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Original Article

A Comparative Study on Diesel Engine Performance Characteristics with Hybrid Blended Biodiesels

Santhosh Poojary[1*], Sushanth H. Gowda[2]

[1]*Nitte (Deemed to be University), NMAM Institute of Technology (NMAMIT), Department of Biotechnology Engineering, Nitte, Karnataka, India.*
[2]*Department of Mechanical Engineering, St Joseph Engineering College, Mangaluru, Karnataka, India.*

**Corresponding Author: drsanthoshnellikatte@gmail.com*

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Abstract - *In the present comparative study, the biodiesel was produced from four non-edible seed oils sourced from Pongamia Pinnata, Scleropyrum Pentandrum, Calophyllum Inophyllum, Hevea Brasilensis Plants, and Waste Cooking Oil (WCO) from local hotels. The property of the biodiesel is determined by the fatty acid components of the base oil. When the fatty acid esters are formed, the individual fatty acid ester contributes to the overall fuel property of the biodiesel. If the physical property relationship is understood, then the desired quality biodiesel can be obtained by blending different proportions of fatty acid alkyl esters. Ultimately, the expected quality of biodiesel must perform the best in the engine. Based on this concept, the hybrid blends were prepared, and their important physical properties were compensated using a combination of biodiesels. To study the effect of hybrid blending, i.e., the internal mixing of biodiesels, a combination of hybrid blends with complementary fuel properties was obtained by mixing Pongamia (P100), Waste cooking oil (W100), Scleropyrum (S100), Calophyllum (C100), and Hevea (H100) biodiesels, referred to as PWSCH blends. The 10% and 20% individual and combination of these blends were investigated for engine performance, combustion, and emission characteristics on a single cylinder, four-stroke, direct injection, Compression Ignition (CI) Diesel Engine, and these data were compared with pure petroleum diesel characteristics. It was found that the hybrid blending technique can be applied to compensate for fuel properties, and a lower percentage of hybrid blends can be utilized in CI engines along with conventional biodiesel blends.*

Keywords - *Non-edible seed oil, Biodiesel, Hybrid blend, Engine performance, Combustion, Emission.*

1. Introduction

In the current increasing environmental pollution issues and the persistent demand for sustainable energy options, biodiesel has raised as a viable substitute for traditional diesel fuel [1]. The advent of hybrid blended biodiesels, a combination of traditional biodiesels and fossil fuels, offers an exciting opportunity to influence the benefits of renewable energy while maintaining the performance characteristics essential for diesel engines [2]. As an alternative fuel, biodiesel presents an environmentally friendlier option than conventional diesel, with continuous advancements [3]. Leveraging non-edible, underutilized feedstocks from indigenous sources for the production of biofuels is the most effective method to resolve the issue of food competing with fuel.

The exhaustive study on numerous non-edible oil biodiesels fuel properties, performance, and emission studies reported that the non-edible oil biodiesels can perform admirably in diesel engine applications and reduce most regulated emissions [4]. The biodiesel production process for non-edible seed oil is not entirely different from that for edible oil sources [5]. However, the presence of higher FFA and gummy substances may incur additional costs. Base- or acid-catalyzed transesterification, a cheaper and widely accepted method, can be used to produce biodiesel from these sources on a pilot scale for domestic applications even in rural settings.

Blending biodiesel with traditional fossil fuels is another effective strategy for improving fuel efficiency and environmental performance [6]. Common blends, such as B10 (containing up to 10% biodiesel) and B20 (20% biodiesel), allow users to enjoy the benefits of both fuel types while minimizing the impact on engine performance [7]. This blending process can be performed at distribution terminals, where biodiesel is added to petroleum diesel before it is distributed locally. The incorporation of biodiesel enhances fuel lubricity and increases the cetane number, which is essential for optimal engine combustion and efficiency [8]. By utilizing these blends, consumers can reduce their carbon footprint while maintaining the reliability and performance of their diesel engines. Implementing advanced engine technologies is essential for maximizing the performance of biodiesel and ensuring a seamless transition to this renewable fuel source [9]. Innovations such as the application of nanoparticles can significantly improve internal combustion engine efficiency when using biodiesel as an alternative fuel [10]. Furthermore, research into the compatibility of biodiesel with existing diesel engines is ongoing, addressing potential challenges and enhancing overall performance. As manufacturers adopt these advanced technologies, the benefits of biodiesel, including improved public health and environmental outcomes, become increasingly evident [11]. Fostering a collaborative approach between fuel production and engine technology can pave the way for a more sustainable and efficient transportation system. As the biodiesel research has continued for decades, the realistic usage is ever-increasing all over the world. There are numerous sources that have been added to the biodiesel production feedstock list.

The ultimate biodiesel usage in any application requires stringent quality compliance. One of the methods of improving biodiesel fuel properties is by complementary blending, which is proposed by many researchers. Moser [12] studied the pennycress and seed oil from meadow foam-based biodiesel properties enhancement by complementary blending with palm, cottonseed, camelina, and soybean biodiesels and achieved improved viscosity, low temperature operation, and oxidative stability properties. Chen et al. [13] investigated the improvement of non-edible Tung oil biodiesel properties by blending with palm and coconut biodiesels at 60:20:20 and complemented the desired properties except oxidation stability.

Wakil et al. [14] reported the blending of rice bran, sesame, and Moringa oil biodiesels and reported noteworthy effects on fuel properties. Even though numerous diesel blends of biodiesel have been studied extensively, there is scant literature on the production and engine study of a mixture of biodiesel-diesel blends obtained from various sources. Arbab et al. [15] used a binary blend of palm oil and coconut oil-based biodiesel to improve the fuel properties and engine performance and reported that a 20% binary blend showed greater performance and emission characteristics. Nalgundwar et al. [16] reported that lower proportions of palm-jatropha dual blends can certainly improve performance characteristics (except NOx) of a direct injection diesel engine.

The main objective of the present study is to produce biodiesel from four non-edible seed oils sourced from Pongamia Pinnata, Scleropyrum Pentandrum, Calophyllum Inophyllum, Hevea Brasilensis Plants, and Waste Cooking Oil (WCO), and dwelling into the comparative analysis of diesel engine characteristics when utilizing mixtures of hybrid blended biodiesels, focusing on parameters such as engine performance, combustion, and emission analysis.

