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Investigations into the Combined Effect of Mahua Biodiesel Blends and Biogas in a Dual Fuel Engine

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Abstract: Rapid depletion of conventional fuel sources has led to the use of alternative fuels and implementation of variant engine technologies to reduce deleterious emissions being released and deliver thermal energy for numerous applications. This research aims to study the usage of mahua methyl ester in a single-cylinder 4-stroke CI engine, optimized to operate in the dual fuel mode. Performance, combustion and emission characteristics are recorded and compared with diesel with the sole aim of finding the blend that provides adequate performance and diminishing emissions. To this effect, the percentage of mahua biodiesel blend, load, biogas flow rate and methane fraction are varied. The experimentation is conducted using three mahua biodiesel blend variants namely B10, B20 and B30. Gaseous fuel comprising biogas (CH_4 and CO_2 in ratio of 3:2) and methane (CH_4) are incorporated in the dual fuel condition at 8 litre per minute (lpm) and 12 lpm. B20 blend demonstrated better performance and emission characteristics. The addition of biodiesel (B20) showed more than 5% improvement in brake thermal efficiency. Additionally, comparing with normal diesel mode, B20 showed lower CO (0.061%) and NO_x (615 ppm) emissions. In the dual fuel condition, methane and biogas are effective in reducing the NO_x emissions, but with a negative repercussion of extortionately elevated HC and CO emissions. The best combination is deduced to be B20 mahua biodiesel at 8 lpm of biogas flow rate in the dual fuel mode due to better performance and emission characteristics.

Keywords: dual fuel; NO_x reduction; mahua; biogas flow rate; methane fraction; biodiesel

Citation: Kshatriya, A.S.; Tiwari, P.; M, S.; Yunus Khan, T.M.; Abdul Khadar, S.D.; Mansour, M.; M, F. Investigations into the Combined Effect of Mahua Biodiesel Blends and Biogas in a Dual Fuel Engine. *Energies* **2022**, *15*, 2057. https://doi.org/10.3390/en15062057

Academic Editor: Dmitri A. Bulushev

Received: 10 February 2022
Accepted: 9 March 2022
Published: 11 March 2022

1. Introduction

Due to the strict enforcement of the emission norms, researchers are motivated to develop alternative engine technologies with different fuel blends to tackle the harmful emissions produced during combustion of crude oils. In addition, development of newer fuel and engine technologies is imperative to meet the energy demands. Energy is one of the most vital constituents for the development of any country and sustainability of modern economy. The world energy demand is increasing exponentially and a major portion of the world's energy is supplied by petrochemical sources. These energy sources are depleting and may get exhausted soon. Fuel crisis and rising petroleum costs are detrimental to the economy. India is the second most populated country and third biggest consumer of petrochemical products in the world with current consumption of 4,690,000 barrels per day [1]. One viable solution to this complicated issue is the use of blended alternative fuels. Biodiesel is one of the clean combustion alternative fuels produced from the domestic and renewable resources. It is biodegradable, non-toxic and oxygenated fuel made from any animal fat or vegetable oil [2,3].

The biodiesel chosen for this investigation is mahua. It is a medium to large tree of the Sapotaceae family, Madhuca longifolia. The Latifolia type is widespread in the Indian subcontinent and Southeast Asian countries. In India, two species of the Madhuca genus, Madhuca Indica and Madhuca Longifolia, can be successfully cultivated in wastelands and dry fields. The tree is popularly known as the "Indian butter tree" [4]. The production potential of mahua seed is about 60 MT per annum. The current estimated production of mahua seed oil is 1.8 MT per year [5,6]. mahua oil has a specific gravity that is 9.11% greater than diesel. At 400 °C, the kinematic viscosity of mahua oil is 15.23 times that of diesel. The kinematic viscosity of mahua oil decreases significantly as temperature rises, as does the proportion of diesel in fuel blends. There are several research studies conducted by a number of investigators involving conversion of conventional diesel mode to dual fuel mode as well as incorporating biodiesel in engine operation. Jyoti and Reddy [7] reported that a 20% blend of mahua biodiesel with standard diesel gave the optimum blend. They found that the brake thermal efficiency increases by 1% but the brake specific fuel consumption (BSFC) decreases by 3.1% because of poor mixture formation resulting from low volatility, high viscosity and density of mahua biodiesel than neat diesel fuel. It was also found that the HC, CO and CO_2 emissions decreased by 16.2%, 11.4% and 5.3%, respectively. However, the higher oxygen content in fuel leads to higher cylinder temperature and promotes oxidation of nitrogen; thus, NO_x emission increases by 8.4%.

