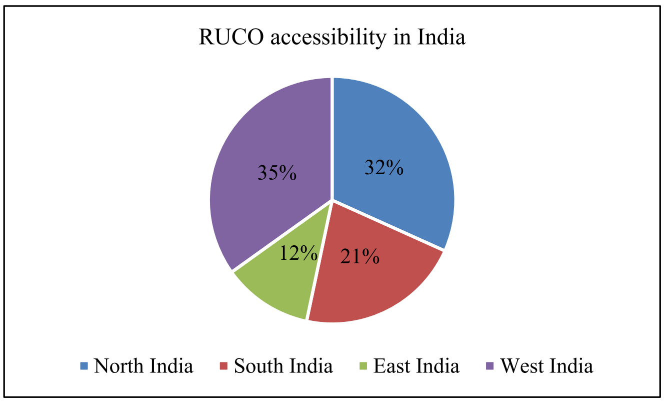


Fig. 1. The total share of RUCO in different parts of India [10].

the Indian Government launched the National Mission on Biodiesel nearly 20 years ago, however, with little success in the transport sector [9]. To reduce the diesel cost, and provide alternative means to sustain energy resources, the Food Safety and Standard Authority of India (FSSAI) have put forward Repurpose Used Cooking Oil (RUCO) as a prospective feedstock. The total amount of used cooking oil available in India is about 366 million kilograms [10] and its distribution in different regions is shown in Fig. 1. It is evident from Fig. 1 that majority of used cooking oil available in India is in the northern and western parts of the country, where the state of Haryana in the north produces around 5.5 tons per year [10]. Based on the information provided, a truck engine is chosen in this work for the optimisation of waste oil biodiesel blends for automotive applications in northern India.

1.1. Biodiesel production

According to the FSSAI [11], out of the 25 billion litres of vegetable oil consumed residentially and commercially in the country, around 2 billion litres of used cooking oil are generated. The National Policy on Biofuels [12] proposes the use of waste and/or wasteland to produce biodiesel for up to 20% blending with diesel. Waste cooking oil is a non-edible feedstock that can be utilised, and thus renamed as repurpose used cooking oil, for biodiesel production through the most common process of transesterification [13]. This consists of a series of chemical reactions whereby lipids from RUCO (triglyceride, diglyceride, and monoglyceride) react with alcohol, in the presence of a catalyst, to give fatty acid methyl esters (FAME), and a less desirable by-product which is glycerol. The insolubility of the reactants renders the process slow; catalyst concentration and type, alcohol type and molar ratio, free fatty acid/water content, temperature, reactor configurations, and mixing methods are factors that influence reaction time, quality, viscosity, and yield [14,15]. Several studies have been conducted on the productivity of FAME from various non-edible feedstock sources at different conditions and using various catalysts, with a biodiesel yield ranging from 89.5% to 98.26% depending on the materials and methods used [16]. Soares Dias et al. [17] proposed lime as an effective catalyst for biodiesel production obtaining a yield of 97% during the methanolysis of rapeseed oil. Calcium diglyceride was suggested as a catalyst for biodiesel production, however, a study showed that its use is not applicable due to its deactivation when exposed to air and its associated high purification expenses [18]. Jamil et al. [19] considered a combination of copper and calcium metal organic framework catalysts for the transesterification of waste cooking oil giving an optimal yield of 84.5%. The optimisation of the FAME production from an ultrasound assisted transesterification of blend of oil feedstocks (palm and sesame) has been investigated for reaction time, alcohol to oil ratio, and catalyst amount to reach a yield of 95.89% [20]. The transesterification process has also been optimised by Outili et al. [21] to reduce energy and resource consumption for the economic and environmental sustainability of the production practice. In any case, regardless of the resources used, and whether conventional or assisted synthesis processes are employed, transesterification is the conventional, well-researched way of biodiesel production [22,23]. Therefore, the kinetic and thermodynamic studies of optimising yield is not the focus of this piece of work.

One major factor which is reported to limit the use of biodiesel as an alternative fuel is its higher cost of production in comparison to using fossil diesel [24]. Direct working costs, such as equipment (reactors, piping, insulation), installation, and land procurement are considered when looking at the capital investment of a conversion plant. Brunet

Table 2
Research summary of SoA on optimisation of biodiesel blends.

Investigators	Optimisation models and tools	Model parameters and optimised data points	Useful inferences
Rajkumar et al. (2022) [33]	MOGA & MATLAB	~B35 as optimised blend if NO_x is the major concern without sacrificing performance and CO_2/HC emissions	3 fitness functions are defined to include the various effects of biofuel operation on engine characteristics
Katekaew et al. (2021) [34]	RSM with a rotatable central composite design	~B23 of WCO biodiesel blend with yang hard resin diesel-like fuel at 1700 rpm provide increased engine efficiency and minimal exhaust emissions	Recommendation of diesel-like fuel from hard resin WCO biodiesel blend (~B20) as a clean substitute for diesel
Simsek et al. (2021) [35]	ANN & RSM	~B22 of animal fat biodiesel is the optimal blend for maximum brake thermal efficiency, and minimum emissions and fuel consumption	Recommendation of RSM and ANN for effectively modelling diesel engine operating parameters
Aydin et al. (2020) [36]	ANN & RSM	~B32 biodiesel blend and 470 bar fuel injection pressure are the optimum engine operating parameters	ANN with RSM support as a good tool for prediction and optimisation of diesel engine operated with biodiesel blends
Arbab et al. (2014) [37]	Optimisation tool in MATLAB	JPC20 (23% Jatropha, 55.9% Palm, 21.1% Coconut) is the optimised blend for engine emissions and performance characteristics	The optimised blend of 20% biodiesel and 80% diesel exhibited the maximum engine power
Maheshwari et al. (2011) [38]	Multi-objective optimisation	~B13 Karanja biodiesel blend with an injection timing of 24 °bTDC is found to be the optimum fuel blend and injection setting	Injection timing influence on performance is of less weightage compared to emission characteristics

et al. [25] reported a total capital investment of around 7.46 million US dollars (USD) for conventional processes, and 12.76 million USD for alternative biodiesel production processes. Castellini et al. [26] indicated 12.99 million USD as the total capital cost for an industrial scale plant. Other costs are associated with the operation of a plant and involve material, labour, overheads, and utility expenses. The operating costs are highly dependent on the type of feedstock used (contributing to up to 70% [27]), and on the location of the conversion unit as it dictates taxes, electricity/water prices, cost of person months of labour, and expense of transport. The price of biodiesel to users is affected by all production costs; in 2021 India the average biodiesel price varied between 67 INR/l to 79 INR/l, including goods and services tax (GST) at 12%, based on the city where it is sold [28]. This work deals with the operating costs supplied by BioD, an existing biodiesel producer in India, and thus neglects the effect of the capital investment which is assumed to have been covered already.

1.2. Biodiesel blends

Normally, the properties of biodiesel, regardless of the feedstock, are similar to diesel characteristics and thus using biodiesel blends (B) in a diesel engine does not require major retrofitting. For that reason, this paper does not provide detailed engine testing or model results. For RUCO biodiesel, the recommended operating blend is 20% due to the higher viscosity of WCO compared to petroleum diesel, which reduces injection rate and corrosion, and favours spray characteristics in an engine [29].

Thangaraja and Srinivasan [30] conducted a techno-economic assessment of B20 coconut biodiesel which demonstrated the potential of the alternative fuel over diesel in internal combustion engines, with favourable overall engine results of neat coconut biodiesel, but incurring a NO_x penalty at high loads. The study revealed that B20 exhibits higher net energy ratio, and energy productivity than fossil diesel [30]. However, the fuel cost per unit volume of B20 is 2% higher than the price of fossil diesel [30], keeping in mind that diesel prices back then were lower than nowadays. The increase in price could be alleviated by a suitable choice of non-edible and cheaper feedstock.

