Journals Books Publishing Support Login

ISSN: 1742-6596

OPEN ACCESS

The open access *Journal of Physics: Conference Series (JPCS)* provides a fast, versatile and cost-effective proceedings publication service.

Latest published conferences

Vol 2688 Go

Conference archive

2024 Go

View forthcoming volumes accepted for publication.

If you would like more detailed information regarding *Journal of Physics: Conference Series* please visit conferenceseries.iop.org, and if you are interested in publishing a proceedings with IOP Conference Series please visit our page for conference organizers.

Conference organizers can use our online form and we will get in touch with a quote and further details.

Most read

Latest articles

JOURNAL LINKS

- Journal home
- Journal Scope
- Information for organizers
- Information for authors
- Contact us
- Reprint services from Curran Associates

JOURNAL INFORMATION

2004-present
Journal of Physics: Conference Series
doi: 10.1088/issn.1742-6596
Online ISSN: 1742-6596
Print ISSN: 1742-6588

IOP

Table of contents

Volume 2688

2024

Previous issue Next issue

7th International Conference on Mechanical Engineering Research 2023 (ICMER 2023) 12-13 september 2023 Kuantan, Malaysia

Accepted papers received: 05 January 2024

Published online: 23 January 2024

Open all abstracts

Frontier Automotive Technology

Enhancement of Efficiency and Mitigation of Pollutan Emissions in a Compression Ignition Engine by the Utilization of Rice Bran Oil as Green Fuel

M. Norhafana, C.K. Ihsan, M.M. Noor, A.A. Hairuddin, K. Kadirgama, D. Ramasamy and A.M. Hussein

View article PDF

JOURNAL LINKS

Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Enhancement of Efficiency and Mitigation of Pollutan Emissions in a Compression Ignition Engine by the Utilization of Rice Bran Oil as Green Fuel

To cite this article: M. Norhafana *et al* 2024 *J. Phys.: Conf. Ser.* **2688** 012024

ENHANCEMENT OF EFFICIENCY AND MITIGATION OF POLLUTAN EMISSIONS IN A COMPRESSION IGNITION ENGINE BY THE UTILIZATION OF RICE BRAN OIL AS GREEN FUEL

M.Norhafana[1,*], C.K.Ihsan[2], M.M.Noor[1], A.A.Hairuddin[3], K.Kadirgama[1], D.Ramasamy[1], A.M.Hussein[4]**

[1]Faculty of Mechanical & Automotive Engineering Technology, Universiti Malaysia Pahang Al-Sultan Abdullah, 26600 Pekan, Pahang, Malaysia
Phone: +6094246255; Fax: +6094246222
[2]Jabatan Kejuruteraan Mekanikal, Politeknik Muadzam Shah, 26700 Pahang, Malaysia
[3]Faculty of Mechanical and Manufacturing Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia
[4]Technical Engineering College/ Kirkuk Engineering Technical College, Kirkuk 36001, Iraq.

[*]Corresponding email: *norhafana@yahoo.com / **muhamad@umpsa.edu.my

Abstract

The current investigation involved the implementation of a research experiment aimed at assessing the operational and emission attributes of a compression ignition direct injection engine comprising a single cylinder. The engine was fuelled with rice bran oil (RBO), and its performance was analysed under different engine loads. The performance metrics that were analysed included the brake specific fuel consumption BSFC), brake thermal efficiency (BTE), exhaust gas temperature (EGT), and cylinder pressure. The exhaust emission parameters that were investigated include carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), and oxide of nitrogen (NO_X). The study compares the results obtained from an experimental investigation involving different variants of rice bran oil (RBO50, RBO75, RBO100) with those obtained from a diesel engine (RBO00). The lowest BSFC obtained for RBO100 is around 0.29 kg/kWh at maximum load conditions (75 %), while the highest obtained for RBO00 is 0.33 kg/kWh. For all operations of diesel and RBO blends, it was discovered experimentally that the BSFC increases until 25 % of engine load and then starts to decline as the engine load is raised. At normal engine load circumstances, RBO75 has the highest thermal efficiency, while RBO00 has the lowest. The high EGT reading of RBO50 blends was due to the high calorific value (CV) of the fuel blends, which produced more heat per unit mass than RBO75 and RBO100. RBO75 achieved the highest cylinder pressure under both half and full load scenarios. RBO00 (pure diesel) achieved the lowest cylinder pressure under both half and full load scenarios. RBO outscored diesel in terms of efficiency of engine. The exhaust emission characteristics that were assessed included NO_x, CO_2, HC, and CO. The experimental outcomes of the study using rice bran oil-based fuels, specifically RBO50, RBO75, and RBO100, are being contrasted with those of diesel fuel (RBO00). The findings indicate that emissions of CO, CO_2, HC, and NO_X are lower when using RBO75 and RBO100 compared to diesel fuel. Furthermore, an analysis was conducted to determine the HC emissions of both RBO75 and RBO100 fuels at two distinct engine speeds, specifically 3500 rpm and 2000 rpm. The HC emission level for RBO75 was observed to be at its peak of 211 ppm when the engine speed reached 3500 rpm. The RBO50 fuel exhibits lower levels of CO emissions, measuring at 1.2% (3500 rpm) and 0.32% (2000 rpm). Similarly, CO_2 emissions are also reduced with RBO50, measuring at 8.3% (3500 rpm) and 6.9% (2000 rpm). These exhaust emission reductions are observed when comparing RBO50 to diesel (RBO00) and other fuel mixtures, under a 75% load condition. Elevated levels of NO_X emissions were detected in diesel fuel (RBO00) at concentrations of 499 ppm (3500 rpm) and 599 ppm (2000 rpm). In comparison to other fuels such as RBO50, RBO75, and RBO100, these higher NOx emissions were noted. In summary, the emission properties of RBO

including CO_2, CO, NO_X, and HC, was determined to be RBO50.

Keywords: compression ignition engine; rice bran oil, performance characteristic, emission characteristics

1 Background of Study

Numerous investigations have been undertaken in recent years with the aim of formulating viable substitutes for petroleum-based commodities [1-3]. The depletion of global fossil fuel reserves is occurring at a concerning pace, necessitating the identification of viable alternatives in light of increasing demand and declining supply of these fuels [4]. The transportation sector plays a large role in the depletion of fuel resources, mostly due to the considerable number of automobiles that populate road networks [5]. In addition, the usage of fossil fuels is considered the leading cause of air pollution and global warming. [6, 7]. Given the historical development of diesel engines specifically designed to function with pure diesel fuel, it becomes imperative to identify alternative fuels possessing comparable attributes in order to sustain the operation of current diesel engines [8-10]. Despite the existence of multiple proposed alternate fuels for diesel engines to supplement mineral diesel, the persistent challenge of costly engine modification persists [11].

Biodiesel sources are widely distributed across global regions, rendering them geographically accessible and so qualifying as locally-sourced commodities. Moreover, the utilization of these fuels can effectively mitigate the environmental repercussions associated with diesel engines, owing to their significant reduction in CO_2 emissions and engine exhaust pollutants [12-15]. The differentiation of biodiesel grades, derived from different feedstocks, is frequently observed in accordance with the American Society for Testing and Materials (ASTM) fuel standard. The practice of incorporating biodiesel into mineral diesel is a commonly employed method for introducing biodiesel as a viable fuel for direct utilization in diesel engines [16, 17]. The determination of the maximum proportion of biodiesel-pure diesel, as stipulated by the blended fuel standard, is contingent upon the properties of the biodiesel feedstock [18]. Hence, the examination of the tested fuel characteristics emerges as the foremost factor in ascertaining the ideal blend ratio [19, 20].

Rice bran oil, also known as RBO, has been one of the many waste-oriented [21]. This is because RBO has been shown to reduce the cost of producing biodiesel by a significant amount [22]. Rice bran refers to the outermost layer of rice that is acquired during the processes of milling, whitening, and polishing. Rice bran is predominantly employed as livestock feed or utilized as an inexpensive solid fuel in nations including Vietnam, China, India, Indonesia, and Bangladesh [23, 24]. The rice bran composition ranges from 16-32 wt% and is influenced by factors such as the rice variety and milling process [25]. The existence of a functional lipase enzyme within RBO results in a significantly higher concentration of free fatty acids (FFA) compared to the bran oil derived from other cereal grains. Therefore, it may be concluded that a significant proportion, approximately 60-70%, of the RBO is deemed unfit for eating, particularly in relation to its use in food products [26]. The prospect of converting non-edible rice bran oil (RBO) into biodiesel has drawn significant attention for the generation of RBO's volumes [27, 28].

The primary aim of this research is to investigate the effects of varying proportions of RBO mixed with pure diesel fuel on the efficient and exhaust emission attributes of a diesel engine. The experiment's scope is being broadened to determine the ultimate values of operating parameters and determine the particular combination of these values that produces the most positive outcomes.