Patel and Shah [8] found that the engine works smoothly on biodiesel with the performance comparable to that of diesel. The heating values of blends lower than 20% were almost the same as diesel but all other blends had lower values. Gum formation on the injector was reported in blends with higher content of biodiesel. The consumption of biodiesel blends was found to be higher than diesel due to its higher flashpoint and viscosity. The biodiesel produces marginally lower output characteristics, lower torque and power output than diesel. Acharya et al. [9] conducted a comparative analysis on the oxidation and storage stability of mahua and jatropha biodiesels and concluded that the presence of 76.8% unsaturated fatty acids in jatropha makes it more prone to oxidation than mahua biodiesel with 58.81% unsaturated fatty acid for an induction period of jatropha and mahua oil of 3.75 h and 8.2 h, respectively. Oxidation stability can be increased by blending the biodiesel of jatropha and mahua with 20% and 30% mineral diesel, satisfying the EN-590 and Bureau of Indian Standards (BIS) limits for 20 h. Nanoparticle addition in biodiesel improves performance and emission [10]. Feroskhan and Ismail [11] studied the effects of the composition of biogas on a dual fuel CI engine. They concluded that the dual fuel mode enhanced the combustion quality and brake thermal efficiency. They also found that the exhaust temperature slightly increased and volumetric efficiency slightly reduced due to the presence of CO_2 in biogas. However, it did not vary much when methane flow rate was increased.

Another research study that was undertaken to explore the effects of biogas flow rate and addition of cerium oxide in the dual fuel mode in CI engine discovered that high biogas flow rates are an efficient way of minimizing diesel usage. Biogas was found to contribute up to 80% of overall energy release [12]. Kapilan et al. [13] found out that the efficiency of the CI engine with mahua biodiesel was improved by the induction of LPG. There is also a drastic reduction in smoke emission. Aklouche et al. [14] used synthetic biogas at varying equivalence ratio in the dual fuel mode and deduced with incrementing equivalence ratio, volumetric efficiency and peak pressure falls. Thermal efficiency increased with increasing equivalence ratios and specific energy consumption was found to decrease mainly due to the improvisation of combustion. Nalgundwar et al. [15] suggested the use of biodiesel blends of jatropha and palm and observed higher brake thermal efficiency and low specific fuel consumption for the blend containing 90% diesel, 5% jatropha and 5% palm. With augmenting biodiesel percentages, the BSFC showed a considerable increase, NO_x was higher, CO was lower for fuel containing low biodiesel concentration but increasing biodiesel quantity led to high CO due to improper combustion. Gawale and Srinivasulu [16] tested diesel and ethanol accompanied biodiesel blend and found that the CO and HC emissions were very low due to the presence of extra oxygen in comparison with neat diesel engine, but a slight increase in smoke and a substantial increase in NO_x were also observed.

Nema and Singh [17] operated a CI engine fuelled with soya bean and rapeseed methyl ester blended with Al_2O_3 nanoparticle and remarked that minor improvisation in brake thermal efficiency was recorded at 50% loading. HC and CO emissions reduced due to a decline in soot oxidation temperature and by the addition of aluminium oxide, 10–15% NO_x reduction was observed. Kumar et al. [18] analysed the effect of blending with mahua biodiesel oil on emission characteristics and found a reduction in CO and HC emissions, as large amounts of oxygen lead to oxidation. They also observed that the increase in quantity of mahua biodiesel led to a decrease in ambient and exhaust gas temperature. Banapurmath et al. [19] employed swirl augmentation techniques in a dual fuel engine. It was reported that HC, CO and smoke were substantially reduced due to enhanced oxygen content causing complete combustion. The addition of ethanol caused a slight increase in NO_x due to increased cylinder pressure and with exhaust gas recirculation, the NO_x values decreased. Kumar and Singh [20] used biodiesel blends of Mexicana Argemone and mahua in a direct injection CI engine and reported lower brake thermal efficiencies due to poor calorific value. Moreover, the presence of additional oxygen molecules caused low HC and CO but rising in-cylinder temperatures led to higher emissions of NO_x. Rahman and Ramesh [21] employed varying methane composition in a predominantly premixed charge compression ignition engine and found a slight increment in thermal efficiency due to improved combustion. Decrement in methane proportion led to reduced smoke and due to retarded ignition start reduced impingement of diesel outside the piston bowl was reported. At higher biogas energy share, unburnt hydrocarbons spiked due to incomplete combustion.