The engine characteristics depend on the quantity of biodiesel in blends with diesel. Numerous studies, similar to those carried out by Gülüm and Bilgin [31,32], have been numerically conducted to obtain the crucial thermophysical properties of biodiesel/diesel fuel blends which affect engine performance and emissions. In this context, a state-of-the-art literature review on the optimised blends of biodiesel is summarised in Table 2. For this purpose, the modelling strategies of artificial neural network (ANN), response surface methodology (RSM), and multi-objective genetic algorithm (MOGA) are widely employed as observed. It is evident that several researchers have attempted to optimise the biodiesel blends for maximum efficiency and minimum emissions with respect to the engine operating characteristics. Solely considering the engine emissions and performance characteristics, the optimised range of biodiesel blend concentration varies from 13 to 35%. Though this type of narrow optimisation helps to choose the correct quantity of biodiesel fuel in conjunction with the injection parameters such as timing and pressure, it lacks the other external constraints such as the feedstock availability, price variation, and production emissions. Similar techniques to those found in literature and described in Sections 2.3 and 2.6 are employed in this work for the salient operating parameters of the system (production plant, commercial engine) with regards to the various relevant criteria of reduced fuel cost, enhanced engine efficiency, and the consideration of surrounding environmental characteristics. In MOGA, it is possible to optimise the biodiesel blends for various constraints of performance, economy, and emission parameters [33]. The optimisation helps choose the correct quantity of biodiesel fuel in conjunction with injection parameters such as timing and pressure. Solely considering the engine emissions and performance characteristics, the optimised range of biodiesel blend concentration varies from 13 to 35%.

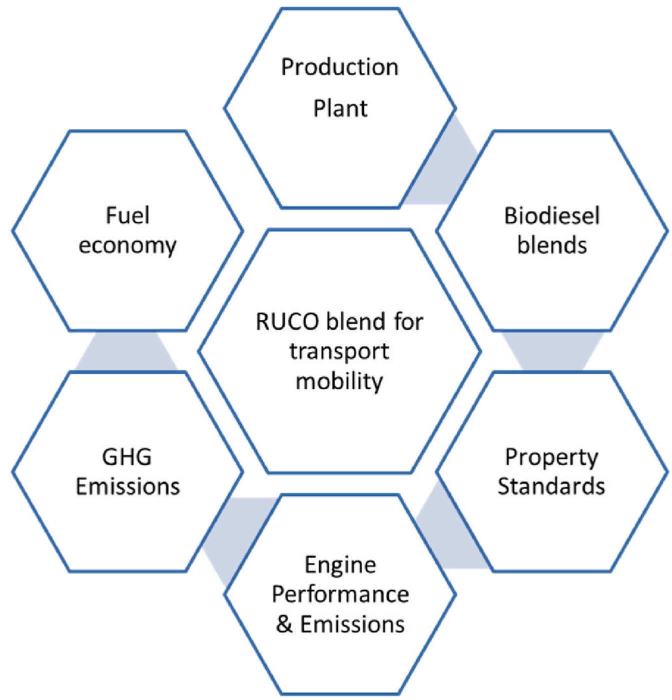


Fig. 2. Considered aspects of this work.

1.3. Objectives of study

Though numerous research studies have investigated the potential of biodiesel fuels from an engine perspective (primarily combustion, performance, and emission), only few investigations have included an analysis of the production, application, and environmental impacts. Some case studies on the integration of biodiesel in China and Malaysia have been conducted [39–41], and a lifecycle assessment for using Jatropha biodiesel in Indian transportation has been performed [42], but an evaluation of the suitable and optimal biodiesel blends for urban commercial transport in the country under varying requirements is still missing. Hence, it seems necessary to assess the potential role of waste energy resources in the country, considering potential end-uses, production pathways, and real-time vehicle applications. The current state-of-art research focuses on the energy-economic-environmental assessment of the real time application of RUCO blends in India, whereas the developed models could be extended universally to other bioenergy resources and low-carbon fuel blend mission requirements. A unique approach (both experimental and modelling) has been attempted to predict and optimise the prominent operating parameters of the system through the consideration of production, engine performance, and environmental and economic characteristics obtained from a specific biodiesel refinery in India. The novelty of the work is the identification of an optimal biodiesel blend by evaluating the energy, engine, and economic indices for effective waste oil processing which assist the biodiesel programme for the emerging Indian commercial transport market needs and expanding population energy requirements. A detailed framework consisting of a machine learning approach with multi-objective genetic algorithm is executed to determine the favourable biodiesel blend to decarbonise commercial transport in Indian cities considering different factors as shown in the pentagons of Fig. 2.

2. Materials and methods

The methodology adopted in this study includes data collection from the chosen biodiesel refinery in the northern state of Haryana as part of

Table 3
Economic input data per reactor (25 tons x1).[1]

Item	Quantity [tons]	Cost [INR/ton]
Used cooking oil	25	45,000 +GST
Methanol	5	29,000 +GST
Catalyst	0.25	8000 +GST
Cooling water	50	60
Electricity		1500
Utilities		3000
Labour		1800
Supervisor		2500
Maintenance & repairs		2000
Operation & suppliers		3000
Insurance		5000
Total cost		**1,973,960 INR 26,382 USD**[1]

Table 4
Gas chromatography results from BioD.

Fatty acid	Concentration [wt %]
Palmitic (C16:0)	40.3
Stearic (C18:0)	4.52
Oleic (C18:1)	43.0
Linoleic (C18:2)	8.27
Linolenic (C18:3)	0.39
Others	3.56

Table 5
Fuel characteristics.

Item	Density [kg/l]	Calorific value [MJ/kg]	Cetane number [−]	Kinematic viscosity at 40°C [mm^2/s]	Price [INR/kg]
Diesel	0.825	42.7	52	3.3	114.69 [7]
Biodiesel	0.8934	39.37	62.05	5.05	52.7

India. Consequently, the tools and data used for model development and optimisation are discussed here.

2.1. Economic data and biodiesel characterisation

According to BioD, a biodiesel production company in India, the biodiesel output of their refinery plant is 100 tons per day, with the average biodiesel output per plant reactor being 22.5 tons per day and a by-product of glycerine amounting to 500 kg.

The provided data from BioD is for one reactor with a capacity of 25 tons. The operational and raw materials costs are reported in Table 3. As indicated by the values, the transesterification process of using methanol and KOH as catalyst gives a biodiesel yield of 90% which is typical of such conversion methods [16]. The selling price of the pure B100 by BioD is set to 52,700 INR/ton, as capped by the government policy for the period from October 2020 to September 2021 [8].

The fuel composition and engine related properties of RUCO biodiesel samples are tested at the Fuel Testing Laboratory of BioD Energy Ltd. The produced biodiesel is characterised with chromatography for compositional analysis and quality checked in accordance with ASTM D6571 standards. The chromatographic results obtained for a RUCO biodiesel sample from BioD are shown in Table 4. The peaks coincide with the major fatty acids present in the gas chromatography table of the Supplementary Material. The composition analysis reveals that the major ester constituents are methyl palmitate (C16:0, 40.3%) and methyl oleate (C18:1, 43.0%). In comparison to research studies [43, 44], the presence of larger quantities of saturated esters reveal that the collected waste oil mixtures correspond to palm oil.

The characteristics of both bio- and fossil diesel, calculated using Kay's mixing rule [45], are reported in Table 5. The properties of RUCO biodiesel are within the standard requirements found in literature [46, 47]. A faster reaction is associated with fuels with higher cetane number, indicating lower combustion emissions; in this work, RUCO biodiesel is found to have a higher cetane number than petro-diesel, in line with results from other works on waste oil biodiesel [48]. Even though biodiesel has almost 8% lower energy content than diesel, engine horsepower, and torque should not be heavily affected, and performance is expected to be smooth [49].

Table 6
Reference for production specific emissions.

Item	CO_2	CH_4 [51]	NO_x [51]	Unit
WCO production	0	0	0	kg em/kg
Electricity [52]	0.697	0	0	kg em/kWh_e
Methanol [51–53]	0.86–2.72	0.0013	1×10^{-5}	kg em/kg
Catalyst (KOH) [51]	2	0.005	5.4×10^{-5}	kg em/kg
Distribution [51]	32	0.01	0	kg em/tbd
Plant operation [51]	2	0	0	kg em/tbd

2.2. Production economy and energy

To account for the total biodiesel production emissions, the preprocessing steps of biodiesel, i.e., plant construction, waste, and biodiesel transport, alongside the raw material production aspects are considered to have an associated emission (em). The reference specific emissions per unit of raw material/infrastructure used are found in Table 6. Since WCO is being repurposed and not produced, there are no associated emissions with it nor with its collection. The CO_2 specific emissions value of methanol varies greatly depending on source, the upper limit is taken as the basis throughout this study, but a comparison of both boundaries is discussed in Section 3.1. The equivalent value of plant operation is a levelised carbon emission for the plant per tonne of biodiesel (tbd) due to its construction and maintenance. The final emission index calculated for RUCO biodiesel in this study corresponds to the total CO_2 equivalent of each specific emission, whereby the greenhouse gas (GHG) equivalent (eq) of CO_2, CH_4, and N_2O (NO_x) are 1 kg $CO_{2,eq}$/kg CO_2, 24.5 kg $CO_{2,eq}$/kg CH_4, and 320 kg $CO_{2,eq}$/kg N_2O respectively. Even though India does not levy an explicit carbon tax, an assumed carbon price of 2.62 INR/kg CO_2 is suggested to emphasise the economic significance of the work [50].