2 Use of Rice Bran Oil (RBO) in a Compression Ignition (CI) Engine for Combustion

RBO has been employed in agricultural settings for the operation of tractors, watering systems, and various other agricultural machinery [24]. According to the researchers, the BSFC of preheated RBO at a temperature of 120 °C, as well as diesel-blended oil with 10% and 20% diesel content, shown elevated values in comparison to pure diesel. The observed phenomena can be ascribed to a decrease in BTE in engines powered by a blend of both fuels, as opposed to engines exclusively fueled by diesel. The level of CO and HC emissions were seen to be most elevated in the scenario involving preheated RBO, followed by RBO-diesel mixes and pure diesel [29].

The observed outcomes can perhaps be attributed to the comparatively lower Low Heating Value (LHV) and cetane number (CN) of RBO when compared with diesel. However, it should be noted that the viscosity, density, and surface tension of RBO were significantly higher than those of petrodiesel. Study conducted an analysis on the performance metrics, namely BSFC and BTE, as well as the emissions of NOx and smoke from an air-cooled single-cylinder direct four-stroke injection diesel engine, specifically the Kirloskar TAF-1 model with a rated power output of 4.4 kW [30]. The engine was operated using three different fuels: petrodiesel, unpreheated rice bran oil (RBO), and warmed RBO at a temperature of 158 °C. The study involved conducting experiments with different in-cylinder pressures (210, 220, 230, 240 bar) while maintaining 1500 rpm and 100% load. Additionally, varied ignition timings (17, 19, 21, 23° BTDC) were employed. Upon utilizing heated RBO, it was determined that an initial timing (IT) of 21 degrees before top dead center (BTDC) and an injection pressure (IP) of 230 bar were the most favorable settings for achieving the highest BTE while simultaneously minimizing BSFC and smoke emission. The findings highlight how important it is to have ideal engine operating conditions in order to achieve optimal levels of efficiency and emissions parameters [31].

In a series of studies, researchers conducted an investigation on the effects of injection pressures (IPs) and injection timings (ITs) on a low heat rejection diesel engine that was fueled with crude RBO (both preheated and unpreheated) as well as petrodiesel [32]. The optimal ignition timing for RBO was found to be 32° TDC, which is higher than the 30° TDC for diesel fuel. Additionally, a pressure of 190 psi was identified as the optimal operating condition for both fuels. In the specific experimental condition where the engine was operated with preheated rapeseed oil (RBO) at an initial temperature of 30° before TDC, which corresponds to the optimal temperature for mineral diesel fuel, the BTE was observed to be 7% lower and the volumetric efficiency was found to be 3% lower compared to the performance achieved with diesel fuel. When compared to petrodiesel, the EGT, sound intensity, and coolant load shown a notable increase of 75 °C, roughly 18%, and 5%, correspondingly. Furthermore, it was observed that the NOx and smoke emissions from the diesel engine operating on warmed RBO at this specific intake temperature (IT) exhibited an increase of 6% and 46% respectively, when compared to the emissions produced by pure diesel fuel.

When the engine was run at 32° TDC and fed with RBO, gains were seen in a number of areas that were thought to be important. This shows how important the settings in which an engine is running are. Researchers conducted an investigation on the blending technique and utilized a fuel mixture RBO20 consisting of 20% RBO and 80% diesel fuel [33]. This fuel blend was then tested in a CI engine with a rated power output of 40.4 kW operating at 3000 rpm. A reduction in BTE and BSFC were found during the operation of the test engine on RBO20 in comparison to diesel fuel. But it's important to note that the temperature of the exhaust gas dropped noticeably, which meant that NOx levels went down. As a result of these findings, the experts have put up the suggestion that RBO20 could potentially serve as a viable substitute for diesel fuel in the context of internal combustion engines.

In general, the use of pure RBO in diesel engines is limited due to its elevated viscosity, as well as its relatively low LHV and CN. However, the implementation of mixing techniques has proven to be efficacious for short-term utilization in existing diesel engines [34-36]. It is important to emphasize that various types of vegetable oils have been shown to exhibit lower LHV and CN in comparison to diesel fuel. These differences have been observed to significantly affect both engine efficiency and emissions characteristics [37-39]. In this study, Hoang [40] conducted an experimental investigation to assess the effects of unheated and preheated Jatropha oil on engine performance and emission characteristics [41-43].

Based on their findings, the BTEs of the engine utilizing unpreheated and preheated (at a temperature of 90 °C) Jatropha oil were recorded as 29.76% and 32.83% respectively, in comparison to pure diesel fuel which exhibited a BTE of 36.19% [44]. Furthermore, the study revealed similar patterns in the emissions of HC, CO, and NO_X as those previously described for RBO. Further investigation is necessary to assess the viability of utilizing RBO, either independently or in combination with petrodiesel, as a long-term fuel source for diesel engines.

In diesel engines, the use of vegetable oil or fuels derived from vegetable oil for an extended period of time has the potential to cause the lubricating oil to degrade and the formation of large sediments within the injector holes and on the piston's crown [45, 46]. In a nutshell, the viability of using vegetable oils as alternative energy sources in diesel engines is contingent on the physicochemical qualities of the vegetable oils as well as the operational parameters of the engine [4, 47, 48].

3 Methodology

The study was carried out with a single-cylinder, four-stroke CI engine. The engine was connected to a dynamometer, which was controlled by a Dynalec controller tasked with overseeing and controlling torque, load, and engine speed. The test conditions and characteristics of the engine are shown in Tables 1 and 2, correspondingly. The fuel compositions utilized in this study consist of four distinct blends: 100% pure diesel (RBO00), a mixture of 50% RBO and 50% pure diesel (RBO50), a blend of 75% RBO and 25% pure diesel (RBO75), and 100% RBO (RBO100).

Table 1: The Specification of Engine

Description	Specification
Type	4-stroke, Horizontal Cylinder, Air-Cooled Diesel Engine
Number of Cylinders	1
Combustion System	Direct Injection
Bore x Stroke	(70 x 55 mm)
Compression Ratio	20.1 +- 0.5
Maximum engine power	3.5 kW
Maximum torque	9.28 Nm

Table 2: Test Conditions

Parameters	**Test Condition**
Type of Fuel	Diesel (RBO00), RBO50, RBO75, RBO100
Engine Speed (rpm)	2000, 2500, 3000, 3500
Fuel Temperature	27 +- 1 °C
Air Temperature	30 +- 1 °C

The test engine's operational and performance parameters were assessed through the utilization of several measuring devices, which were calibrated prior to measurement to ensure accuracy. Table 3 provides a comprehensive overview of the specifications of several measurement equipment.

Table 3: Instruments Specifications

Particulars	**Specifications**
Speed measurement	Dynamometer
Temperature measurement	K-type thermocouples Range : 100˚C to 600 ˚C
	Digital temperature indicator
Fuel measurement	Burette and stop watch
Voltmeter	Range: 0-300 V
	Scale: Nonlinear type
Ammeter	Range: 0-30 A
	Resolution: 0.2 A
Anemometer	Type: Victor 816B

The composition of exhaust gas was quantified by employing the QROTECH QRO-401 instrument. The exhaust emissions are quantified by measuring the concentrations of CO, CO_2, HC, O_2, and NOx. Additionally, the air surplus rate (λ) and the air-fuel ratio (AFR) are determined. Table 4 provides information on the range and accuracy of the QROTECH QRO-401 gas analyzer.

Table 4: Specification of QROTECH Model QRO-401

Sensor	**Measuring Range**	**Resolution**
Carbon Monoxide (CO)	0.0 ~ 9.99 %	0.01 %
Hydrocarbon (HC)	0 ~ 9999 ppm	1 ppm
Carbon Dioxide (CO_2)	0.0 ~ 20.0 %	0.1 %
Oxygen (O_2)	0.00 ~ 25.00 %	0.01 %
Nitrogen Oxide (NO_X)	0 ~ 5000 ppm	1 ppm
λ	0 ~ 2.000	0.001

3.1 Configuration of Experimental Setup
The configuration of the experimental resource is depicted in Figure 1.

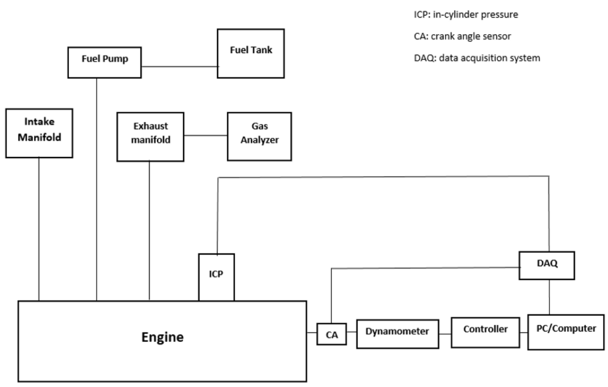

Figure 1: The layout of experimental setup

Rice bran oil was purchased in Selangor, Malaysia, from a local bio-oil producing company. An electric, magnetic stirrer was used to mixing samples of blended rice bran oil with mineral diesel and blending into RBO50 fuel (50% vol. pure diesel + 50% vol. RBO), RBO75 fuel (25% vol. pure diesel + 75% vol. RBO) and RBO100 fuel (0% vol. pure diesel + 100% vol. RBO). Prior to undergoing testing, the blend fuels were subjected to continuous swirling for a duration of one hour in order to ensure optimal blending. Subsequently, a period of one hour was allocated to allow the blend fuels to attain a state of stability [9, 10]. Rice bran oil's use in various blends may have several consequences, such as increased lubricity, reduced ignitability, shorter ID, decreased volatility, and greater CN [49, 50]. The density of the test fuel samples was determined at a temperature of 15 °C using the Mobile Density Meter (model DA-130N). The viscosity measurement was conducted on the test fuels with a digital steady-state kinematic viscosity bath version K23376-KV1000, with a consistent temperature of 40 °C ±0.01 being maintained [51]. Additional fuel attributes that have an impact on the performance of engine power when utilizing mixes of diesel and biodiesel encompass the energy content [52, 53]. Consequently, a limited number of research have been conducted pertaining to energy content evaluations, providing scant information regarding the instruments and equipment employed, as well as the comprehensive technique employed for analysis. [54, 55].

