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Original Article

Combustion Study of Sustainable Hybrid of Jatropha and Waste Cooking Biodiesel-diesel Blends on CI Engine

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Abstract *- Hybrid biodiesel signifies blending biodiesels sourced from non-edible oil jatropha and waste cooking oil. The pressure variation inside the engine cylinder with hybrid biodiesel shows different behavior than raw diesel at various loads. Still, there is a minor change in crank angle degrees at which peak pressure is produced, which is aligned with the efficient operation of the engine. At low load conditions, hybrid biodiesel blends produce higher peak pressure than diesel. Still, peak pressure values are nearly identical as the load reaches its 100% capacity. The beginning of combustion for hybrid biodiesel samples is earlier than diesel but varies about 1 to 3o of crank angle. The value of the peak rate at which pressure increases for diesel fuel at low load is 1.83 bar/deg and increases with load, attaining 6.71 bar/deg at full load condition. The value of* the peak rate at which pressure increases *at low load for a hybrid biodiesel fuel sample containing 5% biodiesel each (J5W5) is 2.56 bar/deg and increases with load attaining 6.47 bar/deg at 100% loading condition. The maximum limit of the rate at which heat is released for different hybrid biodiesel blends at full load ranges from 53.39 J/CAD for J10W10 to 58.32 J/CAD for J5W5. The combustion analysis performed on hybrid biodiesel blends reveals that the lowest biodiesel proportion blend (J5W5) performed nearly identical to diesel fuel for various loading conditions.*

Keywords *- Hybrid biodiesel, Mass fraction burned, Ignition delay, Heat Release Rate (HRR), Rate of Pressure Rise.*

1. Introduction

Ever-increasing energy demand has led to extensive use of conventional fuels in fast dwindling and environmental deterioration [1]. Diesel, a non-renewable energy source, is an extensively used form of energy in India specifically by the transportation sector. About 66% of the total energy consumed by the transportation sector accounts for diesel. Energy use by India's transportation sector is growing at a rate of 5.5%, which is the fastest in the world. Crude oil production during 2022-23 is at 29.18 Million Metric Tonnes (MMT). Around 12.6% of our oil demand is fulfilled through indigenous sources; currently, 87.4% depend on imported crude oil to fulfill the domestic oil market [2]. An emerging nation like India lacks the financial capacity to spend a huge sum on imports and increase the trade deficit [3]. The widespread utilization of conventional fuels for various commercial and residential activities has led to human health problems due to its emissions. Considering technological and environmental aspects, the development of sustainable biofuels (Biodiesel (BD) and ethanol) can be seen as a long-term solution [4]. Sustainability is a balance between economic, social, and environmental factors [5]. The biodiesel refers to alkyl esters that are suitable for use in diesel engines as fuel due to their comparative properties with diesel fuel [6]. Biodiesel is a substitute for diesel and has less global warming potential because carbon present in biodiesel originates from the air [7]. Besides reducing air pollution and providing energy security, biodiesel usage in India can also generate rural employment [8]. The national biodiesel mission launched by the Indian Government was focused on only one feedstock, namely jatropha, to achieve a 20 percent blending target with diesel. Still, it could not be materialized due to insufficient feedstock supply and lower oil yield of jatropha [9].

From the total production cost of biodiesel, about 80 to 85 %age of the cost is attributed to feedstock cost. To establish a self-sustaining biodiesel industry, biodiesel production by blending feedstock can be a viable solution [10]. It is more economical to adopt locally developed liquid fuel in the blended form with diesel to suit the unmodified diesel engine than engine modifications to suit the new raw fuel [11]. India lacks the financial means to produce biodiesel using food oils and needs to focus on non-edible oils like jatropha, neem, Karanja, sal, etc., for biodiesel production as India is the importer of edible oils [12]. Apart from providing low-cost oil for biodiesel production, jatropha plantations would serve many benefits, like wasteland utilization, tribal community development, and a decrease in greenhouse gas emissions [13].

In 2003, the National Biodiesel Mission was launched, aiming for 20% BD blending with diesel by 2011-12. This mission was never achieved as biodiesel production depended on only non-edible seeds jatropha. Later, it was discovered that seed oil from jatropha could not fulfil the blending targets. This mission was eventually abandoned by August 2008 [14]. The Government of India declared a National policy on biofuels in 2018, aiming 10 % reduction of the import of crude oils by 2022 by producing biofuels from indigenous and sustainable feedstocks like animal fats, oils not suited for people's consumption, and oils discarded as waste, also called second generation feed stocks [15]. But the Central Government, through the Ministry of Petroleum & Natural Gas, amended the National Policy on Biofuels -2018 in 2022, citing an indicative target of 5% blending of biodiesel in diesel /direct sale of biodiesel proposed up to 2030 by setting up new Second Generation (2G) biorefineries and developing new feed stocks [16].

Although there has been a significant increase in interest in the electric transportation system, ethanol and biodiesel, in combination, continue to represent over 90% of renewable transport fuels. In 2017, a total of 336.5 million barrels of biodiesel were manufactured worldwide [17]. The biodiesel blends consist of biodiesels derived from waste oils and fats and non-food oils can be very effective solutions to meet supply challenges faced by biodiesel industries. Under Indian conditions, a non-edible oil-yielding jatropha plantation is best suited due to its adaptability to waste and arid land and higher oil yield in comparison to other plants [18, 19]. Vegetable edible oil consumption in India has grown by six percent to 24.3 MMT as a result of population growth, expansion of the food processing sector, and spurring demand from household and bulk buyers, and about 65 percent of the total demand is met by imports [20]. The majority of vegetable oil is employed for deep frying and its improper disposal causes serious water contamination and human health problems [21]. Cooking oil waste can produce biodiesel economically because it is quite less expensive than vegetable oil [22].