Ramesha et al. [22] reported the combustion, performance and emission characteristics of a biogas fuelled CI engine using fish oil as pilot fuel. Brake thermal efficiency of dual fuel engine was found to be very low due to higher fuel consumption and low combustion temperature. Fish oil methyl ester proved to be of higher efficiency (32%), higher specific fuel consumption for biogas and fish oil was observed. NO_x and smoke were observed to be very low for the dual fuel mode due to the dilution of oxygen and higher methane fraction leading to reduced soot formation tendency, the same reason was equally responsible for high amounts of HC and CO formation. Saravanan et al. [23] carried out experiments on a variable compression ratio CI engine fuelled with biodiesel of rapeseed and mahua. The performance characteristics showed higher BSFC and low brake thermal efficiency (BTE). CO and HC emissions were reduced due to refrained unburnt mixtures and enhanced oxidation process, but the repercussions came with increased NO_x due to an increased amount of oxygen. Hariharan et al. [24] studied the influence of hydrogen enrichment in a dual fuel engine test rig operated with cashew nutshell oil. It was found that the unburnt HC and CO were effectively reduced with the employment of biodiesel because of enriched oxygen presence. Adding hydrogen supported the benefit as CO formation reduced due to zero carbon molecular structure which is also responsible for lower carbon dioxide emissions. Lower smoke levels were also recorded with addition of biodiesel and hydrogen as high diffusivity increased mixture homogeneity, but NO_x values spiked due to an increase in flame speed and enhanced calorific value. Kumar et al. [25] assessed the behaviour of octane fuels with a mahua-fuelled dual fuel engine. Mahua oil proved to be inferior in terms of thermal efficiency compared to diesel due to its higher viscosity and poor atomization. Moreover, the poor quality of combustion led to lower NO_x but high amounts of smoke, HC and CO.

Advanced engine technologies such as dual fuel, partially premixed combustion, reactivity controlled compression ignition (RCCI) and homogeneous charge compression ignition (HCCI) provide better performance and emission characteristics. A dual fuel engine replaces convention fuel and provides better NO_x and smoke emissions. In total, 50 to 80% of energy can be substituted through the dual fuel mode. Biogas, CNG and hydrogen can be used as primary fuels in dual fuel engine [26]. Partially premixed combustion is used to improve the combustion by varying the injection timing [27]. RCCI mode is used to utilize both high octane number and high cetane number fuel in CI engine. Alcohols, in generally provide better performance compared to conventional mode [28]. Alcohol with biogas can be used in RCCI mode [29]. Up to 50% addition of alcohols showed better stability similar to a conventional diesel engine [30]. HCCI mode is a combination of SI engine's fuel mixture in CI engine's ignition mode. It provides ultra-low NO_x and smoke emission [31].

Raw biogas contains many gases such as methane, carbon dioxide, ammonia, H_2S, nitrogen and water vapour. In this, major constituents are methane and carbon dioxide. It is better to remove some of the gases before utilizing biogas in the engine. Upgradation from raw biogas to biomethane will ensure the safer environment of the engines. Many techniques are used to convert raw biogas into a useful one which includes a cryogenic temperature condensation system [32]. However, in the present study, simulated biogas (a mixture of CH_4 and CO_2) is used instead of raw biogas.