2. Materials and Methods

The non-edible seed and oils were ethically procured from farmers and local hotels through a fair price negotiation. For biodiesel synthesis, methanol as an alcohol reagent, sulfuric acid (serving as the acid catalyst), and sodium hydroxide (acting as the base catalyst) were employed. All these analytical grade chemicals were procured from E. Merck and used without any additional modifications.

2.1. Biodiesel Production

The transesterification reaction is carried out in a 2L capacity, 3-neck flat-bottom, batch glass-reactor, which is fitted with a spiral reflux condenser for alcohol recovery. The oil is preheated to the desired temperature, and base catalyst for good quality oil and acid catalyst for oil with high free fatty acid content, along with methanol, are reacted [17]. The glass reactor is conventionally heated using a Rota-Mantle setup incorporated with a heating mantle and magnetic stirring arrangement (600-800 revolutions per minute) for 1-2 hours. The reaction mixture is added to a separating funnel and left to settle the glycerol phase. The biodiesel production, purification, and fuel characterization are performed at Udupi District Bioenergy Research, Information & Demonstration Centre (BRIDC) with standard protocol. The flowchart of the biodiesel production process is shown in Figure 1.

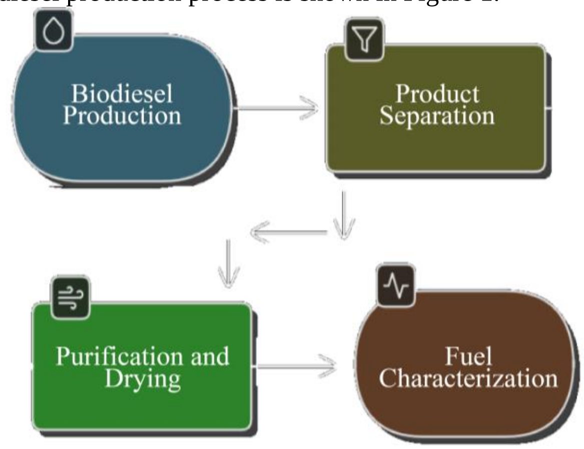

Fig. 1 Biodiesel production process flowchart

2.2. Engine Experimental Setup

The research involved a comprehensive experimental setup where a conventional diesel engine test rig was used under identical conditions, using three different fuel types: standard diesel, 10% usual, and hybrid blended biodiesel, and 20% usual and hybrid blended biodiesel. Key performance metrics such as brake power, fuel consumption, and emissions were meticulously recorded during each test run.

The study utilized state-of-the-art emission analysis equipment to quantify exhaust constituents, including Hydrocarbons, Nitric Oxides (NO_x), Carbon Monoxide (CO), Carbon Dioxide (CO_2), and smoke opacity. The Engine and Emission Analyzers specifications are tabulated in Table 1.

Table 1. Engine and emission analyzers specifications

Component	Specifications
Engine	Kirloskar-India, model- TV1 with IC Engine Software for Data Analysis Single-cylinder Direct injection (220 bar pressure), naturally aspirated, water-cooled 4-stroke (stroke length -110 mm) Bore (87.5mm) Displacement volume- 661.5 cm3, Variable compression ratio (12:1 - 18:1) 3.5 kW rated power at a constant Speed of 1500 RPM
Multi-Gas Analyzer	Model: NETEL-NPM-MGA- 1
Smoke Meter	Model: NETEL-NPM-SM-111B

Table 2. Comparative fuel properties

Fuel	**Fuel properties**		
	Density (kg/m^3)	**Viscosity (mm^2/sec)**	**Calorific value (MJ/kg)**
D100	827	3.32	42.25
P100	894	5.73	38.96
W100	873	4.82	40.64
S100	889	5.46	40.13
C100	891	5.49	39.67
H100	883	5.32	38.53
PWSCH100	884	5.31	39.70

3. Results and Discussion

3.1. Hybrid Biodiesels Fuel Properties

The property of biodiesel is influenced by the fatty acid composition of the parent oil [18]. If the physical property relationship is understood, then the desired quality biodiesel can be obtained by blending different proportions of fatty alkyl esters. Ultimately, an expected quality of biodiesel is to perform the best in the engine. Based on this concept, the hybrid blends were prepared, and their important physical properties (Table 2) were compensated using a combination of biodiesels. To study the effect of hybrid blending, i.e., the internal mixing of biodiesels, one combination of hybrid blend with complimented fuel property was obtained by mixing Pongamia (P100), Waste Cooking Oil (W100), Scleropyrum (S100), Calophyllum (C100) and Hevea (H100) biodiesels referred as PWSCH and the details of blends provided at the abbreviations section.

3.2. Engine Performance Analysis

To evaluate the effect of hybrid blending, the 10% and 20% combination of usual and hybrid blends were investigated for engine performance, combustion, and emission characteristics on a direct injection, four-stroke, single cylinder, Compression Ignition (CI) Diesel Engine, and these data were compared with pure petroleum diesel characteristics. All the experiments were carried out at predefined optimum conditions of the engine for biodiesel operation, a constant engine speed of 1500 RPM at a compression ratio of 18:1, injection timing 21^{0}CA BTDC, and the fuel was injected with 240 bar injection pressure at various engine loads.

The Brake Power (BP), Brake Specific Fuel Consumption (BSFC), Brake Thermal Efficiency (BTE), and Engine Exhaust Gas Temperature (EGT) were compared for all fuel blends [19]. The percentage uncertainty of reading was found to be +0.1% for combustion pressure, crank angle measurement, and +0.2% for load measurement, and for temperature and fuel measurement, the uncertainty was +1 %.

