Journal of Heat and Mass Transfer Research 10 (2023), Serial Number 20, 301 – 314

Semnan University

Journal of Heat and Mass Transfer Research

Journal homepage: https://jhmtr.semnan.ac.ir

ISSN: 2383-3068

Research Article

Multi-Parameter Analysis of Low-Capacity C I Engine Powered with Biodiesel from Various Feedstock using Diesel R K Software

Asfakahemad Shekh*, **Kevin Patel**, **Nikul Patel**, **Bhavesh Pathak**

Department of Mechanical Engineering, Faculty of Technology & Engineering, M S University of Baroda, Gujarat, 390001, India.

ARTICLE INFO

Article history:

Received: 2023-08-30

Revised: 2024-01-02

Accepted: 2024-01-02

Keywords:

Diesel engine;

Biodiesel;

Diesel-Rk;

Combustion;

Performance;

Emission.

ABSTRACT

The application of simulation-based software is the current trend in technology to predict the behaviour of complex phenomena. The combustion process and emissions exertion process of internal combustion engines are critical and complex processes. An attempt has been made to conduct a comparative analysis of combustion, performance, and emissions parameters by the application of "Diesel R K software in the current work. A single-cylinder, diesel engine is used here which is powered by different blends of diesel-biodiesel. In this study Soybean, Karanja, and roselle feedstocks are used as biodiesel. A comparative study was conducted on parameters like rise in cylinder pressure, rate of heat release, exhaust gas temperature, BSFC, ITE, and emission parameters like BSN, carbon dioxide, nitrogen oxides, particulate matter, and smoke opacity. As the blend percentage increased, the highest cylinder pressure moved close to the top dead center (TDC). EGT, BSFC increases and ITE slightly decreases as the amount of SME, KB, and LA in blended increase. All of the SME, KB, and LA blends are discovered to emit more NO_x than diesel. SME20, SME100, KB20, KB100, LA20, and LA100 all produced less smoke than diesel fuel by 43.51%, 60.60%, 48.32%, 59.54%, 44.66%, and 62.56%. 852.25 g/kWh respectively. KB100 omits the highest CO_2 emission of all the fuels. LA20 emitted the lowest specific particulate matter emission at 0.058 g.KW/hr. The optimal ratio that offers the finest results in terms of performance and emissions with biodiesel is LA20.

1. Introduction

Observing the industry's and the automotive sector's rapid growth and development, there is a significant need for crude compounds as fuels. The demand per capita for energy usage has increased as a result of economic growth. Mainly conventional fossil fuels are used to match the said demands. According to the US Energy Information Administration [1], Asia's population and economic expansion will be the main causes of a 50% rise in worldwide energy consumption in 2050 compared to 2020. The most often utilized fuels in the transportation industry are diesel and gasoline [2]. 80% of the energy utilized in this sector, which accounts for 25% of global energy consumption, is used for road transportation [1]. This fossil fuels' consumption is to blame for serious environmental problems including global warming and climate change. Due to supply, supply-side constraints, and significant growth in demand for petroleum fuels, fossil fuel prices have abruptly increased in recent years.

* **Corresponding author.**
E-mail address: *shekh_asfakahemad@gtu.edu.in*

Cite this article as:
Shekh, A., Patel, K., Patel, N., Pathak, B., 2023. Multi-Parameter Analysis of Low-Capacity C I Engine Powered with Biodiesel from Various Feedstock using Diesel R K Software. *Journal of Heat and Mass Transfer Research*, 10(2), pp. 301-314.
https://doi.org/10.22075/JHMTR.2024.31637.1471

Moreover, rules for diesel engine emissions for particulate matter and nitrogen oxide become stringent, and serious questions about environmental issues have been raised by carbon dioxide (CO_2) emissions reduction, a greenhouse gas [3,4]. To address these challenges, there has been an increase in interest in cleaner, non-conventional, and renewable energy sources for the transportation sector. Biodiesel is a good alternative to conventional diesel because of its characteristics like the high value of cetane number, oxygen content, and flash point [5,6].

1.1. Biodiesel as an Engine Fuel

Biodiesel, an unconventional renewable fuel that is innocuous and ecological and able to meet engine power needs and lower emissions, is one such alternative to conventional diesel. As a substitute partially for diesel this renewable fuel for diesel cycle engines is considered as green fuel, and biodiesel has drawn a lot of interest. A wide range of materials, including vegetable oil, wastes like used cooking oil, and animal fat, can be used to make biodiesel [7][8][9]. The choice of feedstock and its availability are crucial for the manufacturing of biodiesel [10]. Many oil-bearing plants are acknowledged as potential sources of biodiesel on a global scale [11,12]. According to the feedstocks utilized in its production, biodiesel is often labelled as a first, second, and third generation [13][14][15].

The 1st generation is derived from feedstocks such as food crops and edible oils like soybean, palm, rice bran, peanut, rapeseed, and sunflower. The 2nd generation comprise-edible raw materials such as mahua oil, jojoba oil, castor oil, roselle oil, karanja oil, and roselle oil [16][17]. The 3rd generation is the most recent generation of biodiesel feedstock, and it uses animal fats, algae, and biomass as feedstock.

Nowadays, the majority of bio-oil is made from used cooking oil, which is gathered from restaurants and homes and is a viable raw material for biodiesel extraction due to its widespread availability [18,19]. Biodiesel has several advantages as a renewable, non-toxic, biodegradable fuel that is suitable for sensitive environments. It can cut back on greenhouse gas emissions. It replaces diesel fuel made from petroleum and is usable in the majority of diesel equipment without major modifications [20,21]. Biodiesel is a good alternative to conventional diesel because of its characteristics like the high value of cetane number, oxygen content, and flash point. Moreover, biodiesel is considered to offer a thermal efficiency advantage over diesel fuel [22] [23].

Biodiesel, which has the index "B" can be utilized in pure form (B100). The fuel characteristics, include a higher side cetane numb oxygen-rich content, and a lower side Sulphur content, lead cleaner combustion process, and comparatively low exhaust emission profiles.

1.2. Production of Biodiesel

Many methods, primarily pyrolysis, micro-emulsion, dilution, and transesterification, can be applied to biodiesel production [24]. Out of this widely adopted technique is transesterification, which has a low operating temperature and pressure requirement as well as a faster reaction time. In this method, raw material is chemically combined with OH in the influence of a catalyst like KOH or NaOH to produce esters. This ester is called Biodiesel [25]. Three different types of biodiesel oils —soybean, Karanja, and roselle— are investigated in this study; while soybean is an edible oil, the other two are non-edible oils and were produced through the transesterification process.

1.3. Simulation on CI Engine: a Review

Many researchers have worked on different simulation techniques to set the engine characteristics numerically for available fuel from all three generations of biodiesel [26][27][28]. Annisa Bhikuning [29]conducted a numerical simulation on a 4-stroke mono-cylinder direct injection CI engine powered with three different fuels i.e. diesel fuel, rapeseed methyl ester (RME), and soybean methyl ester (SME). The injection pressures were set in the 940-1730 bar range, and the engine was simulated at 2000 rpm. The outcome of the numerical simulation showed that for RME and SME, specific fuel consumption (SFC), particulate matter (PM), and CO_2 emissions decrease with increasing injection pressure and are largely the same for diesel fuel for different injection pressures. Also concluded that using biodiesel fuel in diesel engines with higher injection pressures can enhance combustion and lower emissions.