Even though BD has numerous good qualities as a substitute for mineral diesel fuel, it also has a few drawbacks. These include a high cost for the raw materials, increased emissions of regulated NOx from the exhaust, poor stability when stored, limited availability, and poor performance at low temperatures [23]. To address the issue of inadequate BD characteristics, combining BDs in two is an easy, affordable, yet efficient approach. The characteristics of mixed BDs can be roughly gauged through statistical equations, considering the link between BD traits and the fatty acid profile [24-26]. A lot of studies have been conducted on enhancing the properties of fuels by combining two or more BDs, and these findings have been presented in academic journals. However, there is a scarcity of studies focusing on the combustion, performance, and emission analysis of blends of BD and diesel, whether they are dual BD or mixed BDs and diesel blends [27-31]. No publication is available for combustion analysis of hybrid BD produced by mixing jatropha and waste-cooking biodiesel and blending it with diesel.

2. Material and Methods

2.1. Materials

Jatropha oil was derived from jatropha plant seeds harvested in the wasteland for producing biodiesel. The waste cooking oil was procured from a local city restaurant. As the waste cooking oil contains impurities like food particles and gums, it requires a settlement time of at least 48 hours and a filtration process to remove these impurities. The chemicals like alcohol, sulphuric acid (H_2SO_4), and potassium hydroxide (KOH) needed for the trans-esterification process were purchased from the local chemical shop.

2.2. Biodiesel Production

The acid value of the oils, generally expressed as an amount of KOH in mg to neutralize 1 g of oil, is decided by the titration method. An alkaline catalyst is not suitable for high FFA (>1%) oils due to soap formation. The jatropha and waste cooking oils have an acid value greater than 4mg KOH/g, so acid esterification as a pre-treatment to reduce FFA below 1% and then followed by base trans-esterification using alkaline catalyst are preferred for biodiesel production [32]. A two-neck flask made of glass was utilized for biodiesel production. A spiral-form glass tube condenser was fitted in one neck to condense evaporated alcohol, while a second neck was used to enter oil and reactants. The reaction temperature for both oils was 60 oC, and 98% pure sulphuric acid (1% v/v) was employed for acid and base esterification processes. For jatropha oil, 99.9% pure methanol was used at 50% v/v for acid esterification and 25% v/v for transesterification process. For waste cooking oil, methanol was used at 50% v/v for acid esterification and 37% v/v for transesterification process. The molar ratio for acid esterification for both the oils was 12:1, and for the trans-esterification process, for jatropha, 6:1 and for waste cooking oil, 9:1 was maintained. The total time to complete the reaction for jatropha oil was 4h, and for waste cooking oil, it took 4.5h at a constant stirring speed of 800 rpm. Hot water washing was performed on BD at 60 ^{o}C for 3 to 4 times to remove the excess catalyst, alcohol, and by-products. The colour of the produced BD is distinguishable: waste cooking oil biodiesel is reddish black, while jatropha biodiesel is light yellow, as depicted in Figure 1.

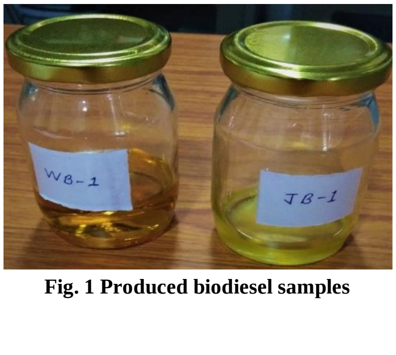

Fig. 1 Produced biodiesel samples

Table 1. Tabulated numerical values of some important Physical and chemical properties of jatropha BD, waste cooking BD, and the D100

Properties	Unit	Diesel	Jatropha BD	Waste Cooking BD
Kinematic viscosity (@ 40 °C)	cSt	2.96	4.16	4.85
Density (@ 15 °C)	gm/cm^3	0.83	0.866	0.906
Calorific value	MJ/kg	42	39.87	37.14
Flashpoint	°C	69	168	156
Cloud point	°C	2	4	13
Pour point	°C	-6	-2	8
Cetane number		50	52	56
Oxidation stability (@110 °C)	hr	65	3.1	11.5

Table 1 displays the chemical and physical parameter values of waste cooking biodiesels, jatropha, and neat diesel.

2.3. Test Fuel Preparation

Six test fuel samples were tested in total; one sample was prepared using neat diesel, and the other five mixed equal volumes of waste cooking biodiesel and jatropha with diesel.

Jatropha and waste cooking biodiesel each have a percentage of blending of 5% by volume with 90% diesel (J5W5); 10% with 80% diesel (J10W10); 15% with 70% diesel (J15W15); 20% with 60% diesel (J20W20); and 25% with 50% diesel (J25W25). By agitating the mixture in a stirring blender for ten minutes at 1000 rpm, the hybrid biodiesel samples were produced.