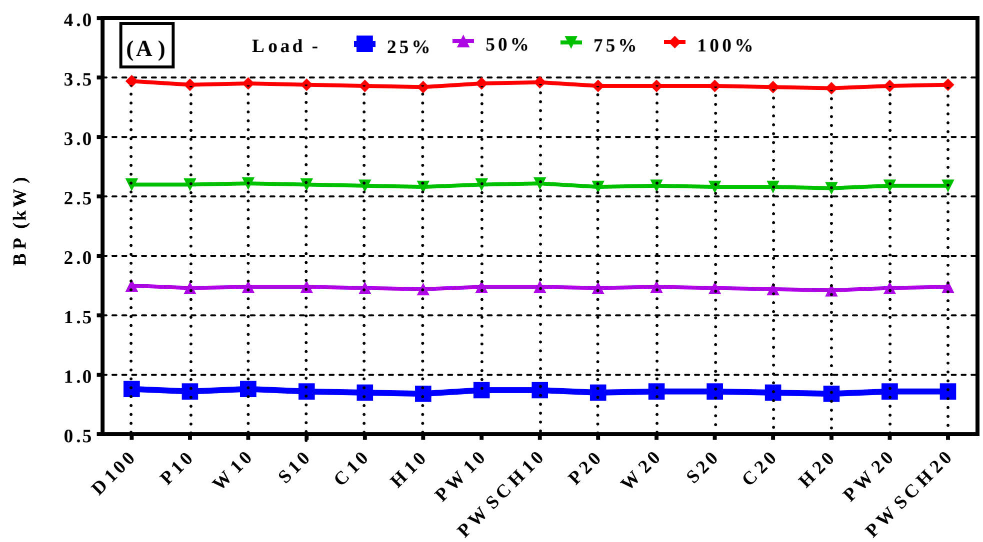

Fig. 2 Comparison of Brake Power (BP) (kW)

The Brake Power (BP) developed for different fuel blends at different engine loads is shown in Figure 2. On an average, for all loads, the W10, S10, C10, PW10, SCHPW10, W20, S20, PW20 biodiesel blends showed almost similar brake power compared to D100. For P10, H10, P20, C20, H20, PWSCH20 blends, 0.5-1% reduction in BP was observed, which may be because of their lower calorific value as well as mixed performance for hybrid blends [20].

Brake Specific Fuel Consumption (BSFC) comparison is shown in Figure 3. Even though overall BSFC for biodiesel blends was higher than D100 at the engine optimum condition, compared to the original engine operating condition, the increase in BSFC for higher percentage biodiesel blends deteriorated. The Pongamia, Hevea biodiesel blends showed higher (BSFC) due to the fact that their lower calorific values [21, 22]. It is observed that novel hybrid biodiesel blends PW10, PWSCH10, PW20, and PWSCH20 compensated for the BSFC of lower calorific value biodiesel blends and showed improved performance. Hence, it is scientifically evident that the decrease in fuel consumption is the result of hybrid blending.

The Brake Thermal Efficiency (BTE) of different fuel blends compared to petro-diesel is shown in Figure 4. At the original engine operating condition, the BTE of biodiesel blends was slightly lower than D100 at lower and full load conditions, but at engine conditions, specifically at 75% load, W10, S10, C10, PW10, and PWSCH10 blends had better thermal efficiency, and the BTE of 20% biodiesel blends also improved. The optimal combination of saturated and unsaturated methyl esters may have enhanced the combustion efficiency of hybrid biodiesel blends, leading to higher thermal efficiency [20, 23]. The BTE of higher calorific value biodiesel blends was found to be better, and also biodiesel blends with lower calorific value and higher density had lower BTE, because of poor combustion efficiency. However, the combination blended the deficiencies of the individual blends and demonstrated improved performance.

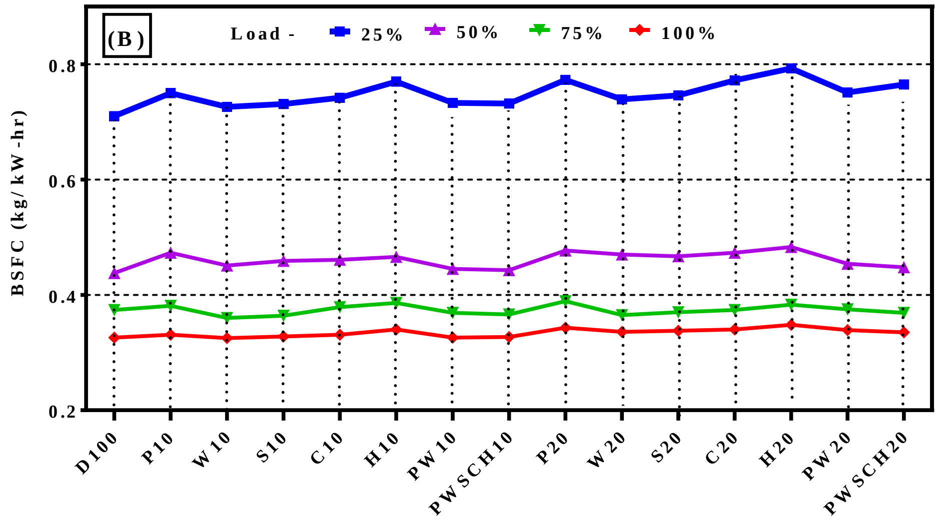

Fig. 3 Comparison of Brake Specific Fuel Consumption (BSFC) (kg/kW-hr)

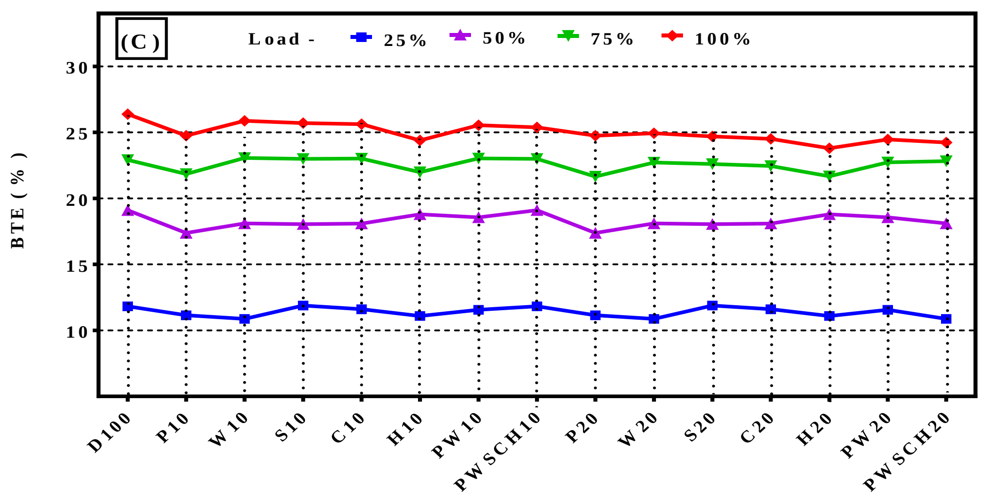

Fig. 4 Comparison of Brake Thermal Efficiency (BTE) (%)