Rajak et al. [30] researched to examine the emission characteristics of all three generation biodiesels at the B20 blend level. A diesel engine was numerically simulated and ran at 1500 rpm under various loads using pure diesel and B20 blends of 1st, 2nd and 3rd generations of biodiesel. The engine was then analyzed with the Diesel-RK software package to investigate its emission characteristics. The result showed that reduction in emissions for biodiesel blends compared to diesel fuel emission characteristics as smoke (BSN) reduced by approx. 55% for jojoba, PM by 5% for coconut, 52.0% for jojoba and 7% for fish oil, NO by 38% for jatropha curcas, and SE by 9% for soybean, 13% for jatropha curcas and 9% for spirulina but carbon dioxides were found to be higher by approx. 0.4% for rapeseed, 0.6% for fish oil. With the engine running at 100% power at 1500 rpm, the various blends of B20 showed a reduced emission.

Datta et al. [31] conducted a numerical simulation investigation on compression ignition engines run on biodiesel-alcohol blends as fuels using the commercial software Diesel-Rk. The investigation shows that biodiesel-alcohol blends have marginally higher brake thermal efficiency (BTE) and brake-specific fuel consumption (BSFC) values. When mixing OH separately with biodiesel i.e., 15% ethanol (by vol.) and 15% methanol (by vol.) reduction in NO_x emissions by 30% and 19 was % observed, respectively. Increase in heat release rate, duration in ignition delay and emission value of PM and smoke recorded for biodiesel-alcohol blends.

Nalgundwar et al. [32] carried out a test on a diesel engine using dual biodiesel blends of palm and jatropha under varied load conditions. The test resulted in blends D90PB5JB5 (90% diesel & 5% each biodiesel) exhibiting a slightly reduced BSFC. 20% diesel and 80% biodiesel, or D20JB40PB40, results in an average 15% increase in BTE. Compared to diesel, all biodiesel blends have lower exhaust gas temperatures. Compared to diesel, the biodiesel blend has lower CO emissions overall. The average increase in NO_x emissions above diesel was 5.3% and 9.2% for the lower biodiesel blends D90JB5PB5 and D80JB10PB10, respectively.

Kumbhar et al. [33] conducted a numerical analysis on CI engines powered by 22 varieties of biodiesels (B100) classified as 1st, 2nd and 3rd generation oil using the entire thermodynamic cycle engine analysis tool Diesel-Rk. During four different engine running loads, the engine's all parameters were examined. The biodiesel made from corn oil was shown to have a higher power output, while the biodiesel made from jatropha oil had lower fuel consumption overall. Waste transformer oil biodiesel was shown to have a 9.1% higher in-cylinder peak pressure than diesel, but all other biodiesels had shorter ignition delays than diesel. While CO_2 emissions were decreased by 12%, the NO_x emissions from biodiesel increased by 30–32%.

Pan et al. studied the effect of fuel additives n-butanol and the post-injection of the fuel on the combustion and emission parameters by CONVERGE 2.3 software. The outcome shows an increase in brake thermal efficiency and a decrease in CO through the reaction $CO + OH = CO_2 + H$ [34].

Bambhania et al. studied the behaviour and the magnitude of the generating bubble during the cavitation effect carried out in the fuel nozzle at the time of fuel injection. They also studied the effect of cavitation on the properties of the fuel spray [35].

Kharkeshi et al. carried out a numerical study with AVL fire software. They investigate the effect of change in fuel injection duration. The range of injection duration was kept between 14.6 to 34.6 CA. As an effect of changing the injection duration in-cylinder pressure, the mean effective pressure decreases where specific fuel consumption increases [36].

Al-Dawody et al. [37] conducted a theoretical investigation on direct injection diesel engines run by Soybean Methyl Ester (SME) blends and diesel based on the simulation tool Diesel-RK. According to the calculated results, all biodiesel blends have lower Bosch smoke numbers (BSN) and particulate matter (PM) than diesel. In comparison to diesel, all SME blends have lower thermal efficiency, power, and SFC. The NO_x emissions from all SME blends were observed higher by more than 28%.

Gad et al. investigated the effect of the blend made from 10 to 20% mandarin essential oil, 80 to 90 % diesel and 10 % propanol by volume. Also studied was the combined effect of EGR. The outcome of the experiment was cylinder pressure and HRR decreased by 3% and 2.5% respectively. Also, a reduction in BSFC was found by 5% & 22% for MO10 (10% Mandarin 90% diesel) and MO20 (20% Mandarin 80% diesel) [38].

Due to the engine's fuel consumption, technical requirements, and labour costs, experimental testing of the engine requires significant time and costs more money. The purpose of the present study is to evaluate the performance, combustion, and emission characteristics of compression ignition engines running on diesel and biodiesel (B100) and their blends. The engine properties are analyzed using Diesel-RK, a numerical tool for full thermodynamic engine analysis. Engine characteristics for biodiesel and diesel like indicated thermal efficiency, brake specific fuel consumption, maximum cylinder pressure, exhaust gas temperature, BSN, NO_x and CO_2 emissions, and soot emission were examined here in this study.

2. Simulation Method and Material

2.1. Diesel Rk Software Model

Internal combustion engine calculations and optimization can be done on the Diesel-RK software package. This software can accurately and professionally simulate an entire thermodynamic cycle engine. This software package provides a tool for multi-parameter optimization. It has an advanced modelling tool for mixture production and combustion. The diesel spray model along with the multi-zone model applied here accounts for the shape and other injection parameters like profile, split injection, drop sizes, the direction of each spray in the combustion chamber, and the intensity of the swirl [39][40]. As a tool, the Diesel-RK software offers a virtual environment for carrying out a variety of trials and combinations for the simulations utilizing different parameters and with different fuels. To improve combustion, performance, and low NO_x and smoke emissions, DIESEL-RK has also been capable of optimization, including the crown piston shape and fuel injection system optimization [41].

Following are the governing equations that have been used by Diesel R K software.

Mass conservation

$$\frac{dm}{dt} = \Sigma_j \dot{m}_j \tag{1}$$

Conservation Equation for Species

$$Y_i = \sum_j \left(\frac{\dot{m}_j}{m}\right)\left(Y_i^j - Y_i^{cyl}\right) + \frac{\Omega_i w_{mw}}{\rho} \tag{2}$$

Energy Conservation

$$\frac{d(mu)}{dt} = -p\frac{dv}{dt} + \frac{dQ_{ht}}{dt} + \sum_j \grave{m}_j h_j \tag{3}$$

Equivalence Ratio

$$\alpha_1 = \frac{\left(\frac{A}{F}\right)}{\left(\frac{A}{F}\right)_s} = \frac{(\dot{m}_a/\dot{m}_f)}{(\dot{m}_a/\dot{m}_f)_s} \tag{4}$$

Frictional Mean Effective Pressure

$$FMEP = \alpha + \beta P_{max} + \gamma V_p \tag{5}$$

Specific Fuel Consumption

$$SFC = \frac{\dot{m}_f}{P_b} \tag{6}$$

Heat Release Rate

1) Ignition delay period

2) $$\tau = 3.8 * 10^{-6}(1 - 1.6 * 10^{-4}.n)\sqrt{\frac{T}{P}} * exp\left(\frac{E_a}{8.312T} - \frac{70}{CN+25}\right) \tag{7}$$