3. Experimental Setup

A Kirlosker single-cylinder water-cooled computerized diesel engine of 3.5 kW rated power and 1500 rpm rated speed is chosen for the experimental setup. It is also outfitted with an eddy current dynamometer and loading unit. The test rig is equipped with various measurement devices and sensors like piezo sensors, crank angle sensors, temperature sensors, and load sensors, along with a data acquisition unit. To measure parameters like peak pressure, heat release rate, mass fraction burned, and start and end of combustion, all of which are necessary for combustion analysis, the experimental configuration is outfitted with the necessary instrument, and signals generated from sensors are interfaced with a computer for data analysis. The line diagram of the set-up is shown in Figure 2, whereas the actual set-up is as per Figure 3.

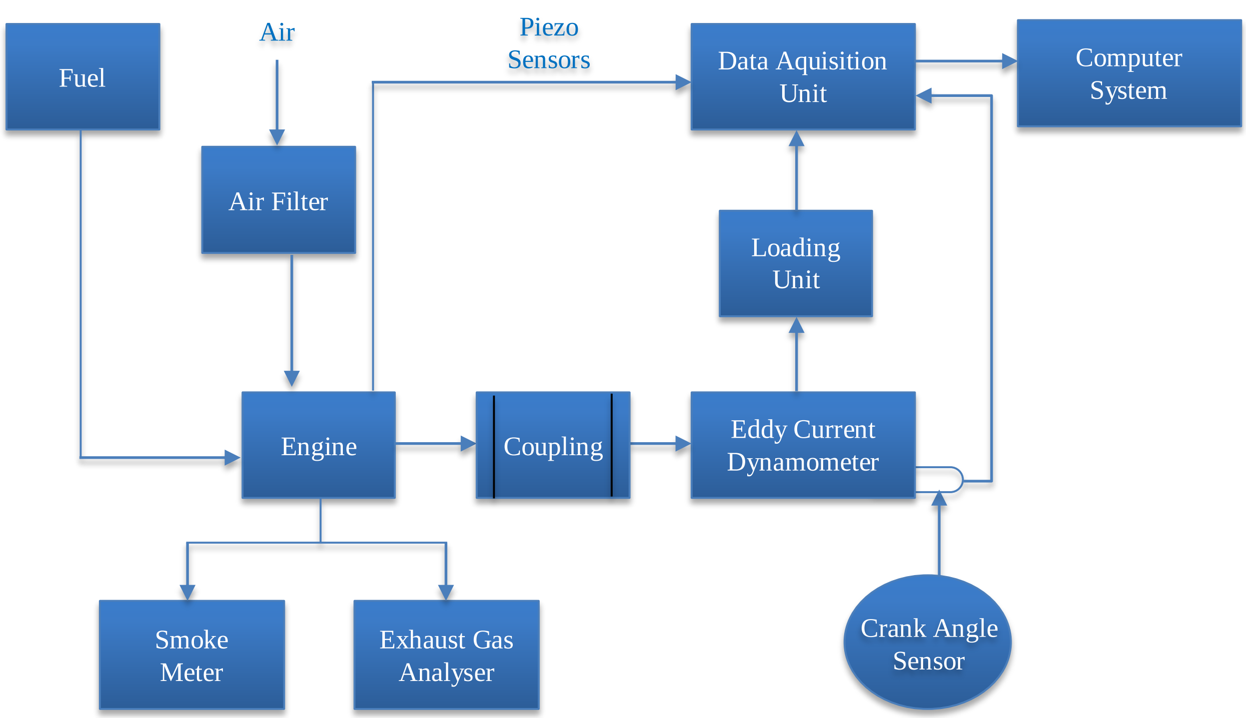

Fig. 2 Line diagram of experimental set-up with necessary fitments

Fig. 3 Computerized diesel engine test rig

4. Results and Discussions

Diesel fuelled engines are called compression ignition engines, as the combustion of injected fuel takes place in highly compressed and heated air. Therefore, in these engines, a high ratio of compression is employed to finely scatter the injected fuel to facilitate evaporation, mixing with air, and subsequent combustion. In order to reduce emissions and BSFC while ensuring that other engine performance characteristics remain within acceptable limits, one must comprehend the effect of the properties of hybrid BD blends on combustion and HRR [33]. The highest pressure achieved inside a CI engine is dependent on the amount of fuel accumulated and burned during the premixed burning phase, known as the first phase of burning. The fuel's capacity to burn and mix well with air is governed by the pressure inside the cylinder [34]. In order to examine the combustion parameters of the hybrid biodiesel fuel samples by baseline fuel, a total of six fuel samples, including D100, were tested on the engine. Combustion characteristics such as variation of in-cylinder pressure, rate of pressure rise, heat release rate of the fuel, and %age of fuel mass burned, concerning crank angle, were analyzed at different engine loads. Table 2 presents the numerical values of different combustion parameters measured from no load to full load conditions for all hybrid BD blends and D100.