The equations used for obtaining the energy factors — net energy ratio (NER), and energy productivity (EP) — and economic parameters — total energy intensiveness (TEI), specific energy (SE), and energy intensity cost (EIC) — of interest follow the recognised methodology employed previously by Thangaraja and Srinivasan [30]. The economic estimations consist of the total costs of production using the transesterification process, and the cost of diesel where blends are used; whereas the energy analysis considers the energy associated with each fuel blend. Some parameters, such as TEI and EIC relate both economic and energy indices.

2.3. Engine model

The chosen engine model in this work is a typical high-load, low-speed truck diesel engine which represents the kind of vehicles used in commercial road transport in India [44]. The engine is a typical medium/heavy-duty diesel engine used on Indian roads for goods transport and complies with the emission standards of Bharat Stage (BS) II [54]. The choice of an older engine version suits the current investigations for optimising exhaust emissions. The standard operating procedure, and the complete specification details of the engine setup could be referred to from the earlier works of the authors [55].

In the baseline experiment, fossil diesel is tested for subsequent comparison of its performance (viz. Brake thermal efficiency),

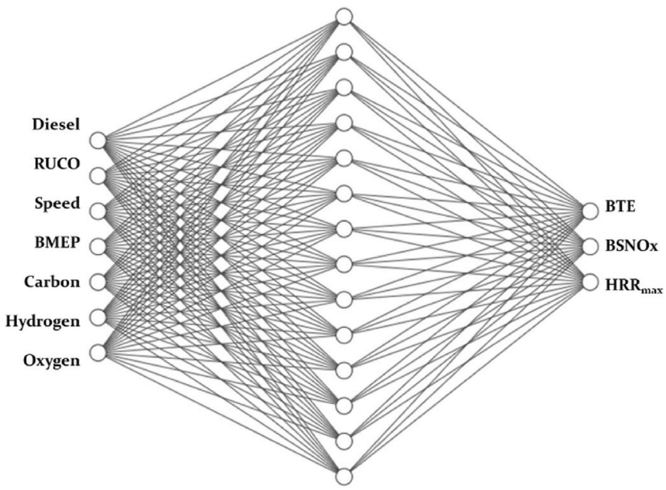


Fig. 3. ANN architecture for emission and performance model.

combustion (heat release rate) and emission (NO_x) characteristics with biodiesel fuels, namely Karanja and Jatropha. The experimental results of this earlier work [12] is used for training an artificial neural network to obtain a detailed prediction of performance, combustion, and emission parameters of diesel, diesel-Jatropha, and diesel-Karanja and then optimising the blend quantity for various engine operating parameters using MOGA [33]. The present work improves on the existing model by optimising the model architecture and key learning variables of the ANN, making the model applicable to a wider variety of fuel compositional derivatives. The ANN is chosen for generating more output predictions within the training range which is helpful for the optimisation. The trained model is modified by including the measured chemical concentration of diesel, diesel-Jatropha, and diesel-Karanja, allowing it to predict engine output parameters for any used biodiesel feedstock, including RUCO biodiesel. The ANN predictions are reliable owing to their effectiveness in capturing the nonlinear relationships, which are prevalent in engine test results. Recent work has shown that such models, which analyse quantitative engine process relationships, can predict the performance and emissions of alternative fuels with relatively small errors [35,36,56]. The developed model assists in relating the fuel composition characteristics such as carbon, hydrogen and oxygen content with engine efficiency, and regulated emissions.

A back-propagation algorithm is employed, and the model is trained using 128 data points comprising diesel and biodiesel operation. The input engine data, such as speed and load, plus the measured chemical composition of RUCO biodiesel are normalised for pre-processing. The ANN is trained with the normalised input data and with the experimentally measured engine outputs of brake thermal efficiency, peak heat release rate, and brake specific NO_x, which represent the essential performance, combustion, and emission parameters of the engine. The seven input and three output layers within the model, which is developed using the computational software Matlab 2019b, are visually described in Fig. 3. The performance of the ANN is assessed by the error that is obtained from the comparison between the target variables (measured data) and the predicted outputs. The number of neurons in the hidden layer is fourteen based on the predictive ability of the network. The ANN predicted outputs of RUCO biodiesel are used in conjunction with the other energy and economic parameters for optimisation using MOGA as described in Section 2.6.

A combination of three loads, 50 Nm (LL), 150 NM (ML), and 260 Nm (HL), at three rotational speeds, 1000 rpm (LS), 1400 rpm (MS), and 2000 rpm (HS), is assessed for six biodiesel blends which are B0, B20, B40, B60, B80, and B100. The results for each combination are brake thermal efficiency (BTE) [%], brake specific NO_x ($BSNO_x$) [g/kWh], and maximum heat release rate (HRR_{max}) [kJ/kg °CA]. Other parameters including NO_x [ppm], brake mean effective pressure (BMEP) [bar], and brake power (BP) [kW] are derived from the study.

The uncertainty/error analysis has been conducted by repeated observation of various parameters of interest at similar operating conditions and the standard deviation (σ) for these data were calculated. The corresponding error according to normal distribution was estimated based on 95% confidence interval following Holman's method [57] as indicated in Eq. (1).

$$Error = \pm 1.95 \bullet \sigma \tag{1}$$

The experimental uncertainty values estimated for the measured quantities in this study are provided in Table 7.

Table 7
Uncertainty errors.

Parameter	Uncertainty [%]
Speed [rpm]	±3.43
Brake torque [Nm]	±2.10
Fuel time [s]	±0.45
Air time [s]	±0.54
Exhaust gas temperature [°C]	±2.28
Cylinder pressure [bar]	±0.98
Nitric oxide [ppm]	±7.00
Brake power [kW]	±0.29
Brake specific nitric oxide [g/kWh]	±1.3
Brake thermal efficiency [%]	±1.13

Table 8
Fuel chemical compositions.

Fuel	Formula	M [kg/kmol]	m_C	m_H	m_O
Diesel (B0)	$C_{12}H_{26}$	170.33	12	26	0
RUCO biodiesel (B100)	$C_{17.5}H_{33.81}O1.93$	275.12	17.5	33.81	1.93

2.4. Combustion emissions

The chemical formulae of both diesel and 100% biodiesel, as sampled by BioD, are found in Table 8, as well as the number of atoms (m) of carbon (C), hydrogen (H), and oxygen (O) in each fuel.

The carbon dioxide emissions for a fuel are calculated from the number of CO_2 molecules produced from the stoichiometric combustion of that blend with air as indicated in Eq. (2). Where χ denotes the biodiesel blend percentage (e.g., $\chi = 0.4$ for B40), and a, b, and c are obtained by solving the balanced chemical equation.

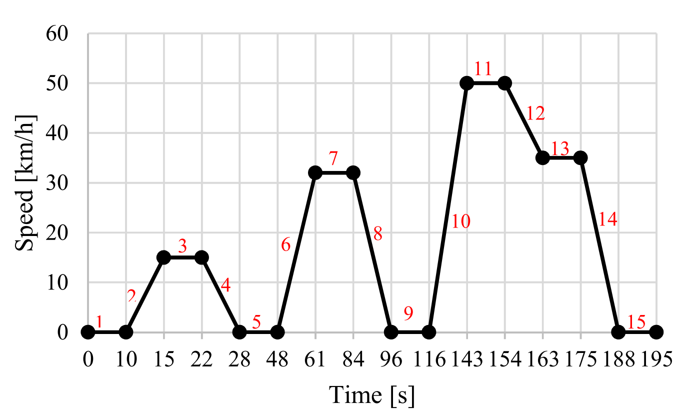


Fig. 4. ECE-15 driving cycle [60].

[1] 1 USD = 74.82 INR.

Table 9
Assigned power settings for driving conditions.