3) Premixed combustion phase

$$\frac{dx}{d\tau} = \Phi_0 * \left(A_0\left(\frac{m_f}{v_i}\right) * (\sigma_{ud} - x_0) * (0.1 * \sigma_{ud} + x_0)\right) + \Phi_1 * \left(\frac{d\sigma_{ud}}{d\tau}\right) \tag{8}$$

4) Mixing-controlled combustion phase

$$\frac{dx}{d\tau} = \Phi_1 * \left(\frac{d\sigma_u}{d\tau}\right) + \Phi_2\left(A_2\left(\frac{m_f}{v_c}\right) * (\sigma_u - x) * (\alpha - x)\right) \tag{9}$$

5) Late combustion phase

$$\frac{dx}{d\tau} = \Phi_3 A_3 K_T (1 - x)(\xi_b \alpha - x) \tag{10}$$

NO_x formation: The basic main equation is

$$N + O_2 \longleftrightarrow NO + O \tag{11}$$

The volume concentration of NO in combustion products is

$$\frac{d[NO]}{d\theta} = \frac{p.2.333{*}10^7.e^{-\frac{38020}{Tz}}[N_2]_e[o]_e\{1 - ([NO]/[NO])^2\}}{RTz\left(1 + \frac{2365}{Tz}.e^{\frac{3365}{Tz}}.\frac{[NO]}{[O_2]}\right)} * \frac{1}{rps} \tag{12}$$

- Exhaust soot Concentration model:

  Exhaust soot concentration

$$[C]_H = \int_{\theta_B}^{480} \frac{d[C]}{dt}.\frac{d\theta}{6\eta}\left(\frac{0.1}{p}\right)^y \tag{13}$$

The Hartridge smoke level Hartridge = 100[1-0.9545 exp(-2.4226[C])]

Particulate Matter Emission

$$[PM] = 565\left(\ln\frac{10}{10 - Bosch}\right)^{1.206} \tag{14}$$

2.2. Material

In this simulation base study, four different fuel types are used of which one is diesel and the other three are biodiesel. One of the biodiesels is soybean oil, an edible oil. Other biodiesel include non-edible oils like Karanja and Roselle [42]. Roselle (Hibiscus sabdariffa) is an annual, erect shrub botanical plant belonging to the Malvaceae family [43]. Diesel, SME100 (Soybean Methyl Ester), SME20, KB100 (Karanja Methyl Ester), KB20, and LA100 (Roselle Methyl Ester), LA20 were the seven fuels examined in this study. A Semiautomatic Digital Bomb Calorimeter was used to find out the calorific value following the IS1350-1966, IP 12/63T standard. A kinematic Viscosity Bath was used to identify the viscosity of the fuels by following ASTM D 445 standards. The transesterification process is carried out using 3 3-neck heating flask, a funnel separator, and a stirrer. the ASTM 6751 was followed for the process of transesterification. Table 1 provides information on the characteristics of diesel, different biodiesels, and their blends [44][45][46][47].

2.2.1. Engine Specification

A mono-cylinder, direct injection profile, and liquid-cooled CI engine were used for the theoretical investigation. Table 1 shows the engine's specifications.

Table 1. Specification of the engine

Engine Specifications	
Manufactured by	Kirloskar TAF-1
Engine stroke and injection profile	4-stroke, DICI engine
Cylinder	1
Bore and Stroke dimensions	87.5 mm × 100 mm
Capacity	0.66 L
Compression ratio	17.5
Rated power output	3.5 kW, 1500 rpm
Injection timing of fuel	23.5° bTDC
Injection Pressure	220 bar
Cooling System	Water Cooling

3. Result and Discussion

In the present study observations were recorded and a further comparison-based investigation was carried out on the combustion, performance and exhaust emissions parameters of fuels i.e., diesel, SME20, SME100, KB20, KB100, LA20 and LA100. Table 2 shows fuel properties of all the blends. These fuels have undergone testing with a full load (100%) condition.

3.1. Combustion Parameter

3.1.1. Cylinder Pressure

The cylinder pressure is affected by the fuel burning rate in the diesel engine's premixed burning phase. The resultant high pressure in the cylinder is produced by proper combustion and a decent heat release rate. For diesel and blends of SME, KB, and LA, Fig. 1 shows the comparison between the simulation results and experimental results of cylinder pressure obtained for SB20 [48]. The maximum cylinder pressure from the simulation is 93.41 bar and the maximum cylinder pressure from the experimental evaluation is 84 bar. The error occurred around 9% which is within range. Fig. 2 indicates the change of cylinder pressure with the change in crank angle at full load and 1500 rpm crank speed. Due to the drastic reduction in heat supply value for the blends, it can be seen that the cylinder pressure for all blends is lower compared to Diesel [49][50]. It should be noted that the highest pressure obtained for diesel, SME20, SME100, KB20, KB100, LA20, and LA100 are 96.38, 93.41, 82.55, 94.85, 84.19, 95.61, and 84.40 bars respectively. The maximum pressure P_{max} of 96.38 bar is discovered for Diesel at a crank.

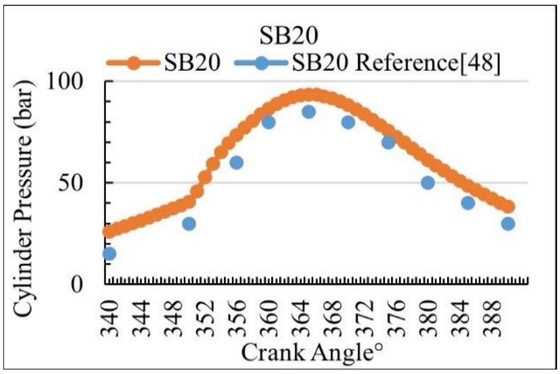

Fig. 1. Compression of simulation Vs Experimental Results for Cylinder Pressure

Table 2. Properties of Diesel and Blends of SME, KB and LA

	Diesel-Biodiesel Blend						
Property	Diesel	SME20	SME100	KB20	KB100	LA20	LA100
Mass composition of Fuel							
C %	87	85	77.3	84.1	77.96	84	78.71
H %	12.6	12.4	12.0	13.5	13.05	13.49	12.12
O %	0.4	2.6	10.8	2.19	8.97	2.25	9.23
Cetane Number	48	48.69	51.3	48.83	57.6	48.5	52.2
Density (kg/m^3)	830	841	876	854.4	891	838	878
LHV (MJ/kg)	42.5	41.28	36.12	41.79	38.91	41.6	38.78
Viscosity (mm^2/s)	3.0	3.34	4.63	3.18	4.86	3.2	4.6

3.1.2. Heat Release Rate

The trend of heat release rate versus crank angle for all tested fuels at 1500 rpm and at full load is shown in Fig. 2. It can be seen that as blends of SME, KB, and LA biodiesel are increased, the value of heat release rate decreases. This graph clearly shows that biodiesel blends had a slower rate of combustion but an earlier start of combustion. The early injection timing and shorter delay in ignition led to an early combustion phenomenon.

The lower amount of released energy in the premixed phase and the lower volatility of biodiesel are due to the slower premixed combustion rate. The SME, KB, and LA biodiesel fuel blends burned rapidly during the diffusion phase because this is when the majority of the fuel is vaporized [48][50][49].