All measurements were carried out on a 200 ml sample that had not been pre-treated. These mixtures were then put through their paces in an air-cooled diesel engine. A pressure level of 200 bar was applied during the engine's injection process. The engine was initiated using a designated fuel mixture and thereafter allowed to reach optimal operating temperature for a duration of 20 minutes. During this particular period, measurements were taken for a wide range of incremental loads, starting with no load and going all the way up to full load. All of the data points have been collected. The measured variables for each load condition encompassed the following parameters: the rate of air flow entering the system, the duration required for 30 cc of fuel to be consumed, the temperature of the surrounding environment, the temperature of the exhaust gas, the flow rate of cooling water exiting the system, and the readings obtained from both the ammeter and voltmeter. In order to ensure the dependability of the measurements, the testing processes were iterated three times.

The most essential factor for determining whether a particular fuel is suitable for use within the fuel standard is its attributes [56-58]. The evaluation of fuel properties holds significant importance in the assessment of alternative fuels prior to engine operation and the analysis of fuel combustion [16, 59]. The fuel characteristic evaluations for pure diesel (RBO00), RBO50, RBO75, and RBO100, together with the corresponding standard test procedures, are presented in Table 5. The fuel density of RBO is frequently seen to be greater than that of diesel fuel, leading to an increased specific fuel consumption for an equivalent engine output [18, 50, 60]. According to Table 5, it can be observed that the density of RBO fuel is greater than that of diesel fuel. This disparity in density is known to have implications for the generation of fuel droplets and the penetration of sprays [61, 62].

Table 5: Results of Tested Fuel Properties

Properties	Testing Method	Diesel (RBO00)	RBO50	RBO 75	RBO 100
Density (kg/m^3)	ASTM D1298	839.7	862.62	874.08	897.0
Kinematic Viscosity (mm^2/s)	ASTM D445-01	4.5	4.4	4.8	5.2
Calorific Value (MJ.kg)	ASTM D4809	45.7140	43.8684	42.9456	41.1000
Cetane Number	ASTM D4737	48	52	54	55

4 Engine Efficiency Analysis

The advantages of utilizing as-used fuels in diesel engines can be observed through many performance indicators, including BSFC, BTE, EGT, engine power output, and/or volumetric efficiency. Furthermore, engine technical aspects such as compression ratio, air-fuel mixture methods, and cooling, and operating conditions, are all major influences on engine performance [63, 64]. Recently, some innovative approaches and updated technology have been developed to enhance engine output power while reducing pollutant emissions [65-67]. Other measures, such as enhancing engine technical characteristics, injection strategy, and so on, have been employed alone or in combination with novel fuel compositions to optimize the combustion process and achieve the best efficiency [68, 69].

4.1 Brake Specific Fuel Consumption (BSFC)

The BSFC is a metric that quantifies the fuel efficiency of an engine in terms of the amount of gasoline consumed per unit of power generated. Figure 2 illustrates the BSFC for different fuel blends, including standard diesel, at various engine loads. The test included pure diesel fuel (RBO00), which served as the baseline, as well as mixes such as RBO50, RBO75, and RBO100.

It was discovered experimentally that the BSFC increases until 25% of engine load and then starts to decline as the engine load is raised for all operations of diesel and RBO blends [70]. This occurrence could be explained by the fact that the proportional rise in engine load is greater than the percentage gain in fuel consumption that has been observed. Additionally, as brake power increases, cylinder wall temperature rises, reducing ignition delay [18, 71, 72] .

As a result, reducing the ignition delay increases combustion while lowering fuel consumption [71]. Lower loads, on the other hand, had seen a faster decline in BSFC than higher loads. At higher load conditions, the rise in BSFC for RBO00 was also greater than for other blends operations. This was because RBO00 has a higher viscosity than other blends. The lowest BSFC obtained under maximum load conditions for RBO100 is around 0.29 kg/kWh, while the highest is 0.33 kg/kWh for RBO00. BSFC is also roughly identical for RBO50 and RBO100.

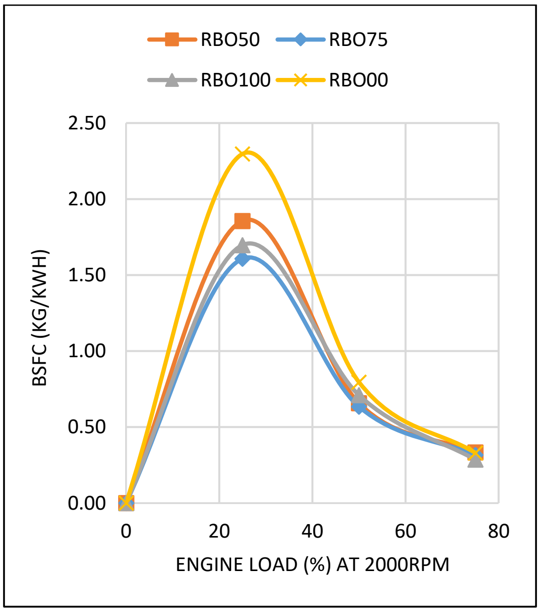

Figure 2: BSFC curve of the test fuels in relation to engine load

4.2 Brake Thermal Efficiency (BTE)

The BTE can be mathematically expressed as the division of the energy in the braking power by the input fuel energy, both measured in suitable units [73]. Figure 3 presents the BTE values for various fuel mixes and regular diesel under varied engine load conditions. The experiment was conducted using several different fuel mixtures, including RBO50, RBO75, and RBO100 samples, in addition to testing with pure diesel fuel (RBO00), which served as the baseline fuel.

When the engine load was increased, there was a noticeable rise in BTE across the board for all of the tasks that involved diesel and RBO blends. When the braking power is increased, there is a corresponding decrease in heat dissipation and an increase in power output. This can be related to the phenomenon that was seen [18, 74]. The BTE of the blend consisting of RBO50 and RBO100 exhibited a comparable trend to that of the RBO75 blend across the range of engine load from 0% to 50%. The BTE exhibited its highest value at an engine load of 75%. The aforementioned observation was probably ascribed to the decreased CV of the RBO100 fuel, which seemed to have a more notable impact in comparison to the inherent oxygen content and higher CN. The atomization of fuel may be compromised due to the increased viscosity of RBO00 compared to fuels with lower viscosity, even when subjected to the same pressure generated by the injector pump [34]. Among the tested models, only RBO00 demonstrated a lower value. The RBO100 exhibits a maximum thermal efficiency of approximately 30.6%. The RBO00 exhibits a minimum thermal efficiency of approximately 3.81%. In conclusion, the findings that are depicted in Figure 3 reveal that RBO75 demonstrates the maximum thermal efficiency, whilst RBO00 demonstrates the lowest thermal efficiency in circumstances with an average engine load.

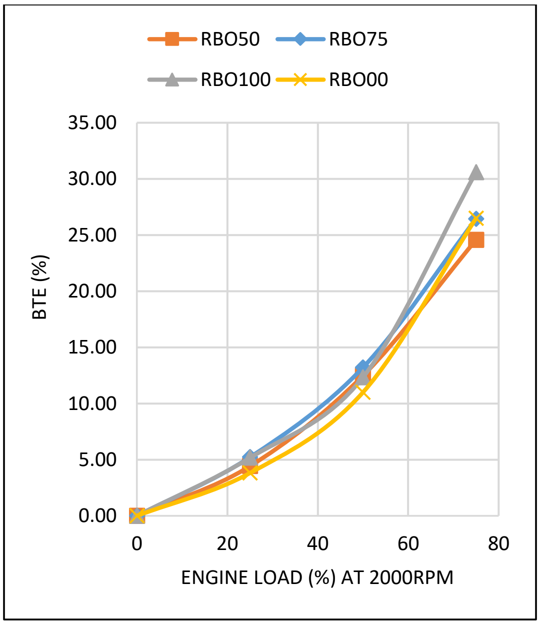

Figure 3: BTE curve curve of the test fuels in relation to engine load

4.3 Exhaust Gas Temperature (EGT)

The EGT refers to the mean temperature of the exhaust gas stream. Figure 4 illustrates the EGT for several fuel blends, including common diesel, under varying engine loads. The test included pure diesel fuel (RBO00), which provided as the baseline, as well as mixes such as RBO50, RBO75, and RBO100.