Condition	Power Setting	ECE-15 legs
Idle	Low rotational speed/Low engine load	1, 5, 9, 15
Cruise low speed	Medium rotational speed/Low engine load	3, 7, 13
Cruise med speed	Medium rotational speed/Medium engine load	11
Cruise high speed	Medium rotational speed/High engine load	
Acceleration from low speed	High rotational speed/Medium engine load	2, 6, 10
Acceleration from med speed	High rotational speed/High engine load	
Deceleration from med speed	Low rotational speed/Low engine load	12
Deceleration from low speed	Low rotational speed/Low engine load	4, 8, 14

$$\chi C_{17.5}H_{33.81}O_{1.93} + [1-\chi]C_{12}H_{26} + aO_2 + 3.76aN_2 \rightarrow b\,CO_2 + c\,H_2O + 3.76aN_2 \quad (2)$$

Considering that throughout the lifecycle of the waste oil that is used to produce the biodiesel, the carbon emitted has already been absorbed by the oil crop, the carbon neutral emissions of the blends are also discussed later in Section 3.3. That is to say that the carbon combustion emissions for B100 are zero, and for other blends the CO_2 emissions account for the carbon content of the diesel amount within the blend.

2.5. Mission characteristics

The modal ECE-15 urban driving cycle (UDC), consisting of a series of acceleration, deceleration, and cruise modes, as displayed in the speed/time graph of Fig. 4, is selected as a representative mission analogous to conditions experienced during inner city driving of commercial cars in Indian metropolises. Although there are some available real-world driving data from India, for example in the cases of Pune [58] and Chennai [59], these are not considered given that the objective of this study is not to estimate the performance of vehicles on Indian roads, but to give generalised comparative information of using biodiesel blends in the Republic. The ECE-15 cycle covers a distance of 1.013 km, with an average speed of 18.7 km/h [60], and consists of fifteen segments or legs numbered in Fig. 4, whereby each leg denotes a change in the engine operation which is prescribed according to Table 9.

To fulfil the goal of the work, the assumptions of a constant vehicle size and weight, along with no change of altitude (no uphill nor downhill driving) nor of ambient conditions are made. In that sense, each driving mode is assigned an engine power setting as listed in Table 9. The selection of power settings is determined by the availability of data provided from the results obtained from the engine model for a combination of rotational speed and engine load settings as explained in Section 2.3. Since the ECE-15 cycle has no high speeds, the fifteen legs of the UDC, indicated by red in Fig. 4, correspond to only five out of the six mentioned power settings, and to six out of eight of the engine conditions.

The duration (Δt) as well as the distance (Δx) covered by each leg is calculated from the speed/time graph. For each leg, the mechanical work (ME) is calculated by multiplying the BP, obtained from the engine model for that power setting, by the respective Δt. The energy requirement is found from ME using BTE, which is then equated to the amount of fuel input (i.e., fuel consumption), for each blend, using heating values and densities. NO_x emissions in grams are calculated from the ME and $BSNO_x$, whereas the CO_2 emissions are obtained from respective CO_2 value of both combustion and production for the consumption. The total of each parameter is normalised with respect to Δx to obtain values per km.

2.6. Biodiesel blend optimisation

Multi objective genetic algorithm (MOGA) is attempted in this study to optimise the biodiesel blend concentration. Several analyses reported in literature target the optimisation of biodiesel blends by considering performance and emission parameters [61,62]. However, the optimisation in this study is performed based on eight major parameters namely net energy ratio [−], energy productivity [l/MJ], fuel cost (FC) [INR/km], energy intensity cost [INR/km], GHG production emissions (GPE) [g/km], CO_2 combustion emissions (CCE) [g/km], NO_x emissions [g/km], and average BTE [%] which consider the economic, environmental, and technical aspects of biodiesel utilisation. The optimisation is used to minimise energy productivity, fuel cost, energy intensity cost, GHG production emissions, CO_2 combustion emissions, and NO_x emissions, while maximising net energy ratio, and average BTE. The optimisation strategy involved in this work is explained in detail in the author's earlier work [43].

The constraint function provides a set of controls to optimise the variables which must be minimised or maximised. The reference values for optimising the fuel cost, GHG production emissions, CO_2 combustion emissions and NO_x are taken from literature as indicated in Table 16. For other parameters, the minimum and maximum values arrived from the current study are considered for minimisation and maximisation respectively. The objective function is defined by considering the different weightage factors on the eight parameters that are involved in engine operation from the production to tail pipe emissions. The beneficial and adverse effects of using the biodiesel are considered in the objective functions. The objective functions with different constraints adopted in this study are as follows in Eq. 3 – 7.

1. Case 1: Considering equal weightage to provide the same level of importance to all the parameters.

$$F_1 = \frac{1}{8}\left(\frac{NER_{max}}{NER} + \frac{EP}{EP_{max}} + \frac{FC}{FC_{max}} + \frac{EIC}{EIC_{max}} + \frac{GPE}{GPE_{max}} + \frac{CO_2}{CO_{2max}} + \frac{NO_x}{NO_{xmax}} + \frac{BTE_{max}}{BTE}\right) \quad (3)$$

2. Case 2: Given that larger biodiesel blends increase NO_x emissions, a higher weightage of 50% is given to NO_x emissions to address the biodiesel NO_x penalty. The remaining 50% is equally distributed over the other parameters as:

$$F_2 = \frac{0.5}{7}\left(\frac{NER_{max}}{NER} + \frac{EP}{EP_{max}} + \frac{FC}{FC_{max}} + \frac{EIC}{EIC_{max}} + \frac{GPE}{GPE_{max}} + \frac{CO_2}{CO_{2max}} + \frac{BTE_{max}}{BTE}\right) + 0.5\left(\frac{NO_x}{NO_{xmax}}\right) \quad (4)$$

Table 10
Fuel blends characteristics.

Blend	Carbon content [wt%]	Hydrogen content [wt%]	Oxygen content [wt%]	M [kg/kmol]
B0 (Diesel)	84.6	15.4	0	170.32
B20	82.3	14.5	3.2	191.31
B40	80.4	13.8	5.8	212.29
B60	78.8	13.3	7.9	233.27
B80	77.5	12.8	9.7	254.25
B100 (Biodiesel)	76.4	12.4	11.2	275.23

Table 11
Production emissions for biodiesel production process.

Item	CO_2 [kg/tbd]	CH_4 [kg/tbd]	N_2O [kg/tbd]	GHG $CO_{2,eq}$ [kg/tbd]
WCO production	0	–	–	0
Electricity	105	–	–	105
Methanol	605	0.29	0.0022	613
Catalyst	22	0.06	0.0006	24
Collection/Distribution	32	0.01	–	32
Plant construction/ maintenance	2	–	–	2
Total	766	0.35	0.0028	775

3. Case 3: Similar to the case 2, 50% weightage for CO_2 emissions is given to consider the combustion carbon emissions. Though biodiesel is considered to be carbon neutral, the CO_2 combustion emissions increase with biodiesel quantities and hence this emission is also considered with more weightage.

$$F_3 = \frac{0.5}{7}\left(\frac{NER_{max}}{NER} + \frac{EP}{EP_{max}} + \frac{FC}{FC_{max}} + \frac{EIC}{EIC_{max}} + \frac{GPE}{GPE_{max}} + \frac{NO_x}{NO_{xmax}} + \frac{BTE_{max}}{BTE}\right) + 0.5\left(\frac{CO_2}{CO_{2max}}\right) \tag{5}$$

4. Case 4: From an economic perspective, the fuel cost of the biodiesel is considered in this constraint function. Hence, 50% weightage is given to the fuel cost, which is expressed as:

$$F_4 = \frac{0.5}{7}\left(\frac{NER_{max}}{NER} + \frac{EP}{EP_{max}} + \frac{EIC}{EIC_{max}} + \frac{GPE}{GPE_{max}} + \frac{NO_x}{NO_{xmax}} + \frac{CO_2}{CO_{2max}} + \frac{BTE_{max}}{BTE}\right) + 0.5\left(\frac{FC}{FC_{max}}\right) \tag{6}$$

5. Case 5: This constraint is mainly concerned with emissions. The main adverse contributions from the biodiesel fuel are its NO_x and CO_2 emissions, and those are considered as the focus emissions of the study. Therefore, each of the NO_x and CO_2 emissions is given a 30% weightage (overall 60% weightage on emissions) and the balance is equally distributed over the other parameters.

$$F_5 = \frac{0.4}{6}\left(\frac{NER_{max}}{NER} + \frac{EP}{EP_{max}} + \frac{FC}{FC_{max}} + \frac{EIC}{EIC_{max}} + \frac{GPE}{GPE_{max}} + \frac{BTE_{max}}{BTE}\right) + 0.3\left(\frac{NO_x}{NO_{xmax}} + \frac{CO_2}{CO_{2max}}\right) \tag{7}$$

The outcome of the MOGA would be the optimal biodiesel quantities that are suitable for the various constraints.