Table 2. Numerical data of various combustion parameters for all hybrid BD blends and D100

		Maximum Cylinder Pressure (bar)		**Mass Fraction Burned at an Angle**		**Net Heat Release Rate (J/CAD)**		**Rate of Pressure Rise (RPR) in (bar/CAD)**	
Fuel	Load (%)	Maximum Pressure	Angle	10 % burn	90 % burn	Maximum HRR	Angle (°)	Maximum RPR	Angle (°)
Diesel	0	44.15	367	-5.96	12.04	15.32	358	1.83	358
	25	51.6	366	-6.74	10.93	28.47	355	3.19	355
	50	57.6	366	-7.98	11.37	37.78	353	4.52	353
	75	63.1	365	-8.98	10.12	53.03	352	6.36	352
	100	67.9	366	-9.29	14.29	58.22	352	6.71	352
J5W5	0	48.91	367	-7.09	7.86	17.69	354	2.56	354
	25	58.85	366	-8.23	9.48	30.45	353	3.93	353
	50	60.45	366	-9.18	11.37	43.12	352	5.11	353
	75	67.99	366	-9.38	13.15	57.87	351	6.37	351
	100	67.96	365	-9.6	12.75	58.32	352	6.47	352
J10W10	0	44.34	366	-6.85	10.84	15.65	357	2.08	356
	25	52.22	366	-7.78	8.89	29.45	355	3.63	355
	50	56.21	366	-7.21	10.93	38.24	354	4.55	354
	75	63.24	367	-8.34	12.29	47.61	353	5.51	353
	100	66.6	367	-9.43	14.15	53.39	351	5.93	351
J15W15	0	46.18	367	-6.73	9.41	16.92	358	2.11	357
	25	51.96	366	-7.53	10.16	26	355	3.29	355
	50	58.49	365	-8.46	14.55	39.04	353	4.7	353
	75	63.35	365	-9.58	11.53	52.06	352	6.19	352
	100	68.67	366	-9.97	14.23	54.05	351	6.42	351
J20W20	0	46.71	366	-6.88	9.25	16,71	357	2.18	356
	25	52.6	366	-7.53	9.44	27.55	355	3.46	355
	50	58.27	365	-8.25	11.34	42.02	353	4.95	353
	75	64.07	366	-9.3	12.55	54.04	352	6.12	352
	100	67.26	366	-9.67	12.78	56.51	351	6.24	351
J25W25	0	46.85	367	-6.92	10.06	16.51	356	2.2	356
	25	52.03	366	-7.26	9.76	26.57	354	3.4	354
	50	58.22	366	-8.21	12.23	40.21	352	4.76	352
	75	64.38	365	-10.4	11.66	52.75	351	5.96	351
	100	68.14	366	-10.56	13.45	56.07	350	6.11	350

4.1. Variation of in-Cylinder Pressure vs. Crank Angle

Figures 4(a)–(e) illustrate the changes in in-cylinder pressure for a crank angle for all hybrid BD blends and D100 under various engine loading conditions. A longer physical ignition delay caused by the biodiesel is higher boiling range may be the main reason for the early pressure rise observed for blends containing lower biodiesel volumetric proportions at lower engine loads when compared to diesel. Owing to a combined effect of properties like higher Cetane number, lower value of viscosity among blends, and increased molecular oxygen, the blend containing 5% biodiesel each in D100 exhibits 48.91 bar peak pressure when engine running with no load condition and follows the trend of generating peak pressure higher than all blends at higher loads.

The increased volatility of the biodiesel and high fuel viscosity result in poorer mixing characteristics and poorer spray atomization, offsetting the improved combustion performance exhibited by hybrid blends with increasing volumetric proportions of biodiesels in D100. For every test fuel, the pressure variation with crank angle along with peak pressure at maximum engine load is nearly identical.