The observed trend in Figure 4 indicates that when the engine load was elevated, there was a corresponding rise in the EGT for the test fuel. The observed phenomenon can be ascribed to the increased use of fuel, which was imperative in order to provide the requisite torque for overcoming the strain on the engine [75]. The minimal constraint imposed by the dynamometer caused fuel combustion to take place at the exhaust manifold region rather than the intended combustion chamber. Consequently, the thermocouple positioned directly at the exhaust port was affected, leading to an elevated EGT measurement even when the engine was not under any load [76]. In Fig. 4, RBO50 mixes have the highest increment, followed by RBO00, RBO75, and RBO100 blends. The high EGT reading of RBO50 blends was due to the high CV of the fuel blends, which produced more heat per unit mass than RBO75 and RBO100. Another factor was the extended ignition delay of RBO50 blends, which contributed to a longer fuel burning process and a greater temperature of combustion gas exiting the combustion chamber. This also explains why RBO75 and RO100 blends with a short ignition delay have the lowest EGT since combustion occurs faster and the EGT is slightly lower before exiting the combustion chamber [77]. At the highest level of engine load, however, there was a decrease in the disparity of BTE, suggesting an improvement in the efficiency of converting heat energy into work. Consequently, the difference in EGT relative to the reference fuel RBO00 was also reduced.

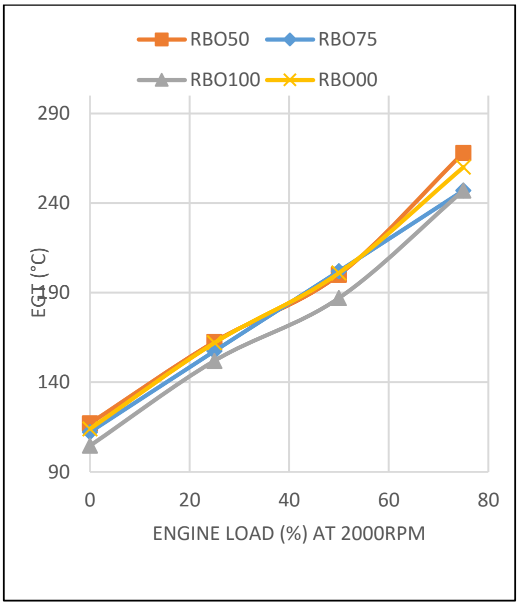

Figure 4: EGT curve of test fuels in relation to engine load

4.4 Cylinder Pressure

The acquisition and analysis of data pertaining to the pressure within the engine cylinder is widely recognized as a crucial aspect of the development and calibration processes for compression ignition (CI) engines. From the pressure graphs that are acquired within the cylinder, one can infer essential pieces of information such as the peak pressure, the indicated mean effective pressure, the optimal pressure for fuel delivery, the combustion time, and the ignition delay [60]. In addition, by making use of the equations that were developed from the first rule of thermodynamics and applying them particularly to ideal gases, it becomes possible to assess and predict several supplementary parameters including air mass flow, combustion diagnosis, and the amount of NO_X emissions [78]. It has been found that the proportion of fuel that is burned during the premixed combustion phase of CI engines, which is sometimes referred to as the initial combustion stage, has a considerable influence on the highest pressure that can be reached inside the cylinder [79]. Peak pressure often rises in response to rising engine loads, and the P-diagram could be used to show how in-cylinder pressure and crank angle are related. Two possible patterns for changes in engine cylinder pressure during blended RBO combustion are as follows: (i) The increased CN and oxygen levels in RBO and its blends, in comparison to petroleum diesel fuel, led to an elevation in peak pressure. (ii) The decreased LHV and increased viscosity of RBO, in comparison to petroleum diesel fuel, resulted in a decrease in peak pressure.

Figure 5 depict the cylinder pressure changes with crank angle under half and full load. RBO75 achieved the highest cylinder pressure under both half and full load scenarios. RBO00 (pure diesel) achieved the lowest cylinder pressure under both half and full load scenarios. Under conditions of full load, the pressure inside the cylinder rises as the ignition delay decreases. The ability of the mixed fuel to combine with air and ignite is dependent on cylinder pressure. The increased oxygen levels of the RBO are what's responsible for their high pressures. The highest peak pressure among the RBO blends was found to be RBO75, followed by RBO25, RBO50 and RBO00, with values of 70.78, 68.46, 66.58 and 64.83 bar, respectively.

One of the important elements in determining cylinder pressure is cetane number. Compared to all other evaluated fuels, RBO has the highest CN and oxygen concentration [79]. Additionally, a fuel with a higher CN typically results in a shorter premixing time and a reduced ignition delay for absolute combustion.

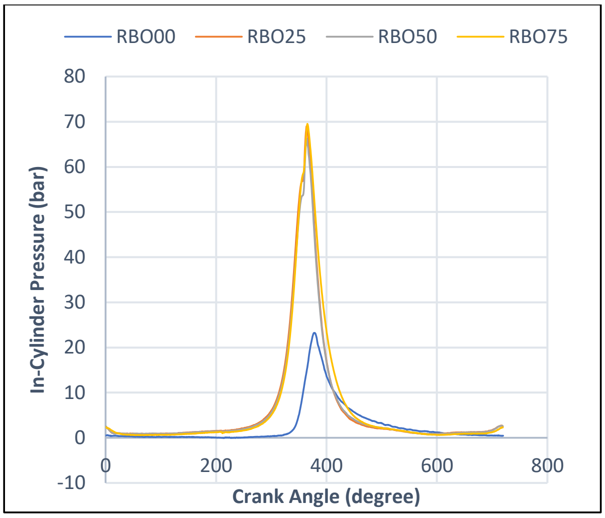

Figure 5 (a) The relationship between cylinder pressure with crank angle under 50 % engine load

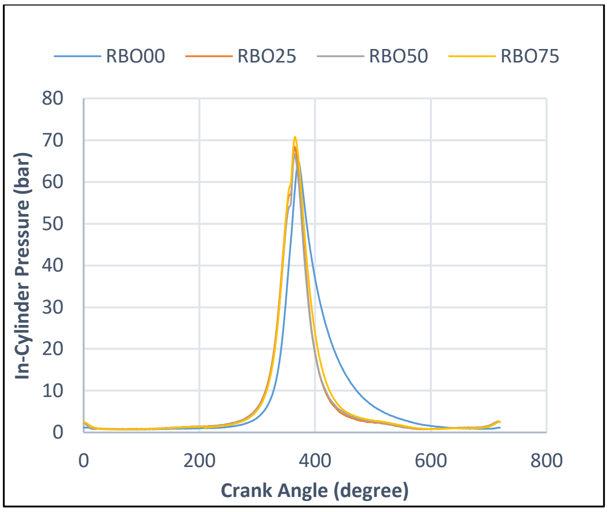

Figure 5 (b) The relationship between cylinder pressure with crank angle under 100 % engine load

5 Exhaust Emission Analysis

5.1 Carbon Monoxide (CO)

Lowering CO is crucial in reducing exhaust emissions. Figure 6 (a) and (b) depict the fluctuations in CO levels in relation to braking power at two different speeds, namely high speed (3500 rpm) and low speed (2000 rpm) correspondingly. The CO emissions were measured under full load conditions, revealing that RBO100 exhibited the lowest concentration at around 0.7%. This was followed by RBO50 with a concentration of 1.2%, RBO75 with a concentration of 1.57%, and the highest concentration of approximately 1.7% was found for

RBO00. The elevated levels of CO seen in RBO00 can potentially be attributed to the prolonged ignition delays (ID) resulting from the fuel used. The study demonstrates that there is a decrease in the air and fuel ratio within the cylinder, which is caused by an increase in BSFC and a longer intake duration (ID). Consequently, this reduction in the air volume available within the cylinder hinders the achievement of complete combustion [18]. As a consequence, this leads to an increase in carbon dioxide (CO_2) emissions. Figure 6 (b) displays the relationship between CO levels and BP at a low speed of 2000 rpm. The emissions of RBO100 and RBO00 were rather high, whereas RBO50 and RBO75 exhibited lower levels of CO emissions. As a consequence, this has an impact on the increase of carbon dioxide emissions. Figure 6 (b) illustrates the presence of CO variation in relation to braking power at a low-speed of 2000 rpm. The emissions of RBO100 and RBO00 were rather high, whereas RBO50 and RBO75 exhibited lower levels of CO emissions.