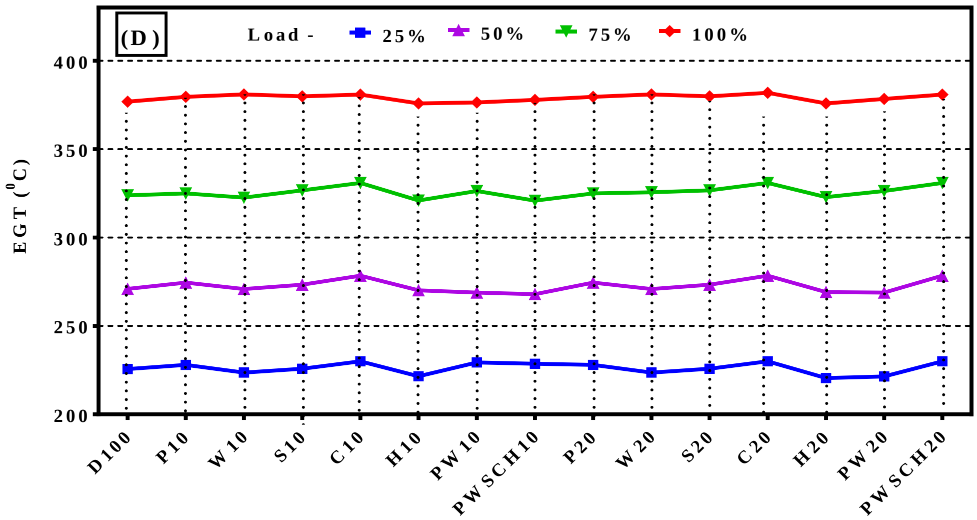

Fig. 5 Comparison of Exhaust Gas Temperature (EGT) (^{0}C)

The comparison of the Exhaust Gas Temperature (EGT) trend for different fuel blends at different loads is shown in Figure 5. In the original engine operating condition, the D100 had the lowest EGT at all engine loads compared to all other biodiesel blends, but at the optimum condition, the blends H10 and H20 showed lower EGT than D100. But for other biodiesel blends, including hybrid biodiesel blends, especially P10, W10, S10, P20, W20, S20, the EGT was on average 3-4^0 °C higher than D100 [24]. At the optimum hybrid blend, the performance of a higher percentage biodiesel blend increased, thereby minimizing heat loss through EGT.

3.3. Engine Combustion Analysis

The combustion characteristics were compared between individual biodiesel blends and hybrid blends. To reduce cyclic variations in the combustion analysis, the average data for 100 cycles at the engine's full load condition were recorded in the IC engine software, yielding mean values for graphical representation with statistical inference.

The Cylinder Pressure (CP) variations for different fuel blends are shown in Figure 6. The average peak cylinder pressure of D100, W10, S10, and PW10 was found to be similar to that of all other blends. However, at the original engine operating condition, all biodiesel blends exhibited higher peak pressure at full load. Since there was a slight increase in ignition delay for hybrid biodiesel blends, which might have caused more fuel accumulation at the premixed combustion stage, resulting in reduced peak pressure [25].

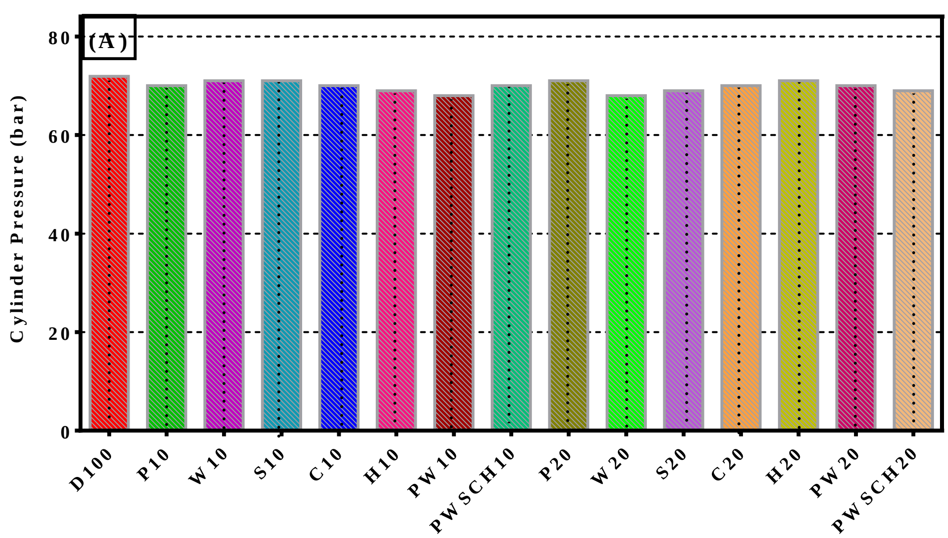

Fig. 6 Comparison of average cylinder pressure (bar)

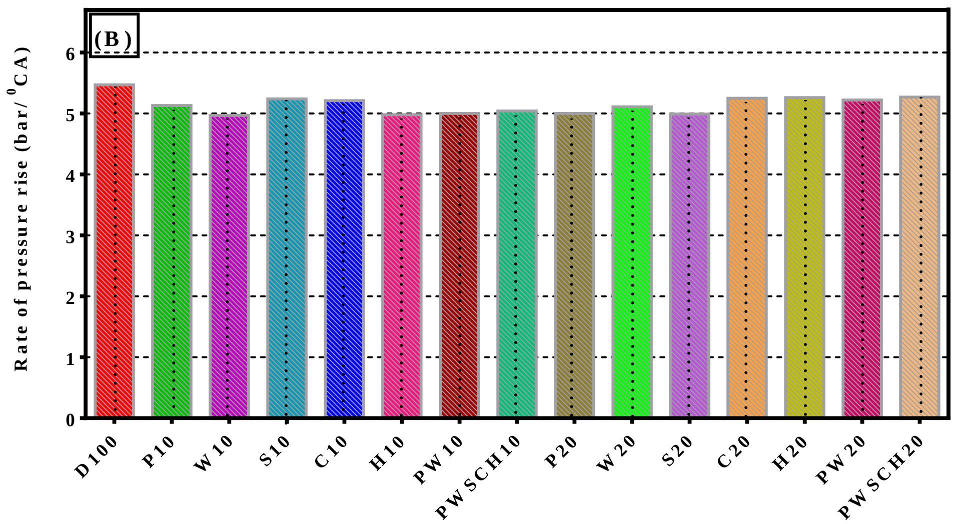

Fig. 7 Comparison of average rate of pressure rise (bar/ ^{0}CA)