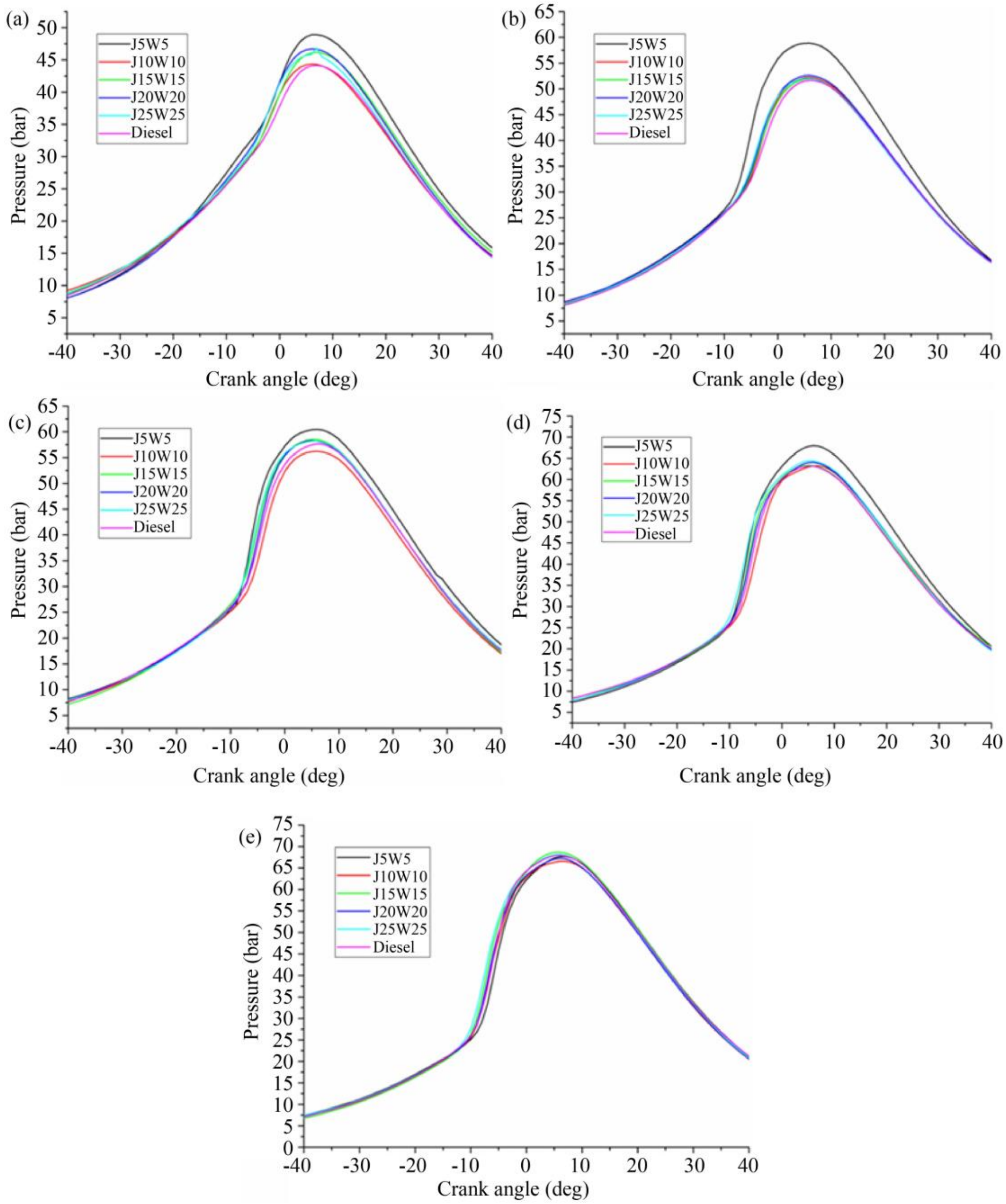

Fig. 4 variation of in-cylinder pressure w.r.t. crank angle at (a) No load, (b) 1/4th load, (c) Half load, (d) 3/4th load, and (e) Full load for all hybrid BD blends and D100.

The 5%, 10%, 15%, 20% and 25% by volume of each biodiesel blended diesel sample give maximum pressure values of 67.96, 66.6, 68.68, 67.26 and 68.14 bar, respectively, at full load, which is comparable to D100 maximum pressure of 67.94 bar which depicts similar behaviour of all blends at full load.

For hybrid BD blends, maximum pressure is reached between 5 to 7º aTDC (after the top dead centre), whereas, for D100, this angle is 6º a TDC at 100% loading operation of the engine. When the engine is operating at 100% load, the highest pressure values are nearly equal and are reached after TDC, ensuring the engine operates safely and effectively. A similar kind of trend was reported by Chen et. al [35].

4.2. Net Heat Release Rate vs. Crank Angle Diagram

The HRR is expressed in Joule per Crank Angle Degree (CAD). Figures 5 (a)–(e) show the HRR diagrams for all test fuels at variable loading conditions. The HRR shows negative values when combustion starts due to the cooling of the air-fuel mixture which is caused by the fuel vaporization. However, once combustion is started, a positive HRR is observed. Premixed air-fuel mixture and ignition delay have a big influence on how quickly the fuel releases heat.