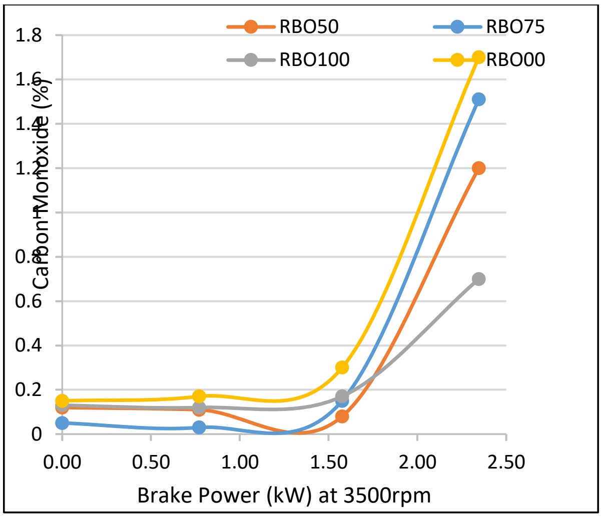

Figure 6 (a) CO changes with BP at high speed (3500 rpm)

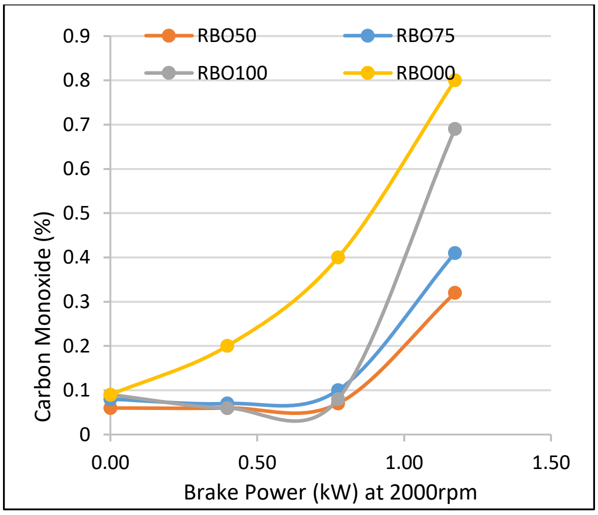

Figure 6 (b) CO changes with BP at low speed (2000 rpm)

5.2 Carbon Dioxide (CO_2)

During the process of combustion of carbon chains included in fuel, a notable gas that is released is CO_2. The CO_2 emission in compression ignition engines substituted with biofuels does not yield a straight general consensus [80, 81]. Several studies have indicated that the utilization of RBO in diesel engines resulted in higher CO_2 emissions in comparison to conventional diesel fuel [74, 79]. Figure 7 (a) and (b) depict the fluctuations in CO_2 levels in relation to BP at 3500 rpm and 2000 rpm. Figure 7 (a) illustrates the graphical representation of the transition from a no-load situation to full load conditions. The study conducted by RBO00 showed that carbon dioxide emissions were consistently higher across all load circumstances, in contrast to RBO50 which exhibited lower levels of carbon dioxide emissions. At full load conditions, both RBO75 and RBO00 exhibit the highest emission levels, accounting for around 10% each. Conversely, the lowest emission level of approximately 8.3% is observed for RBO50.

Figure 7 (b) illustrates the relationship between CO_2 levels and BP at a low-speed of 2000 rpm. Both RBO50 and RBO00 exhibit similar patterns of fluctuation in their graphs when transitioning from a no-load state to full load conditions. The sole distinction lies in the fact that CO_2 emissions for RBO50 were situated at the lower end of the curve, whereas RBO00 exhibited higher levels of emissions. At a low engine speed, the levels of CO_2 emissions from diesel fuel (specifically, RBO00) were comparatively greater at lower speeds when compared to RBO100, RBO75, and RBO50.

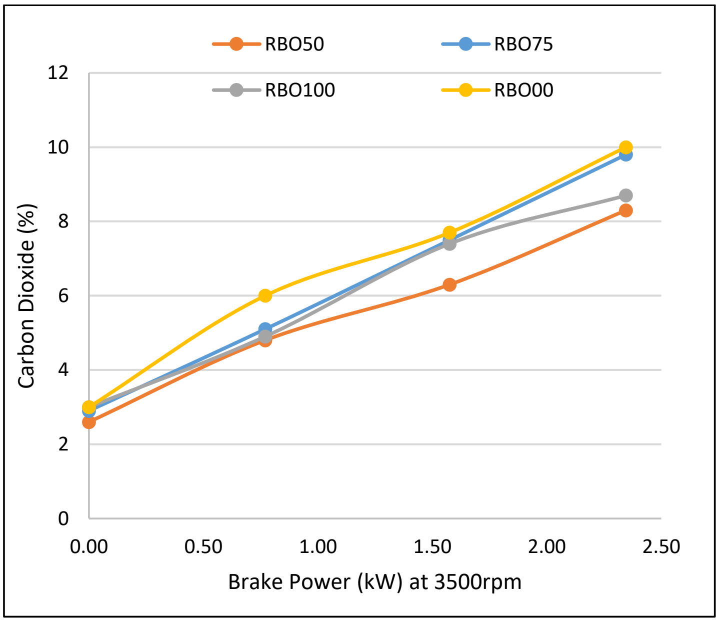

Figure 7 (a) CO_2 changes with BP at high speed (3500 rpm)

5.3 Hydrocarbon (HC)

Figure 8 (a) and (b) depict the fluctuation in HC levels in relation to BP, specifically at low speed (2000 rpm) and high speed (3500 rpm) accordingly. Under varying load circumstances, both RBO50 and RBO75 exhibited equivalent levels of hydrocarbon emissions. This can be attributed, in part, to their nearly identical BSFC. A hydrocarbon emission level of approximately 28 ppm was found for RBO00 under part load settings, whereas a maximum hydrocarbon emission level of approximately 211 ppm was observed for RBO75 under full load conditions. Figure 8 (b) illustrates that the increased hydrocarbon emission observed in RBO100 can be attributed to its higher BSFC. The hydrocarbon emissions of RBO75, RBO50, and Diesel RBO00 exhibited similar variations across different load circumstances, indicating comparable patterns in their emissions behavior.

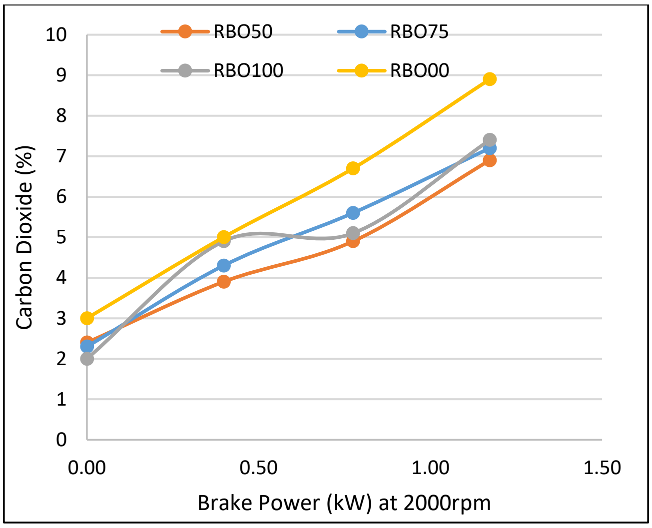

Figure 7 (b) CO_2 changes with BP at low speed (2000 rpm)

The substances resulting from the process of combustion. The application of higher temperatures in RBO fuel has a great impact on the reduction of hydrocarbon condensation, hence leading to a decrease in emissions of HC [82, 83]. An elevation in the cetane rating of RBO results in a decline in HC emissions as a consequence of a reduction in the duration of ignition delay [79, 84, 85].

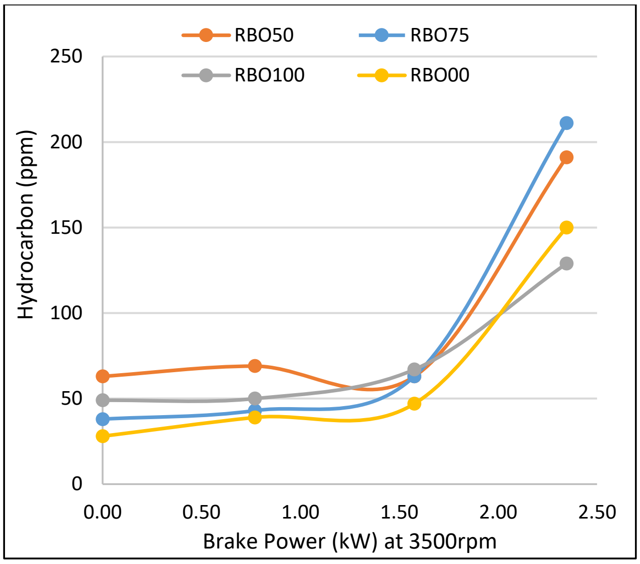

Figure 8 (a) HC changes with BP at high speed (3500 rpm)