In light of the benefits and challenges of the combined effect of biogas and the mahua biodiesel-fuelled dual fuel engine, the present work is an attempt to explore the effects of four input variables (biogas flow rate, percentage of mahua biodiesel in diesel, methane fraction and applied load) on all three characteristics of engine output viz. combustion, performance and emissions. The full factorial study containing 96 experimental trials is carried out for the complete load range of a dual fuel CI engine operated on simulated biogas and biodiesel blends as the primary and secondary fuels, respectively. To the best of the authors' knowledge, such a comprehensive study was not attempted earlier and the results are expected to be helpful in determining the most effective ways of utilizing biogas and mahua biodiesel blends in the dual fuel mode.

2. Materials and Methods

2.1. Fuel Preparation

To use mahua oil inside the engine, its density and viscosity needs to be sufficiently lowered. The transesterification process was carried out to convert neat mahua oil into its methyl ester. Firstly, the mahua oil and methanol were mixed in a specified ratio of 7:1 [33]. NaOH and H_2SO_4 were then added to the mixture and stirred using a magnetic stirrer. Heating is continued at 65–70 °C while simultaneously stirring the mixture for about an hour. Then, decantation is carried out to separate the biodiesel layer and the formed glycerin layer. Further, the resulting mahua methyl ester (MME) is purified with warm water and heated up to 100 °C for sufficient removal of impurities. The final fuel obtained is blended with diesel in proportions of 10%, 20% and 30% by volume thus producing a total of 3 blends for the subsequent investigation.

2.2. Fuel Properties

Table 1 shows the properties of diesel and mahua biodiesel blend. In general, biodiesel's viscosity, density, flash point and fire point are higher compared to diesel. Blending of mahua biodiesel with diesel increases these values. Calorific value of mahua biodiesel is low compared to diesel. It is clearly visible from Table 1 that flash point and fire point of all the methyl ester blends are higher in comparison with diesel. Additionally, augmenting biodiesel proportion in the blend lead to a significant increment in density and reduction in the calorific value. This was justified by Giakoumis and Sarakatsanis [34] as the increased number of double bonds in the biodiesel blends led to a higher density and increased inertness. Additionally, in a study conducted by Oliveira et al. [35], it was suggested that more branching of carbon chain and long carbon chain sizes cause a decrement in calorific value. The cloud point temperature is observed to be nearly the same for all fuels instead of B30.

Table 1. Measured Fuel Properties.

S No.	Properties	Pure Diesel	B10	B20	B30
1	Flash point (°C)	49	67	71	75
2	Fire point (°C)	51	74	76	79
3	Cloud point (°C)	5	5	5	4
4	Pour point (°C)	−38	−4	−5	−6
5	Density (kg/m^3)	833	847	852	856
6	Kinematic viscosity (mm^2/s @ 40 °C)	3.3	3.8	3.9	4.1
7	Calorific value (kJ/kg)	40,600	39,368	37,288	35,640
8	Carbon residue (%)	0.3	0.33	0.45	0.48

2.3. Experimental Setup

The schematic diagram of the experimental test rig is shown in Figure 1. The rig consists of a 4-stroke single cylinder CI engine (compression ratio–17) which can be adjusted to operate in the dual fuel mode. Gaseous fuels comprising CH_4 and CO_2 are supplied into the engine and are stored in separate cylinders at high pressure. The flow of the gases is controlled independently by using control valves. Thermal mass flow meters are employed to measure the flow rates of methane and carbon dioxide. A burette is used to measure the mass flow rate of diesel and biodiesel blends. An eddy current dynamometer is used to load the engine. To record the air flow rate, a U-tube manometer is connected to the orifice meter supplying sufficient oxygen to the engine cylinder. An air box is attached before intake manifold to dampen the air suction pulses from the engine. DiGas emission analyser (Brand: AVL and Model: 444N) is used to record the emission indices such as HC, CO and NO_x emissions. A smoke meter (Brand: AVL and Model: 437C) is connected in parallel to the exhaust to measure smoke levels.