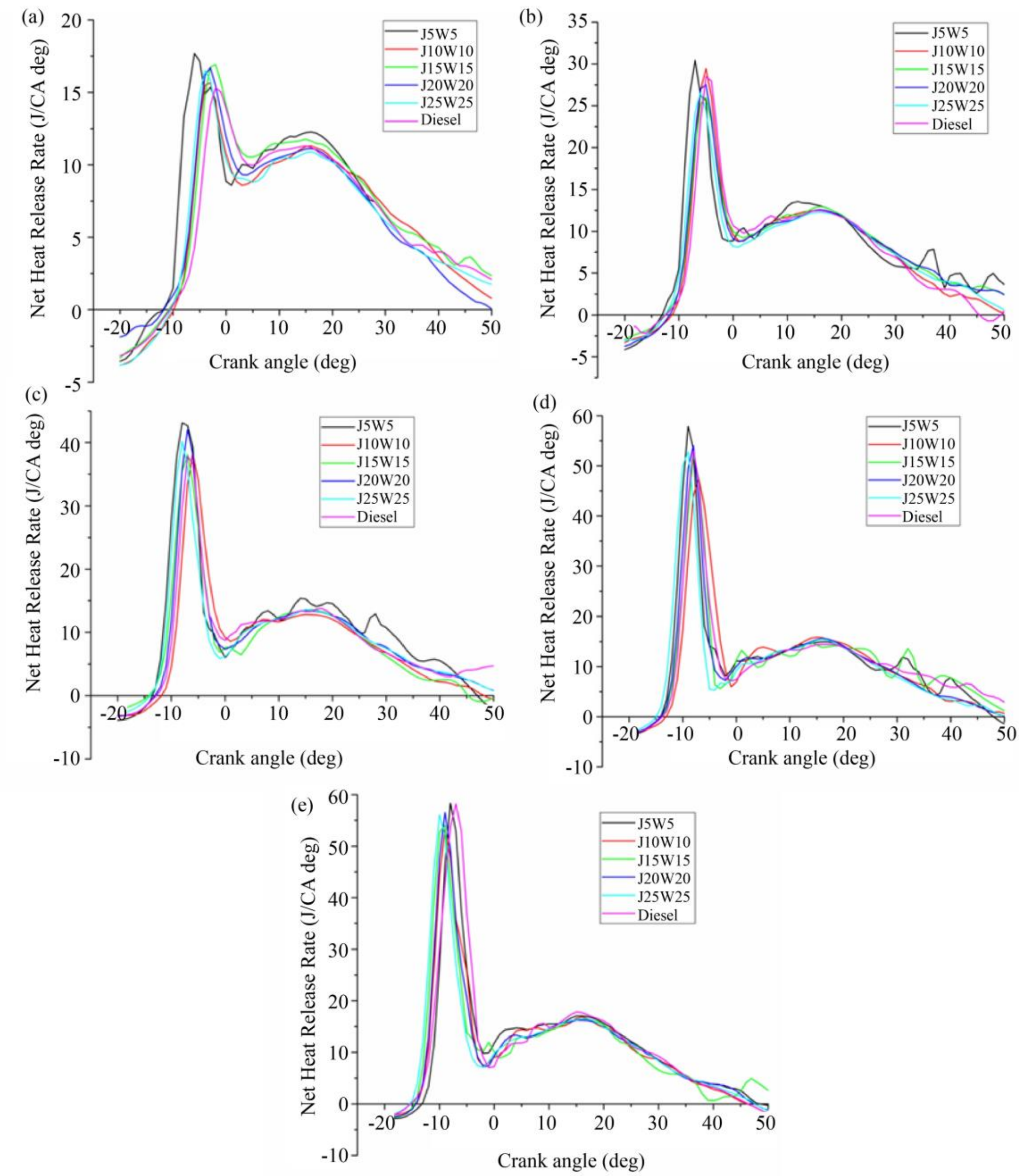

Fig. 5 Variation of net heat release rate w.r.t. crank angle for all hybrid BD blends and D100 at (a) No load, (b) 1/4th load, (c) Half load, (d) 3/4th load, and (e) Full load.

The HRR during the initial combustion phase, where the mixing of air and fuel takes place, is increased at lower as well as higher loads for hybrid BD blends containing lower volumes of BD in blends because of the ideal conditions for premixed combustion and improved combustibility, which is enhanced by the excess oxygen in the fuel. Because more fuel is injected and due to the existence of a favourable air-fuel ratio, all test fuels experience an increase in heat release during the second combustion phase, called controlled combustion, at higher engine loads.

4.3. Mass Fraction Burned (MFB) vs. Crank Angle Diagram

Figure 6 shows the variation of mass fraction burned for all fuel samples. In terms of crank angle degrees, the commencement of combustion is defined as a position of 10 percent of the fuel mass burned. 90 percent fuel mass burned is the indication of the end of combustion. The difference between the 90 percent and 10 percent mass fraction burned positions, expressed in crank angle degrees, is the combustion time [36].