3. Results and discussion

The presentation of the results along with a discussion of their relevance follow next. Justification of some choices and critical observations of the outcomes are discussed.

Table 12
Emissions of fuel blends.

Fuel	GHG $CO_{2,eq}$ prod emissions [g$CO_{2,eq}$/l]	CO_2 comb emissions [gCO_2/l]	CO_2 comb emissions [gCO_2/l] (CN)
B0	3128	2557	2557
B20	2641	2549	2079
B40	2154	2539	1585
B60	1667	2528	1074
B80	1180	2515	545
B100	693	2500	0

Table 13
Energy and economic parameters for biodiesel blends.

Parameter	Unit	B0 [30]	B20	B40	B60	B80	B100
EI	[MJ/l]	136	209	103	68	50	39.48
EO	[MJ/l]	119	205	99	64	46	35.24
NER	[–]	0.870	0.979	0.957	0.934	0.912	0.889
EP	[l/MJ]	0.007	0.024	0.025	0.025	0.026	0.028
TEI	[MJ/INR]	0.99	0.534	0.523	0.519	0.513	0.506
SE	[MJ/l]	44.2	40.8	39.0	37.3	35.6	31.72
EIC	[INR/kg]	137	110	105	99.2	93.59	87.73

3.1. Fuel parameters

This section covers the evaluation of the economic and fuel parameters obtained for different blends, and the technical engine-related factors for using biodiesel blends. The data is obtained by following the methodology presented in Sections 2.1–2.2.

The variation of biodiesel blend prices is acquired from both the selling price of BioD 100% biodiesel, and the price of diesel which are listed in Table 5. There is a linear variation of fuel price in INR/l which indicates that the price of pure biodiesel (assuming no taxes) is almost 50% cheaper than that of diesel, a massive reduction of cost to the consumer. Similar to the price of blends, the density and calorific values for each fuel blend follow the well-known linear trends for biodiesel blends. The obtained data is used in the mission analysis to find the fuel consumption for each blend.

The C, H, and O content in each blend, along with the molecular mass of the fuels is revealed in Table 10. Comparing the tabulated information between Table 10 and literature [47], the BioD WCO biodiesel is within standard limits of carbon content, and negligibly higher than the bound for hydrogen and oxygen contents.

Table 11 lists the carbon dioxide, methane, and NO_x discharges associated with producing B100, along with their GHG carbon equivalent ($CO_{2,eq}$) emissions. The lifecycle GHG $CO_{2,eq}$ emissions of biodiesel from waste vegetable oil reported by Forest Research UK [63], not accounting for the combustion emissions, is 437 g $CO_{2,eq}$/l or 489 kg $CO_{2,eq}$/tbd which is almost 30% less than the total value obtained from this study. However, this is bearing in mind that the upper limit of 2.72 kg CO_2/kg methanol is used for the calculation of the presented figure, and that the carbon content of the reported biodiesel is 77 wt%. When considering the production emission of 0.86 kg CO_2/kg methanol, the total GHG CO_2 eq. production emissions of biodiesel is reduced to 361 kg $CO_{2,eq}$/tbd.

For any of the blends in Table 11, linking the discussion to the lifecycle GHG $CO_{2,eq}$ emissions of fossil diesel, which is calculated as 2557 g $CO_{2,eq}$/l – compared to 3128 in the Forest Research report due to higher carbon content in their considered diesel [63]– shows a stark contrast between the production emissions of biodiesel and its conventional competitor. Associating the production emissions of each fuel to the assumed carbon taxes gives an additional price of 1.81 INR/l for B100 and 8.19 INR/l for B0, when taking the total theoretical prices of biodiesel and diesel to 48.89 INR/l and 102.81 INR/l respectively; this only justifies the case of using higher blend concentrations.

Table 12 holds the CO_2 combustion (comb) emissions for the blends,

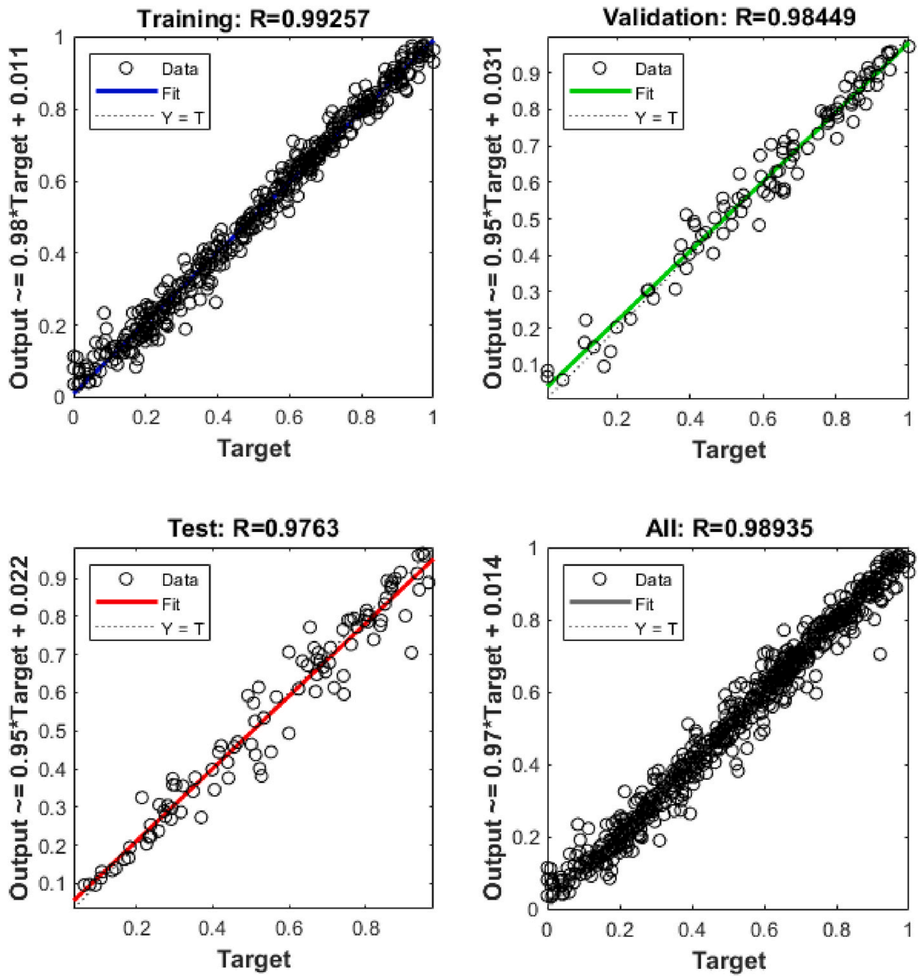


Fig. 5. Overall correlation coefficient of the developed engine model.

Table 14
Engine parameters at different power settings for diesel and biodiesel.

Operating Conditions		BP [kW]		BTE [%]		$BSNO_x$ [g/kWh]		NO_x [ppm]		HRR_{max} [kJ/kg °CA]	
Power setting	BMEP [bar]	B0	B100	B0	B100	B0	B100	B0	B100	B0	B100
LL/LS	2.2	5.38	6.29	25.53	26.44	3.21	3.10	144	281	62.68	54.16
LL/MS	2.2	8.30	9.09	26.57	27.24	3.01	2.64	136	228	66.94	55.47
LL/HS	2.2	10.5	11.9	23.91	25.01	3.77	3.61	119	420	55.63	51.37
ML/LS	6.1	16.7	17.1	37.79	38.48	1.89	2.76	230	686	77.99	69.74
ML/MS	6.1	24.7	25.1	38.82	38.77	3.40	3.30	388	699	78.2	63.22
ML/HS	6.1	33.4	34.8	36.71	37.66	4.46	4.88	310	487	55.89	55.29
HL/LS	10.5	27.5	29.3	35.44	36.15	1.28	2.08	203	762	79.86	88.18
HL/MS	10.5	42.6	42.3	40.37	40.25	3.24	3.10	482	850	76.17	81.70
HL/HS	10.5	54.5	55.4	38.58	40.21	4.82	5.21	425	702	68.31	67.12

along with a summary of the GHG $CO_{2,eq}$ lifecycle/ production (prod) emissions. The combustion emissions are categorised as the actual CO_2 emissions, and the allocation of carbon emissions from the diesel contribution to a blend when considering that biodiesel is carbon neutral (CN). From a regulatory perspective, to encourage the use of biodiesel as a blend, the carbon tax would not be applied to the carbon emissions from the combustion of biodiesel blends but would be added to the combustion of pure fossil diesel, now taking the total taxed price of diesel to 109.51 INR/l — assuming that the carbon tax is in addition to the goods and services tax that is already applied onto the price of diesel of 114.69 INR/kg.