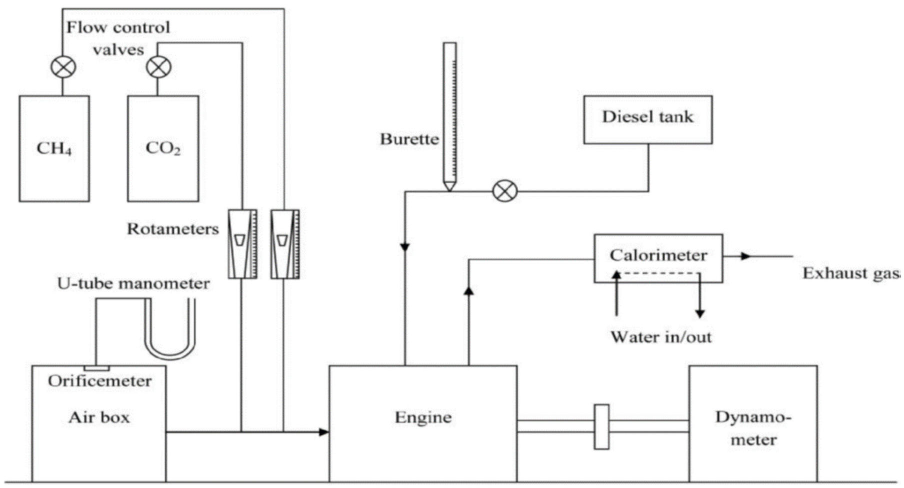

Figure 1. Experimental testing setup.

2.4. Methodology

In the first stage of experimentation, baseline testing with pure diesel is carried out where diesel was injected directly into the combustion chamber for compression ignition. Later diesel is subsequently replaced with biodiesel blends. The engine is tested for performance and emissions characteristics at various loading conditions ranging from 0 N-m to 20 N-m torque. Methane and biogas enrichment in the engine operation is controlled through the flow meters attached to the idle cylinders. A stopwatch is used to measure diesel consumption in the burette and with the aid of AVL gas analyser and smoke meter HC, CO, NO_x and smoke levels are recorded. AVL 444N DiGas analyser was used to measure NO_x, CO and HC (propane equivalent) emissions. It also displays the concentrations of CO_2 and O_2. CO, HC and CO_2 are measured using non-dispersive infrared (NDIR) modules, while NO_x and O_2 are measured using electrochemical analysers. Sufficient time is provided for the readings to stabilize before recording the emissions for better accuracy. The operating parameters used in this study are shown in Table 2. In the figures that follow, BG_8 represents biogas (60% methane fraction) with 8 lpm flow rate with B20 as pilot fuel and CH4_8 represents methane (100% methane fraction) with 8 lpm flow rate with B20 as pilot fuel. In order to ensure repeatability of the readings, a random 25% of the trials were conducted 3 times. Uncertainty analysis for the output parameters is performed using the methodology provided by Moffat [36] and the uncertainty values were found to be less than 3% for all the output parameters.

Table 2. Operating parameters.

Intake Condition	Level 1	Level 2	Level 3	Level 4
Biodiesel blend	B0 (Diesel)	B10	B20	B30
Biogas flow rate (lpm)	0	8	12	-
Methane fraction (%)	60	100	-	-
Torque (N-m)	5	10	15	20

3. Results & Discussion

Performance and emission characteristics of a biogas-fuelled CI engine with mahua biodiesel are presented in this section.

3.1. Brake Thermal Efficiency (BTE)

Figure 2a represents the thermal efficiency of the biodiesel blends compared to diesel at various loads. It was deduced that augmenting biodiesel percentage in the blends led to a boost in brake thermal efficiency. B30 performed best at medial loads whereas B20 showed higher performance at low and high loads. For B20, thermal efficiency escalated by 2.96% at 20 N-m load, in contrast with pure diesel. Ramesha et al. [22] provided a justification stating the attributed quality of biodiesel having rich oxygen content and a truncated ignition delay leading to more thermal energy production during combustion. Figure 2b,c tend to analyse the alterations in BTE, by entrainment of methane and biogas, respectively, both at 0 lpm, 8 lpm and 12 lpm flow rates. Significant fall in brake thermal efficiency is observed by introducing methane, and a further increment in flow rate exacerbates the efficiency, one of the major reasons being lean mixture formation [11]. A similar case is observed with biogas introduction with an average reduction of 2.1% in thermal efficiency at 20 N-m. Patel et al. [37] attributed a reason that high biogas flow rates lead to oxygen deficiency in the engine engendering inferior combustion. Biogas tends to be more advantageous in a dual fuel condition reaching a maximum efficiency of 32.39% at 8 lpm compared to 30.79% displayed by methane at 8 lpm. Compared to Figure 2b,c, biogas provides better efficiency than methane at the same flow rate due to high diesel substitution by methane in the latter case.