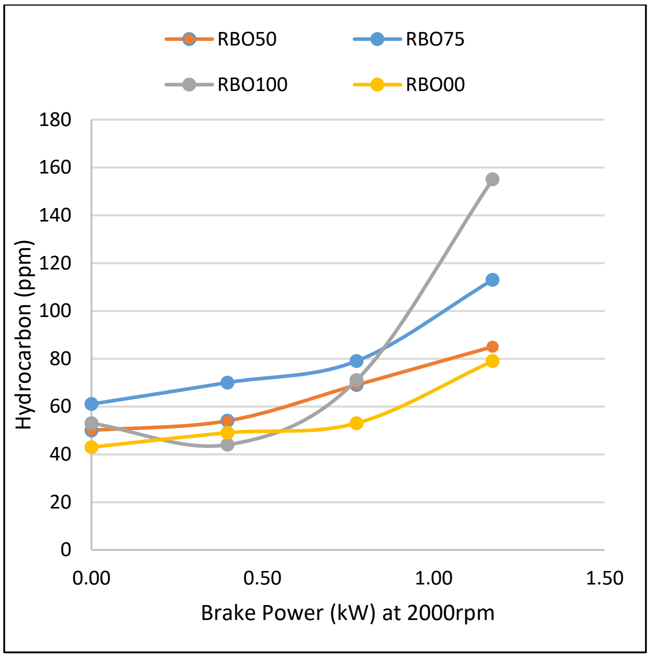

Figure 8 (b) HC) changes with BP at low speed (2000 rpm)

5.4 Oxide of Nitrogen (NOx)

The change in NOx content in relation to BP is depicted in Figure 9 (a) and Figure 9 (b), respectively, at high rates (3500 rpm) and low rate (2000 rpm).

The RBO00 variant demonstrates a maximum value of around 499 ppm under full load conditions. In contrast, the RBO50, RBO75, and RBO100 variants exhibit progressively decreasing values, with approximate measurements of 255 ppm. The fuel mix RBO00, namely diesel, had the greatest levels of NO_X exhaust emissions when compared to other fuel blends within the RBO category. Figure 5(b) illustrates the variation in NOx levels in relation to brake power at a low speed of 2000 rpm. The Diesel (RBO00) exhibited the greatest value of approximately 599 ppm under full load conditions, while RBO50, RBO75, and RBO100 demonstrated lower values, with RBO100 having the lowest at around 319 ppm.

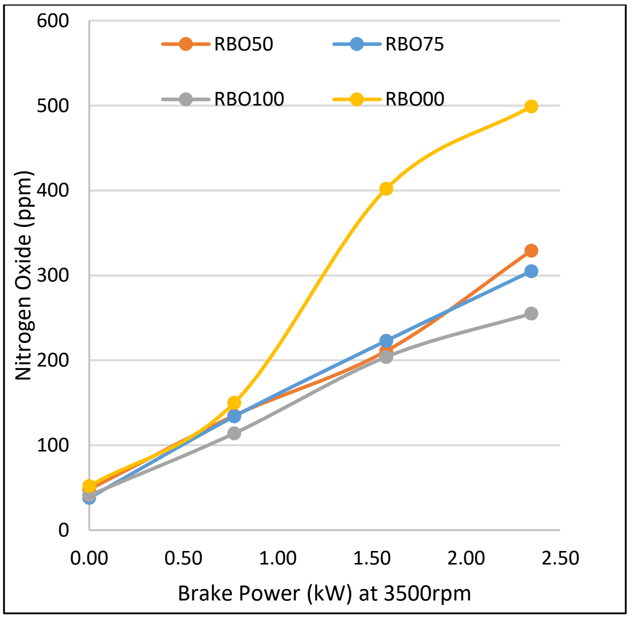

Figure 9 (a) Nitrogen oxide (NO_x) changes with brake power (BP) at high speed (3500 rpm)

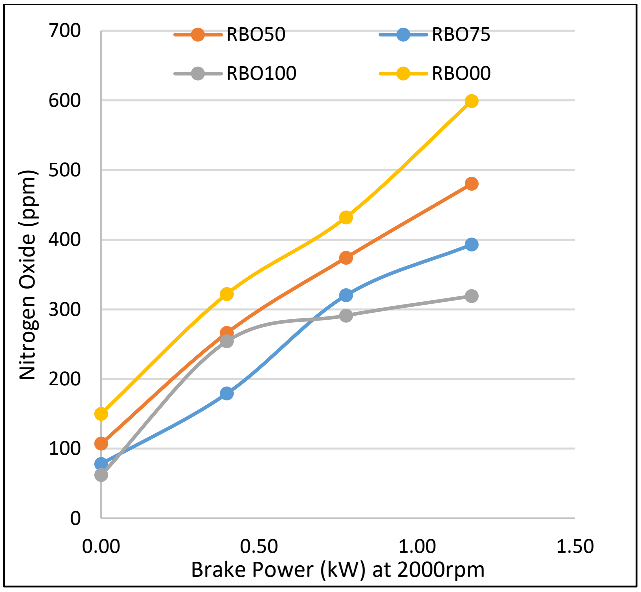

Figure 9 (b) Nitrogen oxide (NOx) changes with brake power (BP) at low speed (2000 rpm)

6 Conclusion

The present study aims to experimentally explore the performance and emission characteristics of a compression ignition (CI) or diesel engine when fueled with mixes of rice bran oil (RBO) and diesel fuel. The blends considered in this study include RBO50, RBO75, and RBO100, with RBO00 representing pure diesel fuel. The findings of the investigation can be succinctly described in the following manner:

6.1 Performance parameters:

- RBO50, RBO75, and RBO100 are suitable for direct utilization in diesel engines without necessitating any changes in design.
- For all operations of diesel and RBO blends, BSFC increases until 25% of engine load is reached, then begins to decline as engine load is raised. The lowest BSFC obtained under maximum load conditions for RBO100 is around 0.29 kg/kWh, while the highest is 0.33 kg/kWh for RBO00.
- At normal engine load circumstances, RBO75 has the highest thermal efficiency, while RBO00 has the lowest.
- The high EGT reading of RBO50 blends because of the high calorific value of the fuel blends, which produced more heat per unit mass than RBO75 and RBO100. Another factor was the extended ignition delay of RBO50 blends, which attributed to a longer fuel burning process and a greater temperature of combustion gas exiting the combustion chamber.
- The maximum cylinder pressure was attained by RBO75 in both half- and full-load conditions. Under both half and full load conditions, the cylinder pressure for RBO00 (pure diesel) was the lowest.
- Rice Bran Oil (RBO) has been identified as promising candidates as alternative fuels due to their extensive resource availability and good performance qualities.
- However, more research into the dynamics of combustion using RBO as a fuel is required for optimal optimization.

6.2 Emission parameters:

- The findings indicate that emissions of CO, CO_2, HC, and NOx are lower when using RBO75 and RBO100 compared to diesel fuel. Specifically, hydrocarbon emissions were observed at two engine speeds (3500 rpm and 2000 rpm) for both RBO75 and RBO100.
- The hydrocarbon emission level for RBO75 was observed to be at its peak of 211 ppm when the engine speed was set at 3500 rpm. The RBO50 fuel exhibits lower levels of CO emissions (1.2% at 3500 rpm and 0.32% at 2000 rpm) and CO_2 emissions (8.3% at 3500 rpm and 6.9% at 2000 rpm) as compared to diesel (RBO00) and other fuel mixtures, under conditions of 75% engine load.
- Elevated amounts of NOx emissions were observed in diesel fuel (RBO00) at levels of

499 ppm and 599 ppm during engine operation at 3500 rpm and 2000 rpm, respectively, in contrast to other fuels like RBO50, RBO75, and RBO100.

- In conclusion, the emission characteristics of rice bran oil were found to surpass those of diesel fuel. A blend including 50% rice bran oil (RBO50) demonstrates an appropriate composition in terms of mitigating the release of CO_2, CO, NO_X, and HC.

In a nutshell, Rice Bran Oil (RBO) has been identified as promising candidates as alternative fuels due to their extensive resource availability and good performance qualities. However, more research into the dynamics of combustion using RBO as a fuel is required for optimal optimization.

7 Declaration of Competing Interest

The authors assert that they do not possess any identifiable conflicting financial interests or personal relationships that may have potentially influenced the findings presented in this research article.

8 Acknowledgement

The financial support by Universiti Malaysia Pahang (www.ump.edu.my) under Research Student Grant PGRS190336 Grant and UMP Research Grant Scheme, Ministry of Higher Education Malaysia through the research project RDU223302 were grateful.