The calculated energy and economic parameters for the biodiesel blends under study are shown in Table 13. As anticipated, the energy input and output follow a declining route as biodiesel blends increase, demonstrating that biodiesel requires less energy demand for production but gives lower available energy to be utilised. The maximum specific energy is for diesel owing to its higher calorific value. This is reflected in the values of net energy ratio; however, unlike what is reported for biodiesel blends from other edible oil feedstock [30], which have higher energy input in comparison to waste oil sources, the NER values for RUCO biodiesel blends are larger than pure diesel. In line with the energy input values, the energy productivity for higher blends is greater than petro-diesel. Total energy intensiveness, a measure of the production energy input per unit cost also shows beneficial results for larger blends. Finally, the values of energy intensity cost reflect the combination of the several factors affecting its constitution.

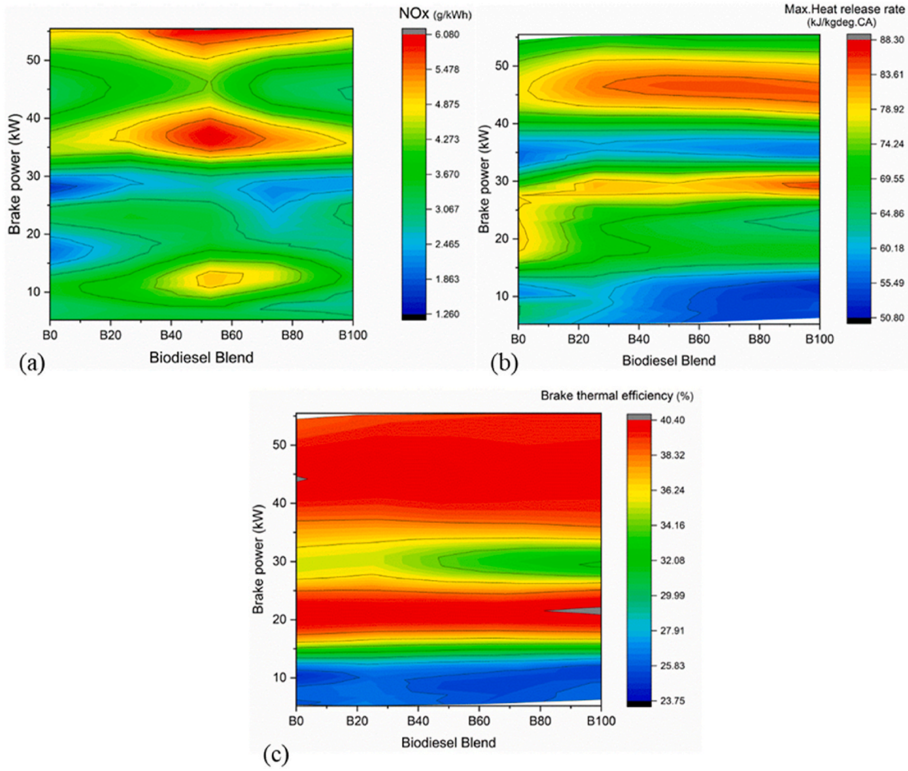


Fig. 6. Variation of engine output parameters for biodiesel blends (a) $BSNO_x$, (b) HRR_{max}, (c) BTE.

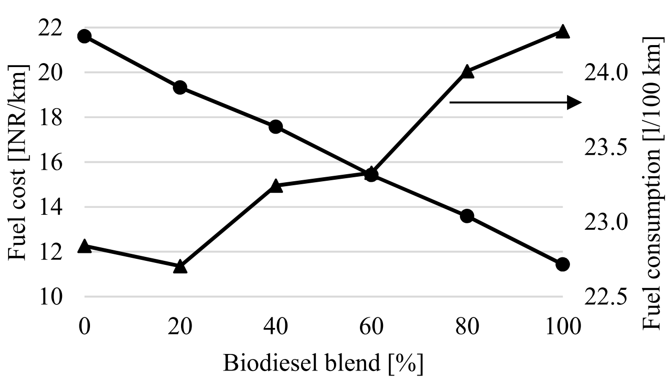


Fig. 7. ECE-15 fuel cost and consumption.

3.2. Engine data

The regression plot for the ANN training is shown in Fig. 5 where R is the correlation coefficient. The R values for training, validation, testing, and the overall method are very close to 1, indicating the accuracy of the current model.

The ANN predicted values of BTE, NO_x, and peak HRR for diesel and for 100% RUCO biodiesel at the various loads and speeds are presented in Table 14. The brake thermal efficiency for B100 is observed to be higher than that for B0 almost at all the speeds and loads. Brake specific NO_x emissions show an increase with load for both fuels, as originally expected [55]. The NO_x concentration, in ppm, from B100 is relatively more than that of diesel due to the inbuilt oxygen content of biodiesel being responsible for larger NO_x productions, as widely reported in literature [64]. B100 shows a reduced trend of peak heat release rate compared to that of diesel. BTE, NO_x, and HRR_{max} values are also obtained for B20, B40, B60, and B80 and are visualised in Fig. 6; details of the engine data for all biodiesel blends can be viewed in the Supplementary Material. In comparison with fossil diesel, the blends of RUCO biodiesel exhibit a marginal increase in the brake thermal efficiency as shown in Fig. 6 (c). The presence of oxygen in the biodiesel molecules, and the higher lubricity of biodiesel blends are considered responsible for efficiency enhancement. The energy release estimates for the test conditions, shown in Fig. 6 (b), are required to understand the

Table 15
Time averaged NO_x for different blends.

Blends	$\overline{NO_x}$ [ppm]
B0	194
B20	240
B40	255
B60	291
B80	312
B100	341

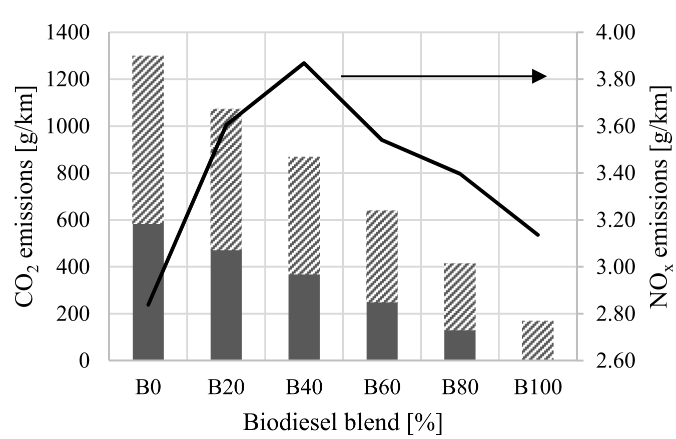


Fig. 8. Total CO_2 emissions breakdown: carbon neutral combustion emissions (filled) and production emissions (patterned) and NO_x emissions of ECE-15.

combustion behaviour of RUCO biodiesel fuel blends. The magnitude of energy release rate is consistently lower for diesel compared to biodiesel blends, concurrently the NO_x emissions are found to be higher with increasing biodiesel blends as evident in Fig. 6 (a). The maximum NO_x concentration (850 ppm) is observed for B100 at full load (260 Nm) and 1400 rpm. All quantitative trends corroborate the observations from research works using ANN [33,65]. The predictions from the engine model appear to be reasonable to be used for further analysis carried out in this work.

3.3. Driving cycle calculations

The key parameters for fuel consumption, emissions, and engine performance are calculated for the ECE-15 driving cycle as per the outlined methodology in Section 2.5. All values for the total legs of the driving cycle and for each fuel blend are found in the Supplementary Material. The fuel cost and consumption per kilometre of the ECE-15 cycle for each blend are visualised in Fig. 7. The fuel price follows a good-fit linear decrease ($R^2 = 0.9991$), like the trend of the biodiesel blend costs. The fuel consumption in volume increases [66] in accordance with the engine performance (efficiency) and thus is affected by the engine mechanical power and energy requirement.

Given that the ppm values of NO_x cannot be summed, the time-averaged concentration of $\overline{NO_x}$ emissions is calculated (summation of NO_x in ppm for each leg, divided by the time duration covered in the ECE-15 cycle which is 195 s). The values for the various fuel blends are listed in Table 15 which correspond to the trend of increasing nitric oxides for higher biodiesel blends.