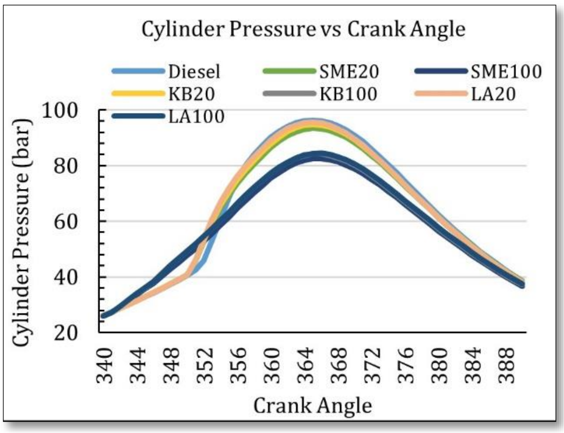

Fig. 2. Variation of cylinder pressure with crank angle

3.1.3. Exhaust Gas Temperature

Fig. 3 shows the relation between the variation in exhaust side temperature of gas and crank angle for diesel and blends of SME, KB, and LA biodiesel at full load.

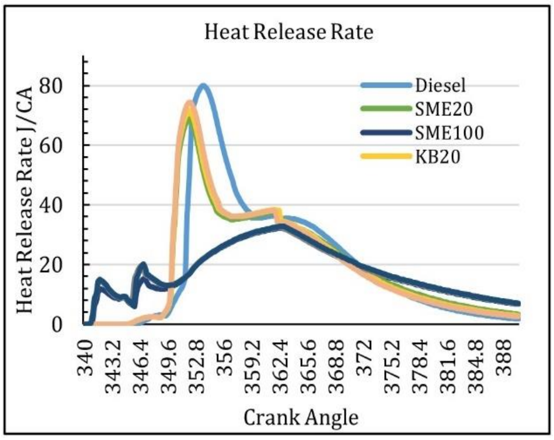

Fig. 3. Heat Release Rate with crank angle

The graphs show that the temperature variance has having same behaviour for all tested fuels, including diesel and blends of SME, KB, and LA biodiesel. LA100 was found to have the highest exhaust gas temperature amongst all seven tested fuels, at 798.2°C at a 532° crank angle. This is because LA100 has superior combustion. After all, it contains more oxygen than the other fuels tested here. The same outcome was also observed by another researcher [51][48][50][49], who found that blends of biodiesel had slightly higher exhaust gas temperatures due to their shorter combustion durations than diesel fuel.

3.2. Performance Parameter

Under full load conditions and at 1500 engine speed the brake-specific fuel consumption (BSFC) and indicated thermal efficiency (ITE) was measured for all types of fuels to better understand how these fuels affect engine performance.

3.2.1. Brake-Specific Fuel Consumption

It is referred to as the quantity of fuel parts used to produce one unit of power. It usually gives an essence of how effectively fuel is utilized by an engine to rotate the power shaft. The trend of brake-specific fuel consumption (BSFC) for the different tested fuels, including Diesel, SME20, SME100, KB20, KB100, LA20, and LA100, is shown in Fig. 4.

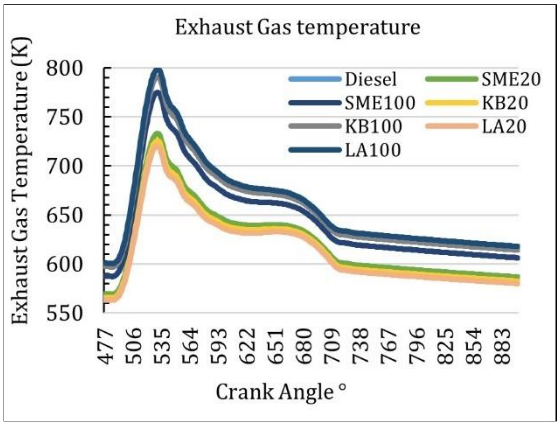

Fig. 4. Variation in exhaust manifold temperature versus crank angle

The graph shows that BSFC is higher for all blends of SME, KB, and LA biodiesel and lower for diesel fuel. The BSFC also rose while the blending ratio increased. The lower heating value of biodiesel leads to a much higher BSFC than diesel [50][49][48].

3.2.2. Indicated Thermal Efficiency

It is termed as the ratio of power developed inside the cylinder and heat energy liberated by fuel i.e. Fuel Power during a specified period. The variation in thermal efficiency with diesel and blends of SME, KB, and LA biodiesel is shown in Fig. 6. It can be seen that ITE reduces as the mixing ratio of SME, KB, and LA biodiesel rises. The thermal efficiency of SME100, KB100, and LA100 is recorded, respectively, as 2.95%, 3.44%, and 3.47% lower than diesel. This is because methyl ester has a lower heating value than diesel fuel [48][49][50].

The average ITE value and ITE change as a percentage for diesel and blends of SME, KB, and LA biodiesel are shown in Table 3.

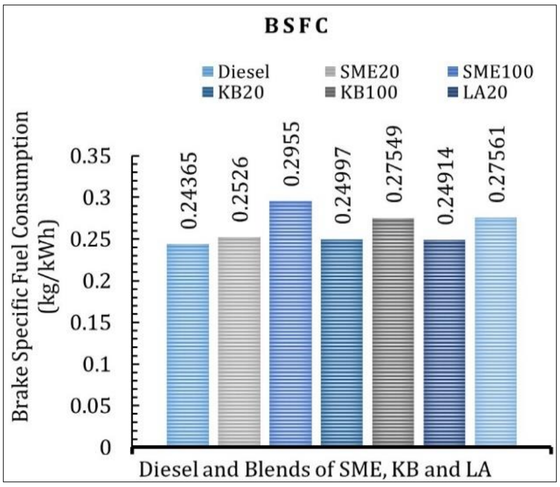

Fig. 5. Brake Specific Fuel Consumption for Diesel and Blends of SME, KB and LA

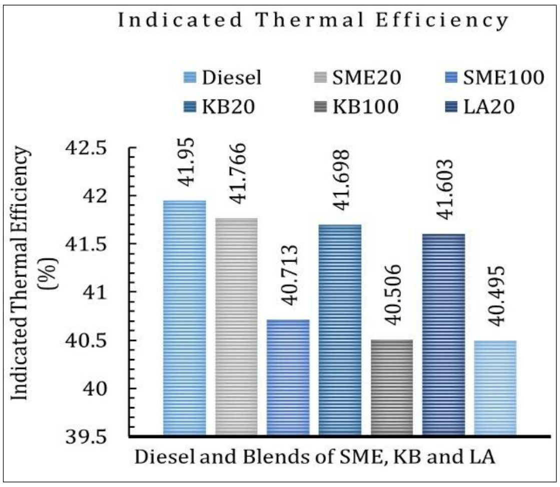

Fig. 6. Indicated thermal efficiency for Diesel and Blends of SME, KB and LA

Table 3. Average value of ITE and percentage change in ITE.

Fuel Type	ITE (%)	% Changes In ITE
Diesel	41.95	-
Sme20	41.766	-0.44
Sme100	40.713	-2.95
Kb20	41.698	-0.60
Kb100	40.506	-3.44
La20	41.603	-0.83
La100	40.495	-3.47

3.3. Emission Parameter

Under full load conditions and at 1500 engine speed to understand the effect on emission factors, Bosch Smoke Number (BSN), specific carbon dioxide (CO_2), Specific Particulate Matter (PM), Nitrogen Oxides (NO_x) and Soot concentration were calculated.