References

1. Abedin, M.J., et al., *Energy balance of internal combustion engines using alternative fuels.* Renewable and Sustainable Energy Reviews, 2013. **26**: p. 20-33.
2. Awad, O.I., et al., *Alcohol and ether as alternative fuels in spark ignition engine: A review.* Renewable and Sustainable Energy Reviews, 2018. **82**: p. 2586-2605.
3. Canakci, M., *NO_x emissions of biodiesel as an alternative diesel fuel.* International Journal of Vehicle Design, 2009. **50**(1-4): p. 213-228.
4. Atabani, A.E., et al., *A comprehensive review on biodiesel as an alternative energy resource and its characteristics.* Renewable and Sustainable Energy Reviews, 2012. **16**(4): p. 2070-2093.
5. mat Yasin, M.H., et al., *Fuel physical characteristics of biodiesel blend fuels with alcohol as additives.* Procedia Engineering, 2013. **53**: p. 701-706.
6. Bhattacharyya, S.C., *Fossil-fuel dependence and vulnerability of electricity generation: Case of selected European countries.* Energy Policy, 2009. **37**(6): p. 2411-2420.
7. Norhafana, M., et al. *A review of the performance and emissions of nano additives in diesel fuelled compression ignition-engines*. in *IOP Conference Series: Materials Science and Engineering*. 2019.
8. Awad, O.I., et al., *Calorific value enhancement of fusel oil by moisture removal and its effect on the performance and combustion of a spark ignition engine.* Energy Conversion and Management, 2017. **137**: p. 86-96.
9. A.K. Azad, et al., *Comparative Study of Diesel Engine Performance and Emission with Soybean and Waste Oil Biodiesel Fuels.* International Journal of Automotive and mechanical Engineering 2015. **12**: p. 2866-2881.
10. Norhafana, M., et al., *The effects of nano-additives on exhaust emissions and toxicity on mankind.* Materials Today: Proceedings, 2020. **22**: p. 1181-1185.
11. A. K. Azad; S. M. A. Uddin; M. M. Alam, *A Comprehensive Study of Diesel Engine Performance With Vegetable Oil: An Alternative Bio-Fuel Source of Energy.* International Journal of Automotive and mechanical Engineering 2012. **5**: p. 576-586.
12. Pandey, R.K., A. Rehman, and R.M. Sarviya, *Impact of alternative fuel properties on fuel spray behavior and atomization.* Renewable and Sustainable Energy Reviews, 2012. **16**(3): p. 1762-1778.
13. Abbaszaadeh, A., et al., *Current biodiesel production technologies: A comparative review.* Energy Conversion and Management, 2012. **63**: p. 138-148.

14. Agarwal, A.K., J.G. Gupta, and A. Dhar, *Potential and challenges for large-scale application of biodiesel in automotive sector.* Progress in Energy and Combustion Science, 2017. **61**: p. 113-149.
15. P.M.Sharif, A.A.H., A.As'arry, K.A.M.Rezali, M.M.Noor, M.Norhafana, A.A.M.Muntasser, S.M.Shareef *International Regulation of Vehicle Emissions Control Rules and Its Influence on Academic Engine Development Experimental Study and Vehicle Manufacturing* IOP: Materials Science and Engineering 469 (2019), 012070, doi:10.1088/1757-899X/469/1/012070 (Indexed by Scopus). 2019.
16. Dharmaraja, J., et al., *Engine performance, emission and bio characteristics of rice bran oil derived biodiesel blends.* Fuel, 2019. **239**: p. 153-161.
17. Norhafana, M., et al., *An Experimental Study of the Performance and Emission Characteristics of a Compression Ignition (CI) Engine Fueled with Palm Oil based Biodiesel.* AIP Conference Proceeding Series, vol. 2059, issue 1, ISSN 0094-243X, American Institute of Physics (Indexed by Scopus). 2019.
18. Hoang, A.T., et al., *Rice bran oil-based biodiesel as a promising renewable fuel alternative to petrodiesel: A review.* Renewable and Sustainable Energy Reviews, 2021. **135**: p. 110204.
19. Benjumea, P., J. Agudelo, and A. Agudelo, *Basic properties of palm oil biodiesel–diesel blends.* Fuel, 2008. **87**(10): p. 2069-2075.
20. Benjumea, P., J. Agudelo, and A. Agudelo, *Effect of altitude and palm oil biodiesel fuelling on the performance and combustion characteristics of a HSDI diesel engine.* Fuel. **In Press, Uncorrected Proof**.
21. Aghbashlo M, T.M., Khalife E, Najafi B, Mirsalim SM, Gharehghani A, et al. , *A novel emulsion fuel containing aqueous nano cerium oxide additive in diesel–biodiesel blends to improve diesel engines performance and reduce exhaust emissions: Part II – exergetic analysis.* Fuel, 2017. **205:262–71.** .
22. Xu, D., et al., *Physicochemical properties, fatty acid compositions, bioactive compounds, antioxidant activity and thermal behavior of rice bran oil obtained with aqueous enzymatic extraction.* LWT, 2021. **149**: p. 111817.
23. Hasan, W., Kafy *Prospect of rice bran for biodiesel production in Bangladesh.* Procedia Eng 2014. **90:746–52**.
24. Acharya , S., Mohanty . , *The use of rice bran oil as a fuel for a small horse-power diesel engine.* . Energy Sources, , 2010,. **Part A Recover Util Environ Eff 2010;**(33:80–8.).
25. Mazaheri, H., et al., *Rice bran oil based biodiesel production using calcium oxide catalyst derived from Chicoreus brunneus shell.* Energy, 2018. **144**: p. 10-19.
26. Zaidel, D.N.A., et al., *18 - Production of biodiesel from rice bran oil*, in *Biomass, Biopolymer-Based Materials, and Bioenergy*, D. Verma, et al., Editors. 2019, Woodhead Publishing. p. 409-447.
27. Sohail M, R.A., Butt MS, Iqbal MJ, Rashid S. , *Rice bran nutraceutics: a comprehensive review.* . Crit Rev Food Sci Nutr, 2017. **57:3771–80.**
28. Charoonratana, T., *Chapter 36 - Cold pressed rice (Oryza sativa) bran oil*, in *Cold Pressed Oils*, M.F. Ramadan, Editor. 2020, Academic Press. p. 391-403.
29. Goga, G., et al., *Performance and emission characteristics of diesel engine fueled with rice bran biodiesel and n-butanol.* Energy Reports, 2019. **5**: p. 78-83.
30. Raghu R, R.G., *Optimization of injection timing and injection pressure of a DI diesel engine fueled with preheated rice bran oil.* . J Homepage Www IJEE IEEFoundation Org 2011;2:661–70.
31. Brijesh, P. and S. Sreedhara, *Exhaust emissions and its control methods in compression ignition engines: A review.* International Journal of Automotive Technology, 2013. **14**(2): p. 195-206.
32. VK., M., *Improving of emissions and performance of rice brawn oil in medium grade low heat rejection diesel engine.* . Int J Renew Energy Resour 2013;3:98–108.
33. Agarwal AK, D.A., *Comparative performance, emission, and combustion characteristics of rice-bran oil and its biodiesel in a transportation diesel engine.* J Eng Gas Turbines Power 2010;132:64503.
34. Saravanan S, N.G., Rao GLN, Sampath S. , *Feasibility study of crude rice bran oil as a diesel substitute in a DI-CI engine without modifications.* . Energy Sustain Dev 2007;11:83–92., 2007.
35. Saravanan S, N.G., Sampath S. , *Multi response optimisation in emission control of CI engine fuelled with crude rice bran oil blend.* . Int J Oil Gas Coal Technol 2012;5:106–20., 2012.
36. Krishna MVSM, R.N., Prasad BA, Murthy PVK. , *Comparative performance with different versions of low heat rejection combustion chambers with crude rice bran oil.* . Arch Mech Eng 2014;61:627–51., 2014.
37. Rakopoulos DC, R.C., Giakoumis EG. , *Impact of properties of vegetable oil, bio-diesel, ethanol and n-butanol on the combustion and emissions of turbocharged HDDI diesel engine operating under steady and transient conditions.* . Fuel 2015;156:1–19., 2015.
38. Koder, A., et al., *Combustion and emission characteristics of a 2.2L common-rail diesel engine fueled with jatropha oil, soybean oil, and diesel fuel at various EGR-rates.* Fuel, 2018. **228**: p. 23-29.
39. Hazar, H., *Effects of biodiesel on a low heat loss diesel engine.* Renewable Energy, 2009. **34**(6): p. 1533-1537.
40. AT., H., *Experimental study on spray and emission characteristics of a diesel engine fueled with preheated bio-oils and diesel fuel.* . Energy 2019;171:795–808.https://doi.org/10.1016/j.energy.2019.01.076., 2019.
41. Deng, X., et al., *Production of biodiesel from Jatropha oil catalyzed by nanosized solid basic catalyst.* Energy, 2011. **36**(2): p. 777-784.
42. Abedin, M., et al., *Performance, emissions, and heat losses of palm and jatropha biodiesel blends in a diesel engine.* Industrial Crops and Products, 2014. **59**: p. 96-104.
43. Chauhan, B.S., et al., *Performance and emission study of preheated Jatropha oil on medium capacity diesel engine.* Energy, 2010. **35**(6): p. 2484-2492.
44. Tainaka, K., et al., *Effects of blending crude Jatropha oil and heavy fuel oil on the soot behavior of a steam atomizing burner.* Renewable Energy, 2019. **136**: p. 358-364.
45. Hoang AT, L.A., Pham VV. , *A core correlation of spray characteristics, deposit formation, and combustion of a high-speed diesel engine fueled with Jatropha oil and diesel fuel.* Fuel 2019;244:159–75., 2019.