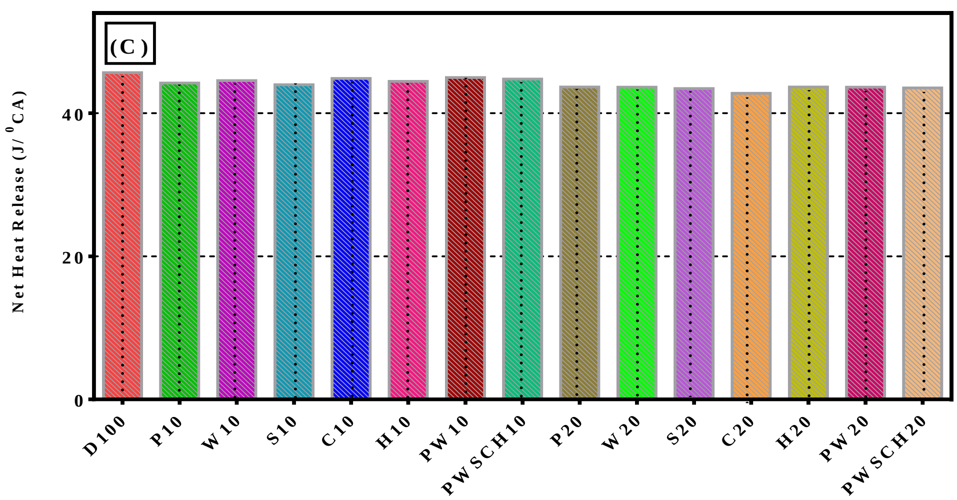

Fig. 8 Comparison of average net heat release (J/^{0}CA)

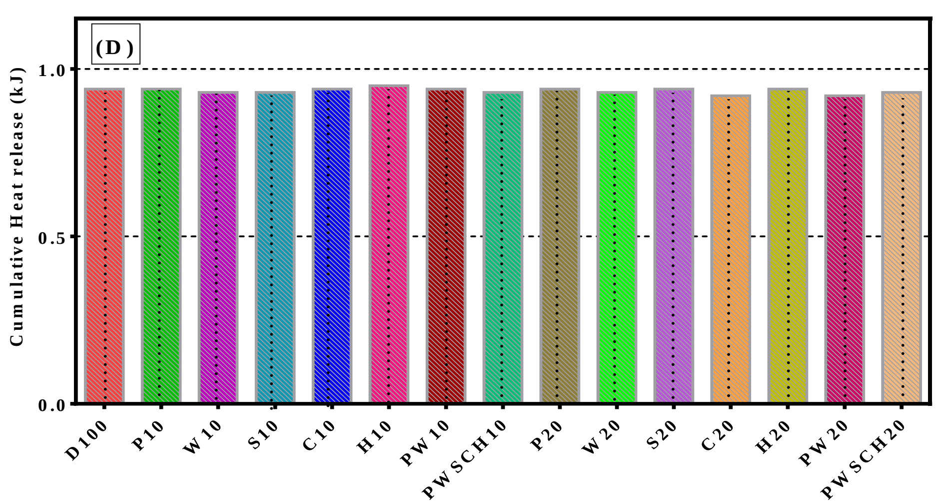

Fig. 9 Comparison of average cumulative heat release (kJ)

The Pressure Rise Rate values (RPR_{Max}) for all fuel blends are shown in Figure 7. The maximum value of pressure rise was obtained for D100 as 5.47 bar per crank angle. The blends S10, C10, C20, H20, PW20, and PWSCH20 showed very close RPR_{Max} in comparison with D100. As observed in the case of usual biodiesel blends, there was a minor variation in the RPR_{Max} value of hybrid blends and D100 at optimum engine conditions of biodiesel operation.

The peak value of Net Heat Release Rate (NHR_{Max}) of fuel blends is represented in Figure 8. The D100 showed the highest NHR_{Max} since conventional Petro-diesel has more calorific value compared to all other biodiesel blends [26]. The biodiesel blends W10, C10, PW10, and PWSCH10 had the highest NHR_{Max} among other blends, but it was less than that of D100.

The maximum Cumulative Heat Release (CHR_{Max}) for fuel blends, as determined by the software based on the area under the net heat release curve, is shown in Figure 9. Because of better atomization and combustion, the heat release rate was comparatively higher at the diffusion combustion phase for all biodiesel blends [27]. Hence, the CHRMax of individual and hybrid biodiesel blends was almost equal to D100.

The comparison of Start of Combustion (SOC), 5%, 10%, 50%, 90% of Mass Fraction Burn (MFB), and End of Combustion (EOC) Crank Angles (^{0}CA) for different fuel blends is shown in Figure 10. The SOC for D100 and H20 (14^{0}CA BTDC), P10, H10, P20, S20, PW20 (15^{0}CA BTDC), S10, C10, PW10, PWSCH10, C20 (16^{0}CA BTDC) and for W10, C20, W20 (17^{0}CA BTDC) was recorded. Compared to D100, slight variations in 5%, 10%, 50% and 90% MFB rates were recorded for all biodiesel blends as it was observed at original engine operating conditions [28]. At optimum engine conditions, also compared to D100, the overall combustion duration of biodiesel blends ranged between 51^{0}CA-56^{0}CA, which was slightly higher than D100 combustion duration (50^{0}CA) because of prolonged diffusion combustion of biodiesel blends.