3.2. NO_x Emission

Figure 3a depicts NO_x emissions of diesel relative to the mahua biodiesel blends. B10 shows a profound reduction in NO_x at full load decrementing by 5.11%. The lowest possible value of NO_x in diesel mode is noted for B20 (615 ppm). It is also extrapolated that with the enhancement in biodiesel quantity in blends, NO_x emissions elevate due to the increased presence of air-borne oxygen leading to an upsurge in combustion temperature. Additionally, the biodiesel blend tends to show a low amount of NO_x than diesel due to inferior combustion quality leading to improper atomization [25]. Figure 3b,c shows the effect on NO_x by entrainment of methane and biogas, respectively. There is a substantial curtailment of NO_x in the dual fuel mode and incrementing the flow rate adds to the benefit, as more displacement of oxygen refrains the process of Zeldovich mechanism by increased substitution of oxygen [14]. At 100% loading, biodiesel at 12 lpm shows a reduction of 46.32% in B20 (362 ppm), and there is a decrease of 40.91% in NO_x using methane at 12 lpm. Thus, it is discerned that at 100% load, the B20 gave better results than the other blends, specifically by employing biogas. Biogas exhibits lower NO_x emissions compared to pure methane due to CO_2 presence in biogas. CO_2 suppresses the combustion and reduces the combustion temperature.