3.3.1. Bosch Smoke Number (BSN)

The Bosch Smoke Number for diesel and blends of SME, KB, and LA biodiesel are shown in Fig. 6. All biodiesel blends have a lower smoke level (BSN) than diesel fuel.

SME20, SME100, KB20, KB100, LA20, and LA100 all produced less smoke than diesel fuel by 43.51%, 60.60%, 48.32%, 59.54%, 44.66%, and 62.56% respectively. This is mostly due to the following factors:

1) Smoke lowers at higher oxygen concentration in the biodiesel, which helps to get accurate fuel oxidation; hence, oxygen inside the fuel decreases a fuel's tendency to form soot [52].
2) Lower C/H ratio in biodiesel tends to have less smoke volume [53].
   Bosch smoke number for SME100, KB100, and LA100 was found to be reduced by 60.60%, 59.54%, and 62.54%, respectively, as compared to Diesel fuel. LA100 has the lowest Bosch smoke number (2.452) out of all the tested fuels.

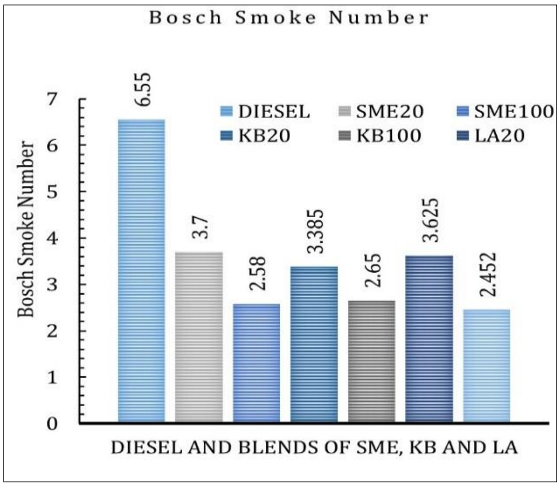

Fig. 7. Bosch Smoke Number for Diesel and blends of SME, KB and LA biodiesel

3.3.2. Specific CO_2 Emission

Specific CO_2 emissions trends for diesel and other blends are depicted in Fig. 7. Compared to the other tested fuels, biodiesel and its blends had the highest CO_2 emissions. Because biodiesel has oxygen in its molecular structure and is burned at a higher temperature than diesel fuel, the oxidation process is enhanced [54]. As a result, the CO_2 emission is higher when using biodiesel. Diesel, SME20, SME100, KB20, KB100, LA20, and LA100 had specific CO_2 emissions of 785.1, 794.85, 846.13, 798.45, 852.25, 803.75, and 836.45 g/kWh, respectively. 852.25 gkWh for KB100 is the fuel with the highest specific CO_2 emission of all the tested fuels.

3.3.3. Specific Particulate Matter Emission

Fig. 8 depicts Specific particulate matter for Diesel and blends of SME, KB and LA. Various parameters like oxygen density, load, speed, fuel injection timing, and air-fuel mixing rate have an impact on PM emission. The combustion chamber's PM emissions were caused by improper combustion. Lower PM emission is caused by high combustion flame temperature, oxygen percentage, speed, and load [55]. When compared to diesel, it has been discovered that all blends of biodiesel have a very good reduction in particulate matter.

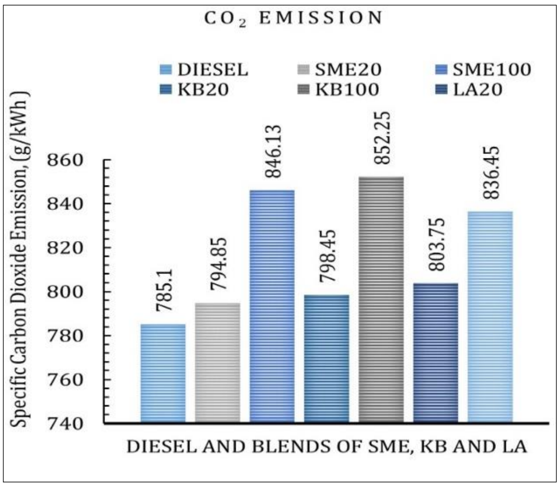

Fig. 8. Specific CO_2 emission for Diesel and blends of SME, KB and LA biodiesel

For SME20, SME100, KB20, KB100, LA20, and LA100, the numerical reduction (percentage-wise) in the emission of particular particulate matter is 48.41%, 65.71, 43.65%, 58.49%, 66.67%, and 53.97%, respectively. The LA20 fuel has been shown to emit 0.058 g.KW/hr which is the least amount of particular particulate matter of any of the tested fuels.

3.3.4. NO_x Emission

The behaviour of NO_x emission versus all the tested fuels is shown in Fig. 9. The NO_x emission has been found considerably higher for all blends of biodiesel. This is due to the biodiesel's higher oxygen content and viscosity, as the fuel's oxygen may contribute more oxygen to the formation of NO_x The primary causes of the rise in NO_x emission are the higher In-cylinder pressure and temperature produced by the early start of the combustion process. With biodiesel, the temperature rise during combustion is at its highest, which increases the formation of NO_x [48][49][50]. Diesel, SME20, SME100, KB20, KB100, LA20, and LA100 each have NO_x emission values of 1075, 1478, 2370, 1560, 2480, 1395, and 2320 ppm, respectively. Pure biodiesel emits twice as much NO_x than regular diesel fuel.

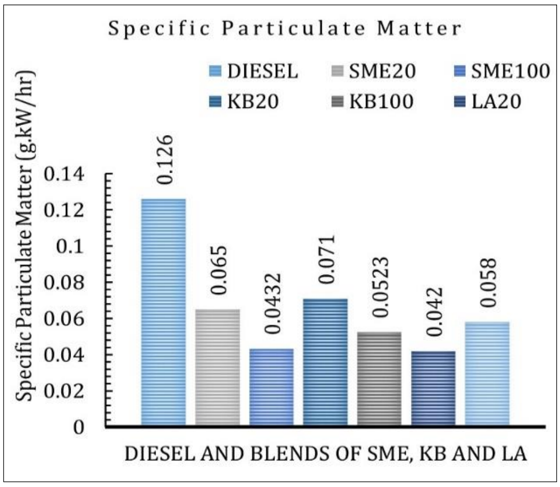

Fig. 9. Specific particulate matter for Diesel and blends of SME, KB and LA biodiesel

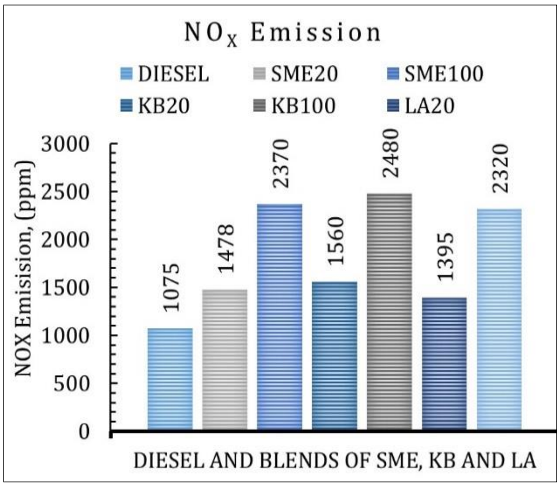

Fig. 10. NO_X emission for diesel and blends of SME, KB and LA biodiesel

3.3.5. Soot Concentration

The concentration of soot in cylinder Diesel and blends of SME, KB, and LA is shown in Fig. 10. A soot carried by the vapour is usually a fine dispersed black carbon particle. The incomplete combustion of hydrocarbons is the main cause of soot. Combustion-related chemical reactions result in soot particle formation, growth, and oxidation. It has been shown that all blends of fuel have lower soot concentrations than diesel fuel. When compared to diesel fuel, the soot concentration in cylinders SME20, SME100, KB20, KB100, LA20, and LA100 is reduced by 17.79%, 51.04%, 15.31%, 52.88%, 12.34%, and 53.07%, respectively.