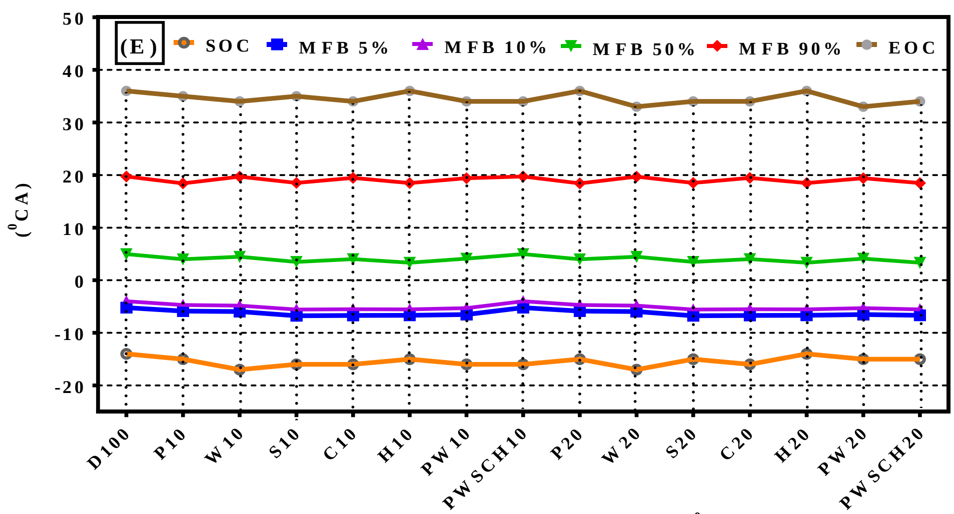

Fig. 10 Comparison of average mass fraction burn (^{0}CA)

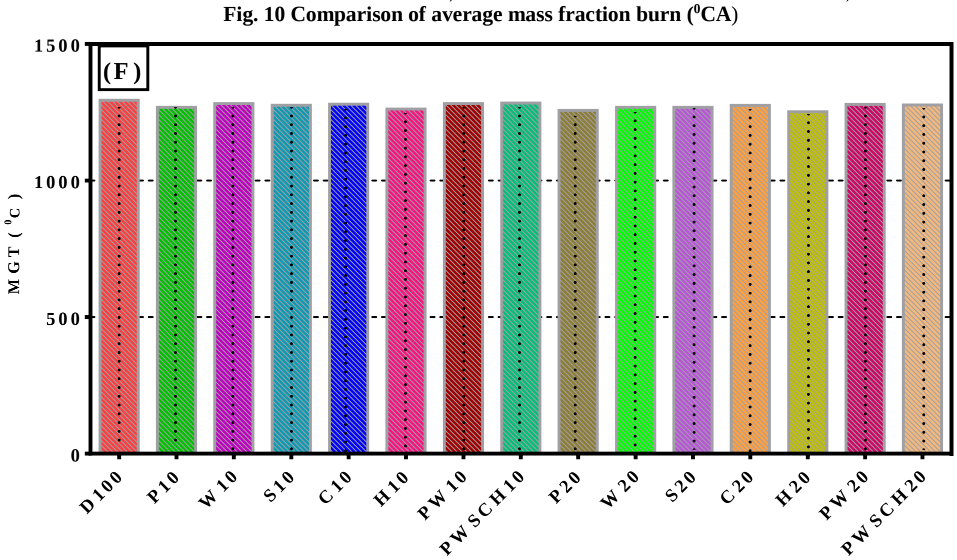

Fig. 11 Comparison of average mean gas temperature (^{0}C)

The maximum in-cylinder Mean Gas Temperature (MGT_{Max}) calculated by the IC engine software for different fuel blends is compared in Figure 11. It is evident from the MGT plot that the blend W10, C10, PW10, PWSCH10, PW20 showed the highest MGT peak value. The lower percentage biodiesel blends showed comparatively higher MGT value because of better combustion [29]. At optimum engine operating conditions, the reduction in MGT value for the hybrid blend was not prominent, as it was observed at original engine operating conditions.

3.4. Engine Emission Analysis

The engine exhaust gas emission analysis of fuel blends was conducted by varying the engine loads using a calibrated multi-gas exhaust emission analyzer and a smoke meter. The percentage uncertainty of UBHC, NO_x, and smoke is below 0.01% and CO, CO_2, and O_2 have the measurement improbability less than 0.02%.

The comparison of fuel blends HC emissions at various engine loads is shown in Figure 12. In comparison with individual biodiesel blends, the hybrid biodiesel blends PW10, PW20, PWSCH10, and PWSCH20 showed almost similar HC emission profiles. Since the formation of HC depends on the prevailing engine conditions, there was no notable difference observed between the biodiesel blends, but compared to HC emissions of D100, the biodiesel blends reduced hydrocarbon emissions by 15-20% [30].

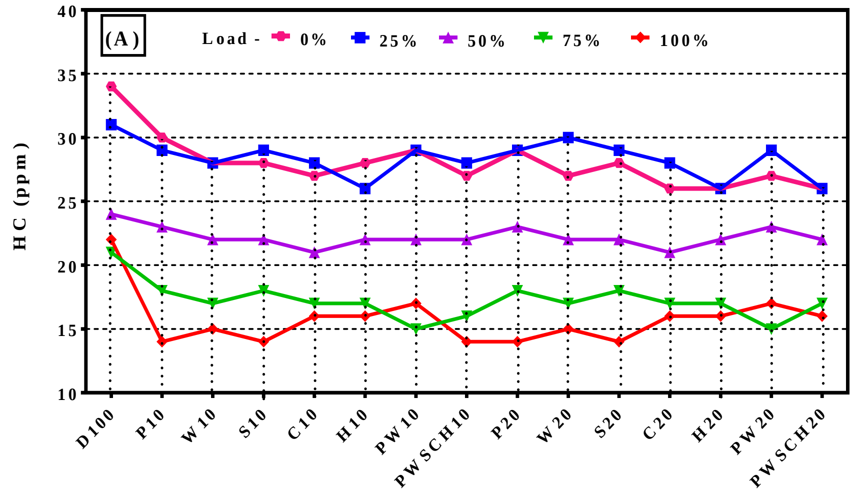

Fig. 12 Comparison of HC emissions (ppm)