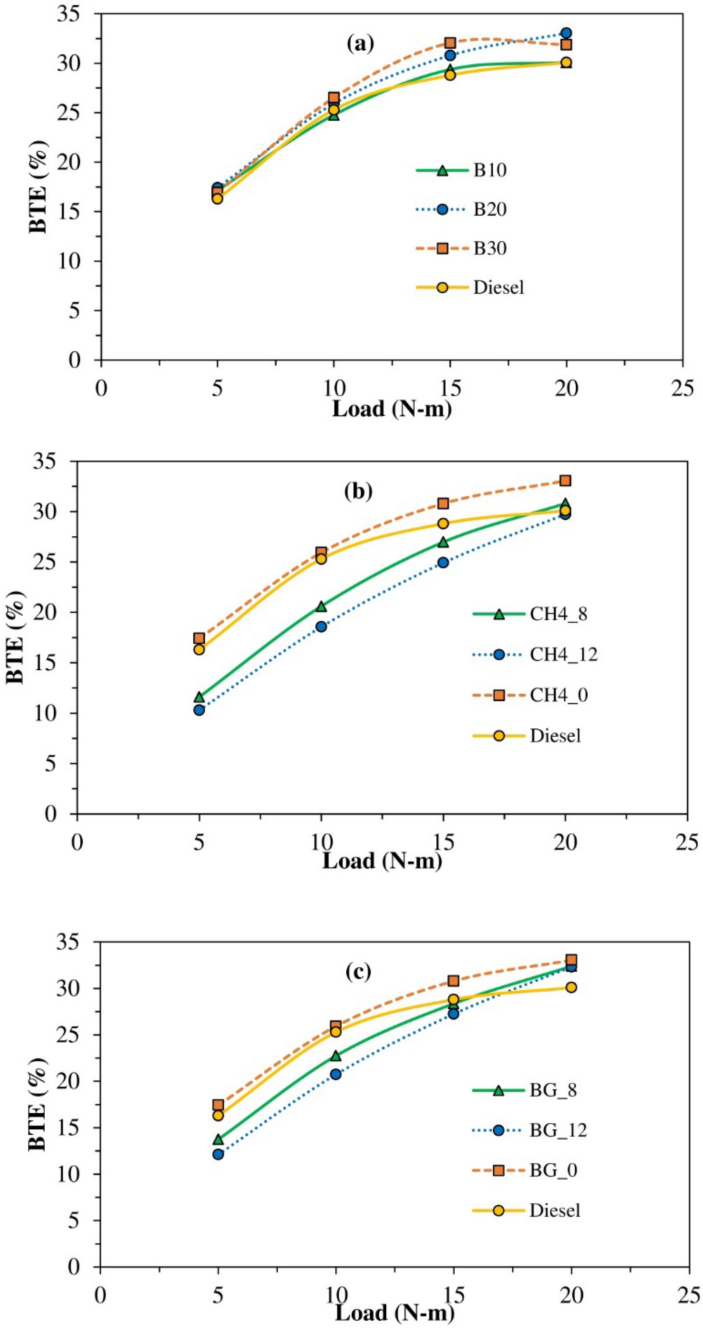

Figure 2. Variation of BTE with load at various (**a**) Mahua biodiesel blend, (**b**) methane flow rate and (**c**) biogas flow rate.

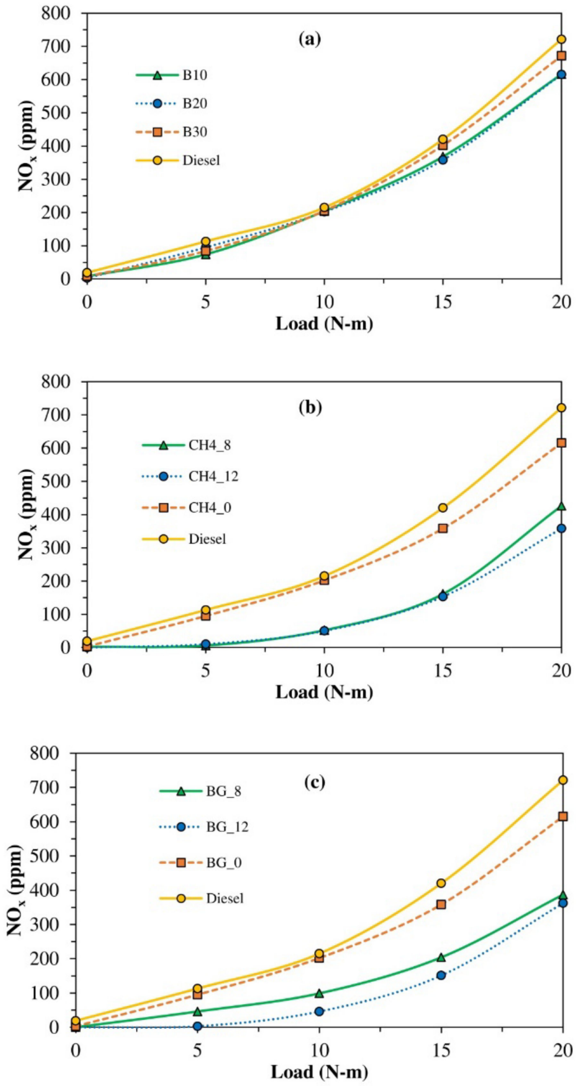

Figure 3. Variation of NO_x emissions with load at various (**a**) Mahua biodiesel blend, (**b**) methane flow rate and (**c**) biogas flow rate.

3.3. Smoke Emission

Smoke emissions of blends with no presence of biogas or methane are presented in Figure 4a. It is deduced that the smoke emissions are lower for B10 blends, and biodiesel augmentation in the blends leads to a high amount of smoke generation. At full load, B10 emanates smoke at 62.9%. The reason for high smoke generation is due to extremely poor atomization due to increased density and large droplets [25]. In the dual fuel mode, the addition of methane and biogas reduces smoke and increasing the methane flow rate further reduces smoke. However, increased induction of biogas, in turn, up-surges smoke levels, which may be due to the reduced amount of oxygen, thus acting as a significant negative factor for combustion and eventually elevating smoke emanation. Biogas at 8 lpm and 12 lpm shows a smoke level of 59.1% and 64%, respectively, for B20. Usage of methane is more viable in reducing smoke as the lowest value is achieved at 12 lpm methane (52.6%), refer to Figure 4b,c. Increase in methane flow rate reduces smoke emissions due to less diesel consumption and more homogeneous combustion.