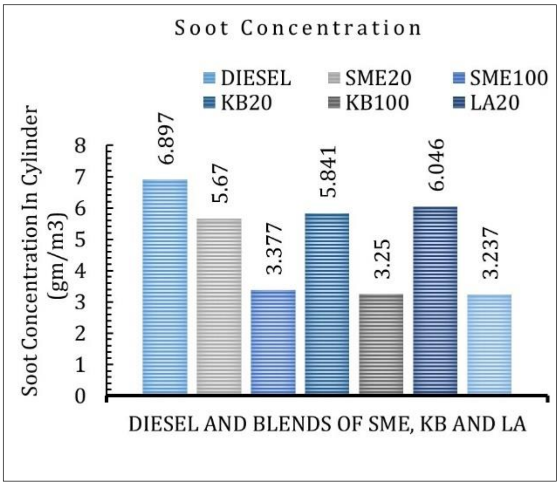

Fig. 11. Soot concentration in the cylinder for diesel and blends of SME, KB and LA biodiesel

4. Conclusions

The purpose of this simulation-based study was to investigate the effect of biodiesel and its blends on the combustion, performance, and emissions characteristics of CI engines which are conventionally powered by diesel. The simulation-based results of this study were carried out from diesel-RK software which provides the following conclusion.

- For all biodiesel and its blends, the maximum pressure in the cylinder is found to shift closer to the TDC which is marginally lower than diesel fuel.
- By comparing the cylinder pressure data of SB20 measured through simulation with the experimentation data, an error occurred around 9% which is within range thus it validates the performance of simulation software for the analysis of the CI engine.
- One of the important factors i.e., heat release rate for all three types of biodiesels (SME, KB, and LA) found to decrease as the blends increased due to an early combustion start and a slower premixed combustion rate.
- Exhaust Gas Temperature (EGT) increases due to the more oxygen content in biodiesel leading to better quality of combustion compared to that of diesel.
- The role of more oxygen content in biodiesel was also observed in a dramatic reduction in BSN and PM with all biodiesel blends when compared to diesel. Oxygen richness improves in complete fuel oxidation and combustion.
- The adverse effect observed as the mixing ratio of all the biodiesel increases, the BSFC increases and indicated thermal efficiency (ITE) decreases. This measurable effect is caused by to lower heating value of biodiesel and its blends.
- Higher combustion-side pressure and temperature value cause early combustion in blends of biodiesel that leads to an increased higher NO_x value in emission for all biodiesel blends, including SME, KB, and LA compared to diesel.
- B 20 of LA was found to be best amongst other blends of LA, KB and SME. B 20 of LA executes lower emissions as compared to Diesel, and provides promising performance results.

Nomenclature

°C	Degree Centigrade
°CA	Crank Angle Degree
BSFC	Brake Specific Fuel Consumption (G/Kwh)
BSN	Bosch Smoke Number
C	Carbon
CN	Cetane Number of Fuel
DF	Diesel Fuel
E_a	Apparent Activation Energy for The Auto Ignition Process (23000...28000 Kj/Kmole)
H	Hydrocarbon
K	Evaporation Constant
NO_x	Nitrogen Oxides
Nu_D	Nusselt Number
p	Pressure In the Cylinder (Pa)
PM	Particulate Matter
p_s	Saturation Pressure of The Fuel Vapour (Pa)
R	Universal Gas Constant (8.3143)
rps	Revolutions Per Second

SME	Soybean Methyl Ester
KB	Karanja Biodiesel
LA	Roselle Biodiesel
SME20	Blend Containing 80 Percent of Diesel Oil And 20 Percent SME
SME100	Blend Containing 0 Percent of Diesel Oil And 100 Per Cent of SME (Pure SME)
KB20	Blend Containing 80 Percent of Diesel Oil And 20 Percent KB
KB100	Blend Containing 0 Percent of Diesel Oil And 100 Per Cent of KB (Pure KB)
LA20	Blend Containing 80 Percent of Diesel Oil And 20 Percent LA
LA100	Blend Containing 0 Percent of Diesel Oil And 100 Per Cent of LA (Pure LA)
T	Temperature In the Cylinder (K)
TDC	Top Dead Centre
x	Fraction of Heat Release
x_0	Fraction of The Fuel Vapor Formed During Ignition Delay and Burnt Out
σ	Fraction of The Fuel Injected into The Cylinder
σ_u	Fraction of The Vapor Formed During the Ignition Period
τ	Ignition Delay (S)
θ	Crank Angle (°C)
ϕ	Equivalence Ratio
Φ	Function For Description of The Completion of Combustion
γ	Adiabatic Exponent of Exhaust Gas
ξ_b	Efficiency of Air Used

Acknowledgements

The authors of this research article neither received nor applied for any of the grants from any of the funding agencies.

Conflicts of 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.

Authors Contribution

A Shekh: wrote the first version of the manuscript; contribute to the simulation; K Patel: contributed to simulation & editing. N Patel: supervision; reviewed and edited, contributed to answering comments. B Pathak contributed to simulation & editing.

References

[1] U. Energy Information Administration, “IEO 2021 Narrative.” [Online]. Available: www.eia.gov.

[2] Covert, T., Greenstone, M. and Knittel, C.R., 2016. Will we ever stop using fossil fuels?. *Journal of Economic Perspectives*, 30(1), pp.117-138. doi: 10.1257/jep.30.1.117.

[3] Özener, O., Yüksek, L., Ergenç, A.T. and Özkan, M., 2014. Effects of soybean biodiesel on a DI diesel engine performance, emission and combustion characteristics. *Fuel*, 115, pp. 875-883. doi: 10.1016/j.fuel.2012.10.081.

[4] Yoon, S.H. and Lee, C.S., 2011. Experimental investigation on the combustion and exhaust emission characteristics of biogas–biodiesel dual-fuel combustion in a CI engine. Fuel processing technology, 92(5), pp. 992-1000. doi: 10.1016/j.fuproc.2010.12.021.

[5] Dubey, A., Prasad, R.S. and Singh, J.K., 2020. An analytical and economical assessment of the waste cooking oil based biodiesel using optimized conditions on the process variables. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp. 1-16. doi: 10.1080/15567036.2020.1839600.

[6] A. K. T, M. Musthafa M, C. R, T. K. Kandavel, T. Mohan raj, and S. G, 2022. Performance characteristics of a variable compression ratio CI engine simulation using artificial neural network. *Energy Sources, Part A*

Recover. Util. Environ. Eff., vol. 44, no. 1, pp. 1912–1922. doi: 10.1080/15567036.2019.1648595.

[7] Olkiewicz, M., Torres, C.M., Jiménez, L., Font, J. and Bengoa, C., 2016. Scale-up and economic analysis of biodiesel production from municipal primary sewage sludge. *Bioresource technology*, *214*, pp.122-131. doi: 10.1016/j.biortech.2016.04.098.