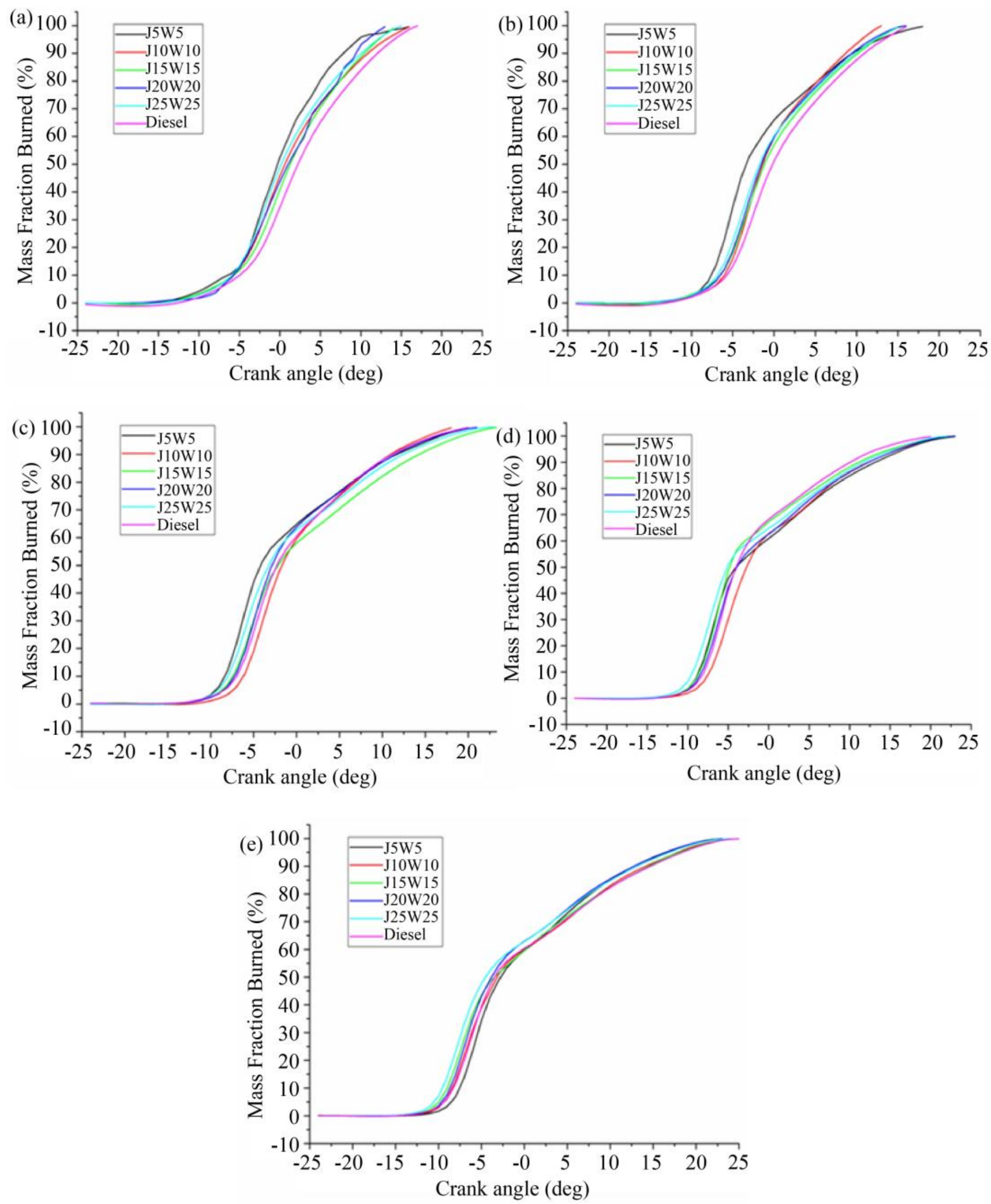

Fig. 6 Variation of %age mass burned w.r.t. crank angle for all hybrid BD blends and D100 at: (a) No load, (b) 1/4th load, (c) Half load, (d) 3/4th load, and (e) Full load.

The timing of the commencement of combustion for D100 and the hybrid BD blends having 5%,10%, 15%, 20%, and 25% by volume of each BD blended in diesel at no load was -5.96o , -7.09o, -6.85o , -6.73o, -6.88o, -6.92o respectively (-ve sign indicates bTDC). As a higher Cetane number yields a smaller ignition delay and BD has a higher cetane number as compared to D100, combustion begins earlier for hybrid BD blends under all engine operating loads. All fuels experience a reduction in ignition delay as engine load increases because high engine loads raise the temperature of gases present inside the engine cylinder, which shortens the physical ignition delay period. Among all the hybrid BD blends, the blend containing the lowest BD proportion in D100 exhibits 95 % mass fraction burned at 7º aTDC as compared to D100 for which it happens at 15º aTDC at no load. The combustion of D100 fuel and all hybrid BD blends advances as engine load increases. When compared to mineral D100, all BD blends exhibit an advanced commencement of combustion at no load, which may be caused by the relatively shorter ignition delay of BD blends.