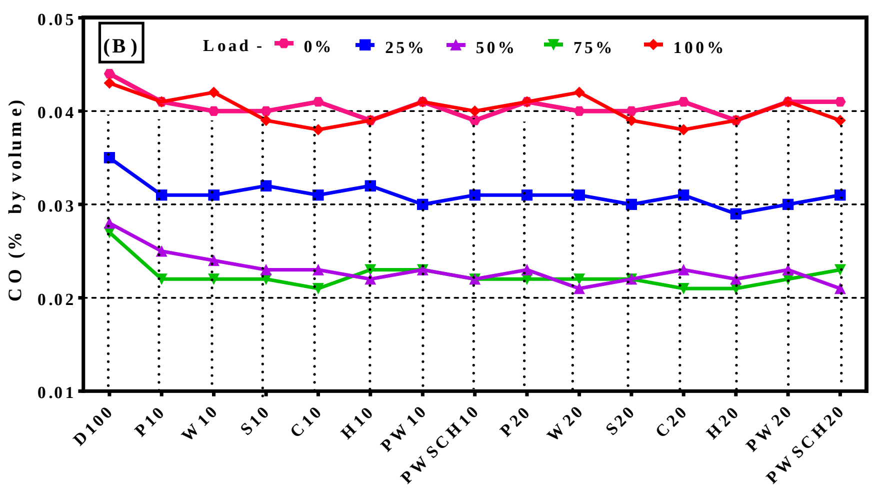

Fig. 13 Comparison of CO emissions (% by volume)

In Figure 13, the variation of CO for D100, individual, and hybrid biodiesel blends is shown for various engine loads. The CO emissions were significantly lower for all biodiesel blends than for the D100 because oxygenated biodiesel blends improved combustion. Similar to HC emissions, the difference between D100 and biodiesel blends in CO emissions was predictable, but between the biodiesel blends, it was not significant. But higher percentage biodiesel blends (20%) showed reduced CO emission due to higher oxygen content [31].

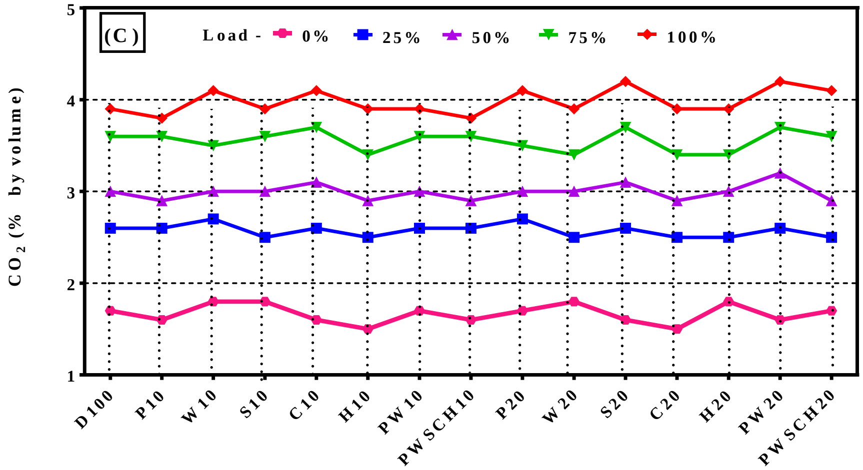

Fig. 14 Comparison of CO_2 emissions (% by volume)

The variation in Carbon Dioxide (CO_2) emissions for fuel blends at different loads is shown in Figure 14. The CO_2 emissions of biodiesel blends were closer to those of D100 at optimum engine conditions, due to the inherent oxygen content and improved combustion, which led to the formation of more CO_2. The individual 10% blends, namely W10, S10, PW10, and PWSCH10, also exhibited higher CO2 emissions, primarily due to their excellent combustion.

In fact, CO_2 emissions were slightly higher for lower percentages of biodiesel blends, as diesel has a high carbon-to-hydrogen ratio, which also contributes to CO_2 emissions [32].

The comparison of NOx emissions for fuel blends at various engine load conditions is depicted in Figure 15. It was noticed that, for all biodiesel blends, at optimum engine conditions of biodiesel operations, the NO_x emissions slightly decreased compared to original engine operating conditions. Since the injection timing was retarded, the mean gas temperature developed inside the engine cylinder was slightly decreased; hence, NO_x emissions were reduced compared to the engine's original condition, but it was still higher than the NO_x emissions caused by D100. The individual Pongamia, Scleropyrum, and Hevea biodiesel blends produced slightly higher NO_x emissions because of higher unsaturation [33], and hybrid blends showed intermediate NO_x emission profiles.

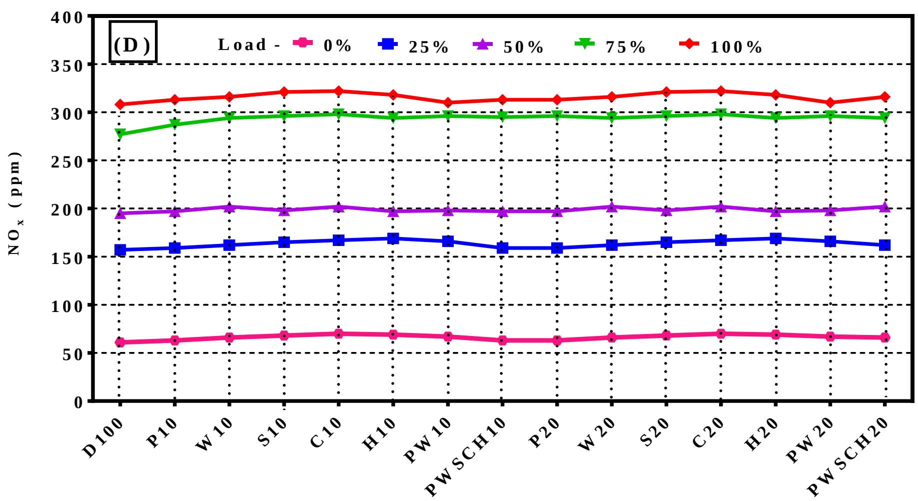

Fig. 15 Comparison of NOx emissions (ppm)

The comparison of Smoke Opacity (SO) values of fuel blends is shown in Figure 16. Compared with D100 smoke emissions, the SO values of all biodiesel blends, including hybrid blends, were reduced. But at lower loads, the average SO values were similar to D100, because of the incomplete combustion, as the trend was similar to the CO emission at lower loads. The reduction of SO values for biodiesel blends was clearly observable at higher loads [34].