The total combustion and production $CO_{2,eq}$ emissions are displayed in Fig. 8. The amount of combustion emissions in the graph, embodied by the filled grey bars, resembles the assumption of biodiesel being carbon neutral: the CO_2 produced upon combustion has already been absorbed throughout the lifecycle of the biomass, particularly that in this case, the biomass is a waste product which if not used would be more harmful. The patterned bars represent the GHGs released during the fuel production, where most of the emissions are generated, particularly for biodiesel blends.

It is worth noting that in comparison to the time-averaged NO_x in Table 15, the amount of NO_x emitted per km, shown in Fig. 8, does not follow the same increasing inclination with blends; the highest NO_x value is at B40 with 3.87 g/km. This is due to other engine-related factors such as combustion and thermal efficiencies at different loads and rotational speeds, as evidenced in Table 14, and as described by other researchers whereby high biodiesel blends under certain conditions can reduce NO_x [67,68].

3.4. Optimised blend

The energy, economics, environment, and performance parameters, for each blend, that are considered for the multi-objective optimisation are compiled in Table 16. These major eight factors govern almost all essential requirements of the engine operation from a fuel perspective. The effective engine operation dictates maximising NER and engine BTE while minimising EP, FC, EIC, GPE, combustion CO_2, and NO_x emissions. As noted, the minor discrepancy in engine BTE for the different fuels is not of a uniform variation with increasing blend which can explain the results of NO_x in g/km that are presented in the previous section.

The reference values for optimising the fuel cost, production emissions, combustion products, and thermal efficiency are taken from literature as referenced in Table 16, while for the other parameters, the minimum and maximum values are arrived at from the current study. The reference value for the cost is taken as the average price of B100 in India (≈70 INR/l) [28] multiplied by the average fuel consumption from the results in Fig. 7. To account for the maximum carbon emissions which need to be reduced, the non-carbon neutral values of combustion emissions are considered.

The choice of the BS-II emission category engine is suitable for controlling the regulated biodiesel NO_x penalty. It is worth mentioning the large disparity of the relative difference between the chosen reference value and the engine exhaust NO_x values. This could possibly be attributed to two causes: the degeneration of the engine life, and/or the non-conformity of the engine to the current more stringent emission legislation of BS-VI [54]. Similar conclusions can be deducted for the reference CCE and BTE reference figures. Nonetheless, the reference choice assists the objective of the current study to explore the worst-case scenario for emissions. The Renewable Fuel Standard [69] recommends that all advanced biofuels must achieve a minimum reduction of 50% GHG emissions compared to baseline fossil fuel emissions, hence the reference value assumed for GPE. The optimisation is carried out for the different objectives as provided in Section 2.6 Table 16

The MOGA adopted in the current study provides the optimum biodiesel blend for various chosen constraints; the five cases are summarised in Chart. 12.6. The optimised biodiesel blend is 62.5% when equal weightage is given for all the parameters of energy, economics, environment, and engine combustion. This is compared to the work conducted by Aydin et al. [36] where an optimised biodiesel blend of 32% was arrived at for an engine load of 816 W considering engine performance and exhaust emissions. Similarly, in a RSM-based optimisation, 23% WCO biodiesel blend is suggested for an engine speed of 1700 rpm when taking into account factors of torque, brake power, BTE, and emission/pollution [34]. In previous works by the authors [33], a ~40% blend has been recommended for equal weightage on performance and emissions. However, the lower blend percentage in the mentioned studies is attributed to the fact that they do not factor in the cost requirements which has a high significance. The results presented in this paper show that the optimal biodiesel quantity decreases to 27.2% when more weightage is assigned to NO_x emissions. This is due to the increased NO_x emissions with higher biodiesel quantities and therefore, the optimised quantity of biodiesel is lower compared to the case of equal weightage for all the factors. This is in line with the observed reduction in blend when NO_x is assigned a higher impact [33], and with the outcomes obtained by Viswanathan et al. [73] suggesting an ideal blend of 20% for maximum efficiency and lowest NO_x emissions. The biodiesel blend slightly increases to 31.2% when 50% weightage is given to CO_2 combustion emissions. When looking at the engine performance

Table 16
Data considered for optimisation.

Fuel	Energy		Economics		Environment		Engine	
	Max	Min	Min	Min	Min	Min	Min	Max
Blends	NER [−]	EP [l/MJ]	FC [INR/km]	EIC [INR/kg]	GPE [g/km]	CCE [g/km]	NO_x [g/km]	BTE [%]
B0	0.870	0.0074	21.5	136.5	714	584	2.84	32.46
B20	0.979	0.0240	19.3	109.3	600	579	3.60	33.07
B40	0.957	0.0246	17.5	104.3	501	590	3.87	32.56
B60	0.934	0.0251	15.4	99.0	389	589	3.54	32.65
B80	0.912	0.0256	13.6	91.49	283	604	3.40	32.45
B100	0.889	0.0280	11.4	87.73	168	607	3.14	32.73
Ref	0.979	0.0074	16.0 [28]	87.73	357	122 [70]	0.18 [71]	42 [72]

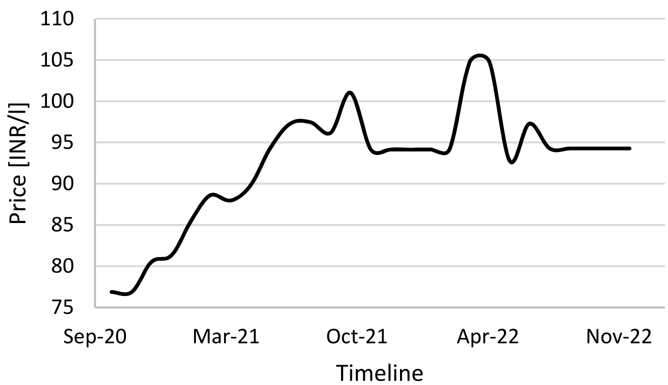


Fig. 9. Fluctuation of diesel price in India between October 2020 to November 2022 [8].

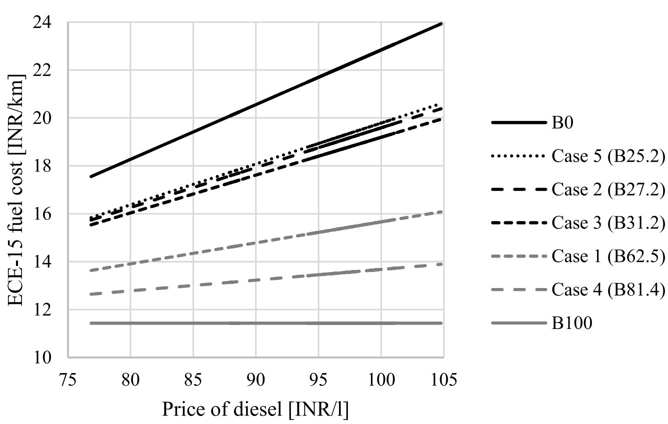


Fig. 10. Variation of ECE-15 fuel cost with diesel price for B0, B100, and each optimised case blend.

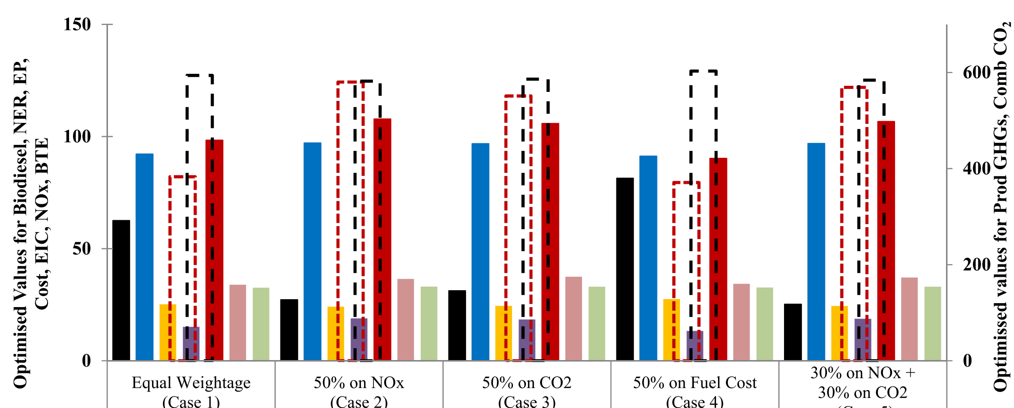
metrics alone, researchers suggest a Nahar oil biodiesel blend of 14% and 5% to achieve minimum fuel consumption and maximum efficiency [74]. From Table 16, it could be noted that minimum CO_2 emissions occur in B20, meaning that giving more weight to CO_2 emissions and equal weightage to all other parameters provide an optimal biodiesel blend of 31.2%. The optimal biodiesel quantity based on 50% weightage for fuel cost is 81.4% with respect to diesel; this is due to reduced fuel cost with the increase in biodiesel fraction in a blend. From an environmental standpoint, the 60% weightage on the emissions (30% each for NO_x and CO_2) demonstrates that a lower 25.2% biodiesel blend is optimum. The reason is attributed to the biodiesel NO_x penalty and increased CO_2 emissions at higher biodiesel fractions. Therefore, the optimisation of biodiesel quantity depends on the various phases involved from fuel production stage to its final discharge emission at the tailpipe. This optimisation is expected to be useful for arriving at an optimal biodiesel quantity that meet the various criteria involved in the substitution with biodiesel fuel for engine operation.