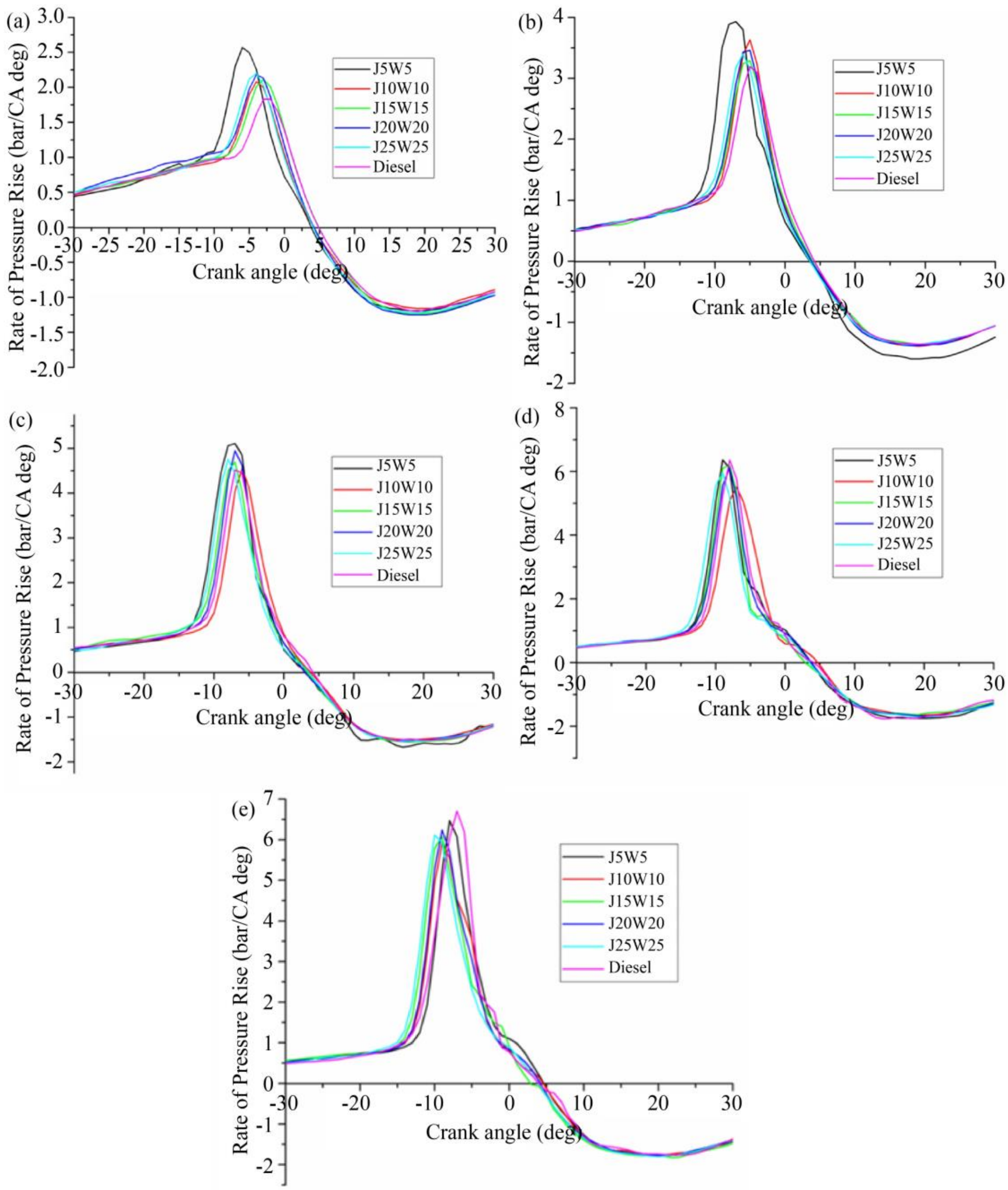

Fig. 7 Variation of the rate of pressure rise w.r.t. crank angle for all hybrid BD blends and D100 at (a) No load, (b) 1/4th load, (c) Half load, (d) 3/4th load, and (e) Full load.

Due to the higher viscous nature of the BD, at higher loads, the ignition of fuel becomes difficult, and a shorter delay period attributed to the higher cetane number is affected, rendering nearly the same start time of combustion for all hybrid BD blends and D100 fuel. The blend containing the lowest BD proportion in diesel showed the advancement in combustion start at lower loads, perhaps as a result of the best possible combination of the fuel's higher cetane value and the blend's decreased viscosity. At lower loads, hybrid BD blends are observed to take less time for 90 % mass fraction burned than D100 fuel; however, at higher engine loads, the time required for both D100 and hybrid BD blends is nearly equal.

4.4. The Rate of Pressure Rise vs. Crank Angle Diagram

Figures 7 (a)–(e) depict the change in the rate of pressure rise w.r.t. crank angle at different loads. For all fuel samples, including D100, The peak rate at which pressure increases rises continuously as the engine operates at different loading conditions, i.e. lower to higher loads. When there is no load, the peak rate at which pressure increases for D100 fuel is 1.83 bar/deg, and when there is a full load, it is 6.71 bar/deg. For the blend containing the lowest BD proportion in diesel, the same is 2.56 bar/deg at no load and 6.47 bar/deg at full load. When operating at full load, the peak rate at which pressure increases for the blend containing the lowest BD proportion in diesel is lower than that of D100 but higher than that of mineral D100 at lower loads.

Because excessive pressure rise can lead to knocking, noise from the engine, irregular engine operation, and negative effects on engine durability, it is thought to be significant. The optimum rate of pressure rise is 8 bar/CA deg for noise and vibration-free operation of the engine [37]. It is evident from the graph, and the values that all of the hybrid BD blends adhere to the diesel engine's knock characteristics because the pressure rise rate never exceeds 8 bar/CA degree under any loading conditions.

D100 and blends containing biodiesel go through the same combustion phases [37]. The peak rate at which pressure increases for D100 fuel is 1.83 bar/deg, which is less than that of hybrid BD blends and ranges from 2.08 to 2.56 bar/deg at no load. The reason is that, in these particular operating conditions, very little fuel is injected into the combustion chamber, and combustion for D100 fuel occurs after the TDC.

However, due to the higher HRR during the initial combustion phase, which is controlled by the intermixing of fuel and air and an increase in the amount of fuel injected with increasing load, the peak rate of pressure rise for D100 fuel is 6.71 bar/deg which higher than value for all hybrid BD blends at full load operating conditions.

5. Conclusion

The appropriateness of the liquid fuel to establish it as fuel for the engine can be ensured by carrying out a combustion analysis of the test fuel. The present study suggests that hybrid BD fuel produced by mixing inedible jatropha and waste cooking BD is quite suitable as a sustainable alternative fuel to mineral D100.

The hybrid BD blend J5W5 is found to produce higher maximum pressure (48. 91 bar) under no load operating conditions compared to D100 (44.15 bar). However, under full load, the maximum pressures of all hybrid BD blends vary around 68 bar, which is nearly the same as those of the D100 value of 67.9 bar, which renders safe operation of the engine. The total combustion time for the D100 and J5W5 blend is 23.58 deg and 22.35 deg at full load, respectively. The commencement of combustion for hybrid BD samples is earlier than D100 but varies about 1 to 3º of crank angle. For all hybrid BD blends, the ignition delay is closer to D100 at full load but shorter at lower loads than D100.

Among all the hybrid BD blends, the blend containing the lowest BD proportion in diesel exhibits a 95 % mass fraction burned at 7º aTDC as compared to D100, for which it happens at 15º aTDC at no load. This advancement may be caused by the lower viscosity of the blend attributed to lower BD volumetric proportion along with the higher cetane number of the blend. For the J5W5 hybrid blend, the same is 2.56 bar/deg at no load and 6.47 bar/deg at full load. When the peak HRR at full load is taken into account, the blend containing the lowest BD proportion in diesel provides results that are almost exactly the same as those of D100 fuel. Because of its overall improved combustion performance at no load that is comparable to D100 performance under full load conditions, the blend containing the lowest BD proportion in diesel (J5W5) can be regarded as optimal.

The HRR graphs are not so conclusive about heat release rate and BD blends. This preliminary analysis reveals that the combustion performance of selected hybrid BD blends is similar to D100, but further research is necessary on the timing of injection, injection pressure, and injection duration to have more insight into combustion behaviour in the diesel engine.

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