[8] de Araújo, C.D.M., de Andrade, C.C., e Silva, E.D.S. and Dupas, F.A., 2013. Biodiesel production from used cooking oil: A review. *Renewable and sustainable energy reviews*, *27*, pp. 445-452. doi: 10.1016/j.rser.2013.06.014.

[9] Jayaraman, J., Alagu, K., Venu, H., Appavu, P., Joy, N., Jayaram, P. and Mariadhas, A., 2023. Enzymatic production of rice bran biodiesel and testing of its diesel blends in a four-stroke CI engine. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, *45*(2), pp. 5340-5351. doi: 10.1080/15567036.2019.1671554.

[10] Chen, H., He, J., Chen, Y. and Hua, H., 2018. Performance of a common rail diesel engine using biodiesel of waste cooking oil and gasoline blend. *Journal of the Energy Institute*, *91*(6), pp. 856-866. doi: 10.1016/j.joei.2017.10.003.

[11] Srinidhi, C., Jawale, M., Utikar, V., Jadhav, S., Acharya, M., Arakerimath, R., Hole, J.A. and Channapattana, S.V., 2022. A comparative performance and emission investigation CI engine fuelled with neem oil esters with varying engine compression ratios. *Heat Transfer*, *51*(8), pp.7990-8004. doi: https://doi.org/10.1002/htj.22677.

[12] Atabani, A.E., Silitonga, A.S., Badruddin, I.A., Mahlia, T.M.I., Masjuki, H. and Mekhilef, S., 2012. A comprehensive review on biodiesel as an alternative energy resource and its characteristics. *Renewable and sustainable energy reviews*, *16*(4), pp. 2070-2093. doi: 10.1016/j.rser.2012.01.003.

[13] Naik, S.N., Goud, V.V., Rout, P.K. and Dalai, A.K., 2010. Production of first and second generation biofuels: a comprehensive review. *Renewable and sustainable energy reviews*, *14*(2), pp. 578-597. doi: 10.1016/j.rser.2009.10.003.

[14] Trabelsi, A.B.H., Zaafouri, K., Baghdadi, W., Naoui, S. and Ouerghi, A., 2018. Second generation biofuels production from waste cooking oil via pyrolysis process. *Renewable energy*, *126*, pp. 888-896. doi: 10.1016/j.renene.2018.04.002.

[15] Nautiyal, P., Subramanian, K.A. and Dastidar, M.G., 2014. Production and characterization of biodiesel from algae. *Fuel Processing Technology*, *120*, pp. 79-88. doi: 10.1016/j.fuproc.2013.12.003.

[16] Patel, N., Bambhania, M. P., Kachhadiya, P. R. and Patel, N. K., 2019. Design and development of small scale Biodiesel production unit. I*nternational Journal of Fluid and Thermal Engineering Design and development of small scale biodiesel production unit,* vol. 4, no. July, 2019, [Online]. Available: https://www.researchgate.net/publication/337945379.

[17] Gavhane, R.S., Kate, A.M., Pawar, A., Soudagar, M.E.M. and Fayaz, H., 2020. Effect of soybean biodiesel and copper coated zinc oxide nanoparticles on enhancement of diesel engine characteristics. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp.1-19. doi: 10.1080/15567036.2020.1856237.

[18] Chatur, M.G., Maheshwari, A. and Campli, S., 2023. Investigation of waste cooking oil–diesel blend with copper oxide additives as fuel for diesel engine under variations in compression ratio. *International Journal of Energy and Environmental Engineering*, *14*(4), pp.791-802. doi: 10.1007/s40095-022-00549-7.

[19] Srinidhi, C., Kshirsagar, P., Joshi, M., Kulkarni, A., Channapattana, S.V., Madhusudan, A., Aithal, K. and Gawali, S., 2022. Effect of fuel injection timing on CI engine fuelled with neem biodiesel blends–a comparative study of experimental and numerical simulation. *International Journal*

of Energy and Environmental Engineering, 13, pp. 395-406. doi: 10.1007/s40095-021-00429-6.

[20] Channapattana, S.V., Campli, S., Madhusudhan, A., Notla, S., Arkerimath, R. and Tripathi, M.K., 2023. Energy analysis of DI-CI engine with nickel oxide nanoparticle added azadirachta indica biofuel at different static injection timing based on exergy. *Energy*, *267*, p.126622. doi: https://doi.org/10.1016/j.energy.2023.126622.

[21] Mishra, V.K. and Goswami, R., 2018. A review of production, properties and advantages of biodiesel. *Biofuels*, *9*(2), pp.273-289. doi: 10.1080/17597269.2017.1336350.

[22] Mirhashemi, F.S. and Sadrnia, H., 2020. NOX emissions of compression ignition engines fueled with various biodiesel blends: A review. *Journal of the Energy Institute*, *93*(1), pp. 129-151. doi: 10.1016/j.joei.2019.04.003.

[23] Gautam, A. and Agarwal, A.K., 2015. Determination of important biodiesel properties based on fuel temperature correlations for application in a locomotive engine. *Fuel*, *142*, pp.289-302.doi: 10.1016/j.fuel.2014.10.032.

[24] Patel, N.K. and Shah, S.N., 2015. Biodiesel from plant oils. In *Food, energy, and water* (pp. 277-307). Elsevier.

[25] Salaheldeen, M., Aroua, M.K., Mariod, A.A., Cheng, S.F., Abdelrahman, M.A. and Atabani, A.E., 2015. Physicochemical characterization and thermal behavior of biodiesel and biodiesel–diesel blends derived from crude Moringa peregrina seed oil. *Energy Conversion and Management*, *92*, pp.535-542. doi: 10.1016/j.enconman.2014.12.087.

[26] Godiño, J.A.V., Aguilar, F.J.J.E. and García, M.T., 2018. Simulation of HCCI combustion in air-cooled off-road engines fuelled with diesel and biodiesel. *Journal of the Energy Institute*, *91*(4), pp.549-562. doi: 10.1016/j.joei.2017.04.002.

[27] Pambudi, N.A., Laukkanen, T., Syamsiro, M. and Gandidi, I.M., 2017. Simulation of Jatropha curcas shell in gasifier for synthesis gas and hydrogen production. *Journal of the Energy Institute*, *90*(5), pp.672-679. doi: 10.1016/j.joei.2016.07.010.

[28] Shen, J., Li, F., Li, Z., Wang, H., Shen, Y. and Liu, Z., 2019. Numerical investigation of air-staged combustion to reduce NOX emissions from biodiesel combustion in industrial furnaces. *Journal of the Energy Institute*, *92*(3), pp. 704-716. doi: 10.1016/j.joei.2018.03.002.

[29] Bhikuning, A., 2021. The simulation of performance and emissions from rapeseed and soybean methyl ester in different injection pressures. *Automotive Experiences*, *4*(3), pp.112-118. doi: 10.31603/ae.4682.

[30] Rajak, U., Nashine, P., Verma, T.N. and Pugazhendhi, A., 2019. Performance, combustion and emission analysis of microalgae Spirulina in a common rail direct injection diesel engine. *Fuel*, *255*, p.115855. doi: 10.1016/j.fuel.2019.115855.

[31] Datta, A. and Mandal, B.K., 2017. Engine performance, combustion and emission characteristics of a compression ignition engine operating on different biodiesel-alcohol blends. *Energy*, *125*, pp.470-483. doi: 10.1016/j.energy.2017.02.110.