46. Hoang, A.T. and A.T. Le, *A review on deposit formation in the injector of diesel engines running on biodiesel.* Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 2019. **41**(5): p. 584-599.
47. Bazooyar, B., A. Ghorbani, and A. Shariati, *Combustion performance and emissions of petrodiesel and biodiesels based on various vegetable oils in a semi industrial boiler.* Fuel, 2011. **90**(10): p. 3078-3092.
48. Che Mat, S., et al., *Performance and emissions of straight vegetable oils and its blends as a fuel in diesel engine: A review.* Renewable and Sustainable Energy Reviews, 2018. **82**: p. 808-823.
49. Khan, S.A., et al., *Prospects of biodiesel production from microalgae in India.* Renewable & Sustainable Energy Reviews, 2009. **13**(9): p. 2361-2372.
50. Norhafana, M., et al., *Emission Characteristics Effect on Rice Bran Oil Enriched with Diesel Fuel on Compression Ignition Engine,* . IOP Conf. Proceeding. , 2021.
51. Adhikesavan, C., D. Ganesh, and V. Charles Augustin, *Effect of quality of waste cooking oil on the properties of biodiesel, engine performance and emissions.* Cleaner Chemical Engineering, 2022. **4**: p. 100070.
52. Sumathi, S., S.P. Chai, and A.R. Mohamed, *Utilization of oil palm as a source of renewable energy in Malaysia.* Renewable and Sustainable Energy Reviews, 2008. **12**(9): p. 2404-2421.
53. Loh, S.K., et al., *First Report on Malaysia's experiences and development in biogas capture and utilization from palm oil mill effluent under the Economic Transformation Programme: Current and future perspectives.* Renewable and Sustainable Energy Reviews, 2017. **74**: p. 1257-1274.
54. Ali, M., et al., *Prospects of microalgal biodiesel production in Pakistan – A review.* Renewable and Sustainable Energy Reviews, 2017. **80**: p. 1588-1596.
55. Mahmudul, H.M., et al., *Production, characterization and performance of biodiesel as an alternative fuel in diesel engines – A review.* Renewable and Sustainable Energy Reviews, 2017. **72**: p. 497-509.
56. Constantino, A.F., et al., *Determination of physicochemical properties of biodiesel and blends using low-field NMR and multivariate calibration.* Fuel, 2019. **237**: p. 745-752.
57. Corral-Gómez, L., et al., *Effect of diesel-biodiesel-ethanol blends on the spray macroscopic parameters in a common-rail diesel injection system.* Fuel, 2019. **241**: p. 876-883.
58. Fu, J. and S.Q. Turn, *Characteristics and stability of biofuels used as drop-in replacement for NATO marine diesel.* Fuel, 2019. **236**: p. 516-524.
59. Zaharin, M.S.M., et al., *Evaluation on physicochemical properties of iso-butanol additives in ethanol-gasoline blend on performance and emission characteristics of a spark-ignition engine.* Applied Thermal Engineering, 2018. **144**: p. 960-971.
60. Norhafana, M., et al., *Experimental Investigation on Performance Characteristics Evaluation of Compression Ignition Engine using Rice Bran Oil as Renewable Fuel*. Engineering Technology International Conference (ETIC 2022), 2022.
61. Tonini, S., M. Gavaises, and A. Theodorakakos, *The role of droplet fragmentation in high-pressure evaporating diesel sprays.* International Journal of Thermal Sciences, 2009. **48**(3): p. 554-572.
62. Ma, L. and D. Roekaerts, *Structure of spray in hot-diluted coflow flames under different coflow conditions: A numerical study.* Combustion and Flame, 2016. **172**: p. 20-37.
63. Ali, O.M., et al., *Analysis of blended fuel properties and engine performance with palm biodiesel–diesel blended fuel.* Renewable Energy, 2016. **86**: p. 59-67.
64. Altarazi, Y.S.M., et al., *Effects of biofuel on engines performance and emission characteristics: A review.* Energy, 2022. **238**: p. 121910.
65. Hoang, A.T. and V.V. Pham, *Impact of Jatropha Oil on Engine Performance, Emission Characteristics, Deposit Formation, and Lubricating Oil Degradation.* Combustion Science and Technology, 2018.
66. Dabi, M. and U.K. Saha, *Performance, combustion and emissions analyses of a single-cylinder stationary compression ignition engine powered by Mesua Ferrea Linn oil-ethanol-diesel blend.* Cleaner Engineering and Technology, 2022. **8**: p. 100458.
67. Norhafana, M., et al. *An experimental study of the performance and emission characteristics of a compression ignition (CI) engine fueled with palm oil based biodiesel*. in *AIP Conference Proceedings*. 2019.
68. Hoang, A.T. and V.V. Pham, *A review on fuels used for marine diesel engines.* Journal of Mechanical Engineering Research and Developments, 2018. **41**(4): p. 22-32.
69. Cao DN, H.A., Luu HQ, Bui VG, Tran TTH. , *Effects of injection pressure on the NOx and PM emission control of diesel engine: a review under the aspect of PCCI combustion condition.* Energy Sources, Part A Recover Util Environ Eff 2020. https://doi.org/10.1080/15567036.2020.1754531., 2020.
70. Surya Kanth, T.A., Sumita Debbarma, Biplab Das, *Effect of fuel opening injection pressure and injection timing of hydrogen enriched rice bran biodiesel fuelled in CI engine.* International Journal of Hydrogen Energy 46 (2021) 28789 - 28800, 2021.
71. Aldhaidhawi, M., R. Chiriac, and V. Badescu, *Ignition delay, combustion and emission characteristics of Diesel engine fueled with rapeseed biodiesel – A literature review.* Renewable and Sustainable Energy Reviews, 2017. **73**: p. 178-186.
72. *The approximation of the laws of the Member States relating to measures to be taken against the emission of gaseous and particulate pollutants from compression ignition engines for use in vehicles, and the emission of gaseous pollutants from positive ignition engines fuelled with natural gas or liquefied petroleum gas for use in vehicles and amending Council Directive 88/77/EEC* **Official Journal of the European Union**, 2000. **Directive 1999/96/EC (2000)**(L44: 1 - 155).
73. Heywood, J., *Internal combustion engine fundamentals*. 1988: McGraw Hill.
74. Chhabra, M., A. Sharma, and G. Dwivedi, *Performance evaluation of diesel engine using rice bran biodiesel.* Egyptian Journal of Petroleum, 2017. **26**(2): p. 511-518.

75. Wan Ghazali, W.N.M., et al., *Effects of biodiesel from different feedstocks on engine performance and emissions: A review.* Renewable and Sustainable Energy Reviews, 2015. **51**: p. 585-602.
76. Dalla Nora, M., T.D.M. Lanzanova, and H. Zhao, *Investigation of performance and combustion characteristics of a four-valve supercharged two-stroke DI engine fuelled with gasoline and ethanol.* Fuel, 2018. **227**: p. 401-411.
77. Yusri, I.M., et al., *Evaluation of engine combustion and exhaust emissions characteristics using diesel/butanol blended fuel.* Applied Thermal Engineering, 2019.
78. Rajasekar, E. and S. Selvi, *Review of combustion characteristics of CI engines fueled with biodiesel.* Renewable and Sustainable Energy Reviews, 2014. **35**: p. 390-399.
79. Ravikumar, M., A. Sivashankar, and S. Suresh, *Effects of rice bran oil blends and engine load on emission characteristics of a variable compression ratio diesel engine.* Materials Today: Proceedings, 2021. **45**: p. 1188-1190.
80. Patel, A., et al., *Sustainable biodiesel production from oleaginous yeasts utilizing hydrolysates of various non-edible lignocellulosic biomasses.* Renewable and Sustainable Energy Reviews, 2016. **62**: p. 836-855.
81. Silitonga, A.S., et al., *Pilot-scale production and the physicochemical properties of palm and Calophyllum inophyllum biodiesels and their blends.* Journal of Cleaner Production, 2016. **126**: p. 654-666.
82. Venu, H., L. Subramani, and V.D. Raju, *Emission reduction in a DI diesel engine using exhaust gas recirculation (EGR) of palm biodiesel blended with TiO2 nano additives.* Renewable Energy, 2019. **140**: p. 245-263.
83. Xiao, H., et al., *Combustion performance and pollutant emissions analysis of a diesel engine fueled with biodiesel and its blend with 2-methylfuran.* Fuel, 2019. **237**: p. 1050-1056.
84. Liu, S., et al., *Effect of a cetane number (CN) improver on combustion and emission characteristics of a compression-ignition (CI) engine fueled with an ethanol− diesel blend.* Energy & Fuels, 2010. **24**(4): p. 2449-2454.
85. Das, P., P.M.V. Subbarao, and J.P. Subrahmanyam, *Effect of cetane number and fuel properties on combustion and emission characteristics of an HCCI-DI combustion engine using a novel dual injection strategy.* SAE Technical Papers, 2015.