The comparison of Oxygen concentration (O_2) in the engine exhaust circulation of fuel blends is shown in Figure 17. The oxygen concentration decreases as the load increases for fuel blends because the air-fuel ratio decreases with load. It is observed that petro-diesel exhaust contains slightly less O_2 compared to biodiesel blends because of the lack of oxygen in the hydrocarbon structure of diesel. There was only a 1-2% variation of O_2 concentration in D100 and individual, hybrid biodiesel blends [35].

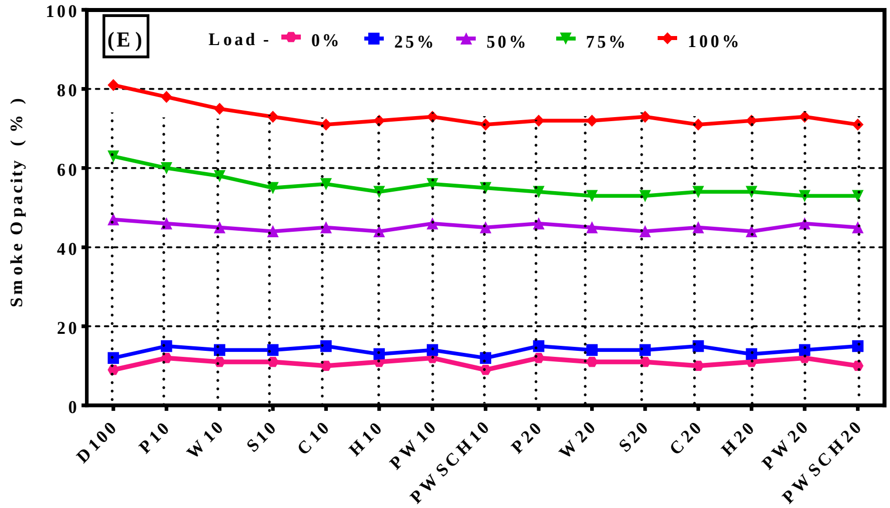

Fig. 16 Comparison of Smoke Opacity (%)

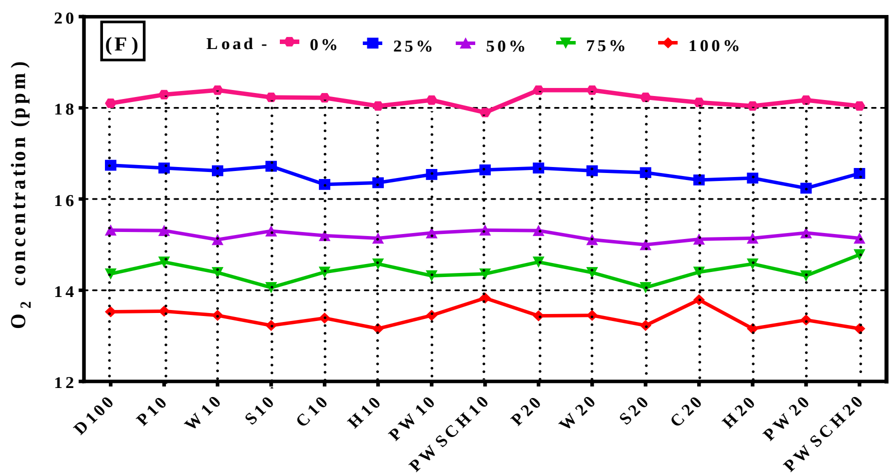

Fig. 17 Comparison of O_2 concentration in exhaust emission (ppm)

4. Conclusion

The engine performance comparison study between the blending of only one type of biodiesel with diesel and a varied percentage of biodiesel was well demonstrated. The present comparative study demonstrated an insight into the mixture of biodiesels (novel hybrid biodiesels) with diesel can perform similarly or even better than individual biodiesel blends. Hence, from this investigation, it can be suggested that the use of a lower percentage of hybrid biodiesels with diesel to overcome the deficiencies of individual biodiesel fuel properties in future practical applications. The comparative study highlights the viability of hybrid blended biodiesels as alternatives to traditional diesel fuels, highlighting the potential benefits of reduced emissions, environmental impact, and sustainable fuel usage. While performance characteristics may vary and the implementation of blended biodiesels requires careful attention to engine calibration and efficiency, the overall findings support further exploration and development of hybrid biodiesel technologies. The pursuit of hybrid solutions not only addresses pressing ecological challenges but also pushes the automotive industry towards a more sustainable future. This study encourages researchers, engineers, and policymakers to collaborate in advancing biodiesel technology and in implementing legislative measures that foster the adoption of renewable biofuels. The combined efforts will pave the way for a cleaner, more sustainable transportation landscape, where hybrid blended biodiesels can play a pivotal role in transitioning from fossil fuel dependency.

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Fuel Blend Abbreviations

D100	-	100% Diesel
P100	-	100% Pongamia biodiesel
P10	-	10% P100+ 90% Diesel
P20	-	20% P100+ 80% Diesel
W100	-	100% Waste cooking oil biodiesel
W10	-	10% W100+ 90% Diesel
W20	-	20% W100+ 80% Diesel
PW10	-	5% P100+ 5% W100 + 90% Diesel
PW20	-	10% P100+ 10% W100 + 80% Diesel
S100	-	100% Scleropyrum biodiesel
S10	-	10% S100+ 90% Diesel
S20	-	20% S100+ 80% Diesel
C100	-	100% Calophyllum biodiesel
C10	-	10% C100+ 90% Diesel
C20	-	20% C100+ 80% Diesel
H100	-	100% Hevea biodiesel
H10	-	10% H100+ 90% Diesel
H20	-	20% H100+ 80% Diesel
PWSCH100	-	30% P100+50% W100+5% S100+10% C100+5% H100
PWSCH10	-	10% PWSCH100+ 90% D100
PWSCH20	-	20% PWSCH100+ 80% D100