3.5. Response to rising fuel prices

The baseline analysis in this study, and the aforementioned results are for a reference diesel price of 114.69 INR/kg or 94.62 INR/l. Over the course of this work, the price of fossil fuels, particularly diesel in India has fluctuated, as perceived in Fig. 9 [8]. With an unstable forecast of energy costs, it was deemed essential to consider the effect of uncertain diesel prices. The biodiesel market in India has not encountered a major change and the prices are not expected to vary tremendously, so the effect of diesel price is the only considered variable.

Granted that the diesel price is an economic factor, this alteration should mostly affect the cost to the end-user, i.e., fuel cost for the driving cycle depending on the blend used. Fig. 10 shows the change in fuel cost per kilometre for the considered blends which are those from the optimised cases, as well as reference B0 (pure diesel) and B100 (pure biodiesel). As expected, if B100 is used, the price to the consumer will remain constant; the higher the biodiesel blend, the less risk there is for massive cost incurrences as displayed in the lower gradient of the blends over 62.5%. Whereas, from a customer perspective, the more diesel concentration there is in the fuel, the higher the cost incurred on them. This poses another incentive to enabling higher biodiesel blends to be used in the Indian commercial road transport market.

It should be noted that the optimisation process is not repeated for every price of diesel but rather the results of optimisation are kept based on the reference price (114.69 INR/kg). The increase in price of diesel favours optimised blends with higher biodiesel content, consequently,



	Equal Weightage (Case 1)	50% on NOx (Case 2)	50% on CO2 (Case 3)	50% on Fuel Cost (Case 4)	30% on NOx + 30% on CO2 (Case 5)
Biodiesel (%)	62.5	27.2	31.2	81.4	25.2
NER (/100) [-]	92.14	97.12	96.82	91.25	96.91
EP (/1000) [1/MJ]	25.2	24.1	24.5	27.5	24.4
Cost [INR/km]	15.1	18.9	18.4	13.3	18.7
EIC [INR]	98.34	107.8	105.8	90.26	106.7
NOx (/10) [g/km]	33.9	36.5	37.5	34.3	37.1
BTE [%]	32.58	33.06	33.05	32.67	33.04
Prod GHGs [g/km]	383	580	551	371	569
Comb CO2 [g/km]	594	582	586	603	584

Chart. 1. Optimised results for different cases.

the results will be less sensitive to the price of diesel.

4. Conclusions

The growing number of diesel vehicles on the road and the ensuing increase in diesel fuel consumption, along with the associated detrimental environmental impact, warrant low emission renewable fuel alternatives. In this respect biodiesel fuels from waste have attracted attention which subjected their use to wider scientific scrutiny. This research study represents a first-of-its kind comprehensive assessment for the Indian context and provides an analysis of RUCO biodiesel blends through the consideration of production, engine performance, and environmental and economic characteristics obtained from a specific biodiesel refinery in India. The study has embedded a machine learning approach to obtain engine performance metrics, an application for an urban driving cycle, and a multi-objective genetic algorithm to determine the favourable biodiesel blend for different scenarios to help decarbonise the commercial transport sector in urban India.

The standalone engine study of blends of diesel and RUCO biodiesel content in a turbocharged multi-cylinder compression ignition engine revealed that compared to fossil diesel, the NO_x emissions increased considerably in biodiesel fuelled engines due to higher in-cylinder temperature and heat release rates. However, implementing the engine data within the analysis of using the engine for a commercial vehicle application in an Indian context shows interesting results that challenge the aforesaid statements due the complex interaction of individual factors when considered as an overall system. In that sense, outcomes show that higher biodiesel blends may result in lower NO_x amounts and ensue minimal effects on engine efficiency.

Based on the optimisation results and depending on the objective that is to be satisfied via the use of biodiesel, optimised blends ranged between B25 and B81. Giving emissions an elevated importance over all other parameters indicates lower blend concentrations in the range of 25%–31%. Whereas, when considering all factors, or prioritising cost — particularly for the case of low-income regions of India — the optimised biodiesel concentration rises to a range of B62.5 to B81.

The results of the optimisation can vary if a different driving cycle is considered. However, the chosen driving cycle, is representative of driving in urban areas which gives confidence in the applicability of the results for such applications. Given the significant health implications of NO_x emissions in populated cities, the government should consider some form of pollution taxation system for urban transportation [75]. Although this might be an ambitious target, but in combination with a carbon taxation, it can create a balance between the economy of transportation, air quality considerations, and environmental impacts. Specific regions of India might have conflicting or different priorities which can be considered in the weightings given in the optimisation process.

The same proposed methodology can be followed for future research with a focus on other renewable biofuels to optimise blends, and through applying data to actual real-life driving cycles that are applicable to urban India or other regions elsewhere with a similar size, population, and transport profile.

Credit author statement

Thangaraja Jeyaseelan: Supervision, Conceptualisation, Writing - original draft, Methodology. **Tala El Samad**: Supervision, Formal analysis, Methodology, Writing - original draft. **Sundararajan Rajkumar**: Software, Visualisation, Writing - original draft. **Abhay Chatterjee**: Data curation, Investigation. **Jafar Al-Zaili**: Conceptualisation, Writing - original draft, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2023.127021.

Nomenclature

Symbol	Meaning
a, *b*, *c*	Number of molecules
ANN	Artificial neural networks
B	Biodiesel blend
BMEP	Brake mean effective pressure
BP	Mechanical/Brake power
BS	Bharat Stage
bTDC	Before top dead centre
BTE	Brake thermal efficiency
C	Carbon
CA	Crank angle
CN	Carbon neutral
CO	Carbon Monoxide
Comb	Combustion
EI	Energy input
EIC	Energy intensity cost
ELM	Extreme learning machine
em	Emission
EO	Energy output
EP	Energy productivity

(*continued on next page*)

(*continued*)

Symbol	Meaning
eq	Equivalent
F	Objective function
FAME	Fatty acid methyl esters
FC	Fuel cost
FSSAI	Food Safety and Standard Authority of India
GHG	Greenhouse gas
GPE	GHG production emissions
GST	Goods and Services Tax
H	Hydrogen
HDV	Heavy-duty vehicle
HL	High engine load
HRR_{max}	Maximum heat release rate
HS	High rotational speed
HSD	High-speed diesel
LDV	Light-duty vehicle
LL	Low engine load
LS	Low rotational speed
m	Number of atoms
M	Molecular weight
MAPE	Mean absolute percentage error
Max	Maximise
ME	Mechanical work
Min	Minimum or minimise
ML	Medium engine load
MOGA	Multi objective genetic algorithm
MS	Medium rotational speed
MSE	Mean square error
n	Number of objectives
NER	Net energy ratio
NO_x	Nitrogen Oxide
O	Oxygen
Prod	Production
R	Correlation coefficient
R^2	Coefficient of determination
Ref	Reference value
RSM	Response surface methodology
RUCO	Repurpose used cooking oil
SE	Specific energy
SEP	Standard error of prediction
SoA	State-of-the-art
tbd	Tonne of biodiesel
TEI	Total energy intensiveness
UBHC	Unburnt Hydrocarbons
UDC	Urban driving cycle
USD	US dollars
V/V%	Volume ratio
WCO	Waste cooking oil
w	Weight
χ	Biodiesel blend percentage
Δt	Leg duration
Δx	Leg distance
σ	Standard deviation

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