[32] Nalgundwar, A., Paul, B. and Sharma, S.K., 2016. Comparison of performance and emissions characteristics of DI CI engine fueled with dual biodiesel blends of palm and jatropha. *Fuel*, *173*, pp. 172-179. doi: 10.1016/j.fuel.2016.01.022.

[33] Kumbhar, V.S., Pandey, A., Varghese, A. and Patil, V., 2021. Comparative assessment of performance, combustion, and emission of compression ignition engine fuelled with different generations of biodiesel. *International Journal of Sustainable Engineering*, *14*(6), pp.2082-2096. doi: 10.1080/19397038.2021.1943043.

[34] Pan, M., Wang, Y., Qian, W., Wu, C., Huang, H., Li, H. and Zhou, X., 2021. Experimental and numerical study on flow, combustion and emission characteristics of CI engine fueled with n-butanol/diesel blends under post-injection strategy. *Fuel*, *292*, p.120267. doi: 10.1016/j.fuel.2021.120267.

[35] Bambhania, M.P. and Patel, N.K., 2023. Hydrodynamic cavitation in the fuel injector nozzle and its effect on spray characteristics: A Review. *Journal of Heat and Mass Transfer Research*, *10*(1), pp.1-20. doi: 10.22075/jhmtr.2023.29165.1406.

[36] Alizadeh Kharkeshi, B., Shafaghat, R., Mohebi, M., Talesh Amiri, S. and Mehrabiyan, M., 2021. Numerical simulation of a heavy-duty diesel engine to evaluate the effect of fuel injection duration on engine performance and emission. *International Journal of Engineering*, *34*(11), pp. 2442-2451. doi: 10.5829/IJE.2021.34.11B.08.

[37] Al-Dawody, M.F. and Bhatti, S.K., 2011. Effect of soybean oil biofuel blending on the performance and emissions of Diesel engine using diesel-rk software. *International journal of engineering science and technology*, *3*(6), pp.4539-4555.

[38] Gad, M.S., He, Z., El-Shafay, A.S. and EL-Seesy, A.I., 2021. Combustion characteristics of a diesel engine running with Mandarin essential oil-diesel mixtures and propanol additive under different exhaust gas recirculation: Experimental investigation and numerical simulation. *Case Studies in Thermal Engineering*, *26*, p.101100. doi: 10.1016/j.csite.2021.101100.

[39] Kuleshov, A. and Mahkamov, K., 2008. Multi-zone diesel fuel spray combustion model for the simulation of a diesel engine running on biofuel. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy*, *222*(3), pp.309-321. doi: 10.1243/09576509JPE530.

[40] Kuleshov, A.S., 2006. *Use of multi-zone DI diesel spray combustion model for simulation and optimization of performance and emissions of engines with multiple injection* (No. 2006-01-1385). SAE Technical Paper.

[41] Sonkar, S.K., Mishra, P. and Baredar, P.V., 2020. A Simulation Based Study on Diesel Engine Using Different Ecofriendly Biodiesel Blends of Cotton Seed Oil and Tallow Oil in Diesel-RK Software. *Journal of Green Engineering*, *10*, pp.5350-5364.

[42] Scott, P.T., Pregelj, L., Chen, N., Hadler, J.S., Djordjevic, M.A. and Gresshoff, P.M., 2008. Pongamia pinnata: an untapped resource for the biofuels industry of the future. *Bioenergy Research*, *1*, pp.2-11. doi: 10.1007/s12155-008-9003-0.

[43] Nguyen, T.A., Maeda, Y., Kuroda, K. and Otsuka, K., 2017. Inclusive impact assessment for the sustainability of vegetable oil-based biodiesel-Part II: Sustainability assessment of inedible vegetable oil-based biodiesel in Ha Long Bay, Vietnam. *Journal of Cleaner Production*, *168*, pp.173-188. doi: 10.1016/j.jclepro.2017.08.238.

[44] Patel, N.K., Nagar, P.S. and Shah, S.N., 2013. Identification of non-edible seeds as potential feedstock for the production and application of bio-diesel. *Energy and power*, *3*(4), pp.67-78. doi: 10.5923/j.ep.20130304.05.

[45] Ramadhas, A.S., Muraleedharan, C. and Jayaraj, S., 2005. Performance and emission evaluation of a diesel engine fueled with methyl esters of rubber seed oil. *Renewable energy*, *30*(12), pp.1789-1800. doi: 10.1016/j.renene.2005.01.009.

[46] Haas, M.J., McAloon, A.J., Yee, W.C. and Foglia, T.A., 2006. A process model to estimate biodiesel production costs. *Bioresource technology*, *97*(4), pp.671-678. doi: 10.1016/j.biortech.2005.03.039.

[47] Shrivastava, P., Verma, T.N., Samuel, O.D. and Pugazhendhi, A., 2020. An experimental investigation on engine

characteristics, cost and energy analysis of CI engine fuelled with Roselle, Karanja biodiesel and its blends. Fuel, 275, p.117891. doi: 10.1016/j.fuel.2020.117891.

[48] Seraç, M.R., Aydın, S., Yılmaz, A. and Şevik, S., 2020. Evaluation of comparative combustion, performance, and emission of soybean-based alternative biodiesel fuel blends in a CI engine. *Renewable Energy*, *148*, pp.1065-1073. doi: 10.1016/j.renene.2019.10.090.

[49] Shrivastava, P., Verma, T.N. and Pugazhendhi, A., 2019. An experimental evaluation of engine performance and emisssion characteristics of CI engine operated with Roselle and Karanja biodiesel. *Fuel*, *254*, p.115652. doi: 10.1016/j.fuel.2019.115652.

[50] Shrivastava, P. and Verma, T.N., 2020. Effect of fuel injection pressure on the characteristics of CI engine fuelled with biodiesel from Roselle oil. *Fuel*, *265*, p.117005. doi: 10.1016/j.fuel.2019.117005.

[51] Atmanli, A. and Yilmaz, N., 2020. An experimental assessment on semi-low temperature combustion using waste oil biodiesel/C3-C5 alcohol blends in a diesel engine. *Fuel*, *260*, p.116357. doi: 10.1016/j.fuel.2019.116357.

[52] Chen, H., He, J. and Hua, H., 2017. Investigation on combustion and emission performance of a common rail diesel engine fueled with diesel/biodiesel/ polyoxymethylene dimethyl ethers blends. *Energy & Fuels*, *31*(11), pp.11710-11722. doi: 10.1021/acs.energyfuels.7b01898.

[53] Canakci, M. and Van Gerpen, J. H., 2001. The Performance and Emissions of a Diesel Engine Fueled with Biodiesel from Yellow Grease and Soybean Oil. In the 2001 ASAE Annual International Meeting Sponsored by ASAE Sacramento Convention Center.

[54] Barabas, I., Todoruţ, A. and Băldean, D., 2010. Performance and emission characteristics of an CI engine fueled with diesel–biodiesel–bioethanol blends. *Fuel*, *89*(12), pp.3827-3832. doi: 10.1016/j.fuel.2010.07.011.

[55] Sharma, D.K. and Verma, T.N., 2020. Characteristics of fish oil biodiesel with the impact of diesel fuel addition on a CI engine. *Journal of Computational & Applied Research in Mechanical Engineering (JCARME)*, *10*(1), pp.245-256. doi: 10.22061/jcarme.2019.4737.1571.