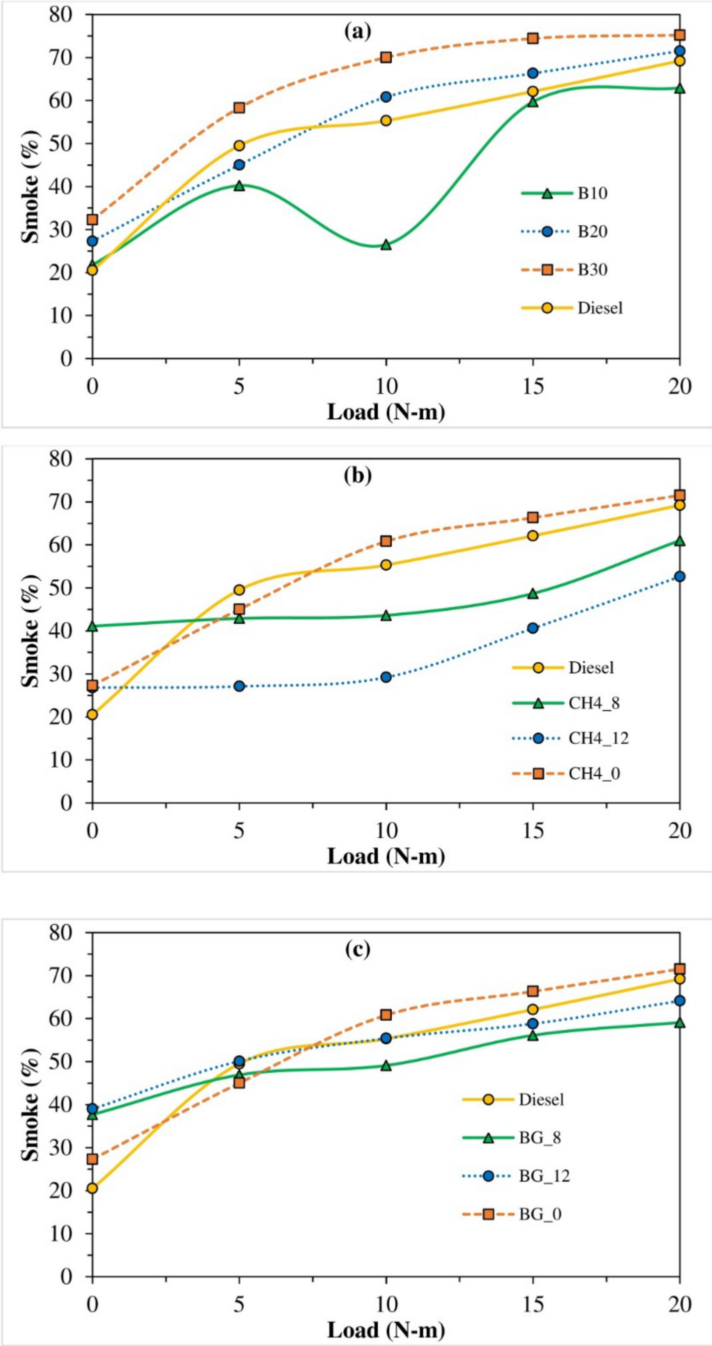

Figure 4. Variation of smoke emissions with load at various (**a**) Mahua biodiesel blend, (**b**) methane flow rate and (**c**) biogas flow rate.

3.4. HC Emission

Hydrocarbon (HC) emissions are caused by partially burned fuel which is generally toxic and deleterious in nature. Through the experiment, insignificant amounts of HC are observed for diesel and biodiesel blends as shown in Figure 5a. This is due to the combined effect of high cooling loss at low load and high combustion temperature at high temperature. Due to high density and viscosity, biodiesel exhibits poor atomization that further leads to poor combustion. However, high combustion temperature at high load improves the combustion and reduces HC emissions. Oxygen available in biodiesel also helps provoke better combustion. As seen from Figure 5b,c, it is deduced that the introduction of methane and biogas with biodiesel (B20) as pilot fuel in the dual fuel mode shows a sharp rise in

HC emissions due to less air inducted and inefficient combustion resulting in rich mixture formation [22]. Another reason might be the high heat of vaporization leading to flame quenching [25]. Methane with biodiesel produces higher HC emissions than biogas with biodiesel. Lower brake thermal efficiency in methane (refer Section 3.1) is also due to the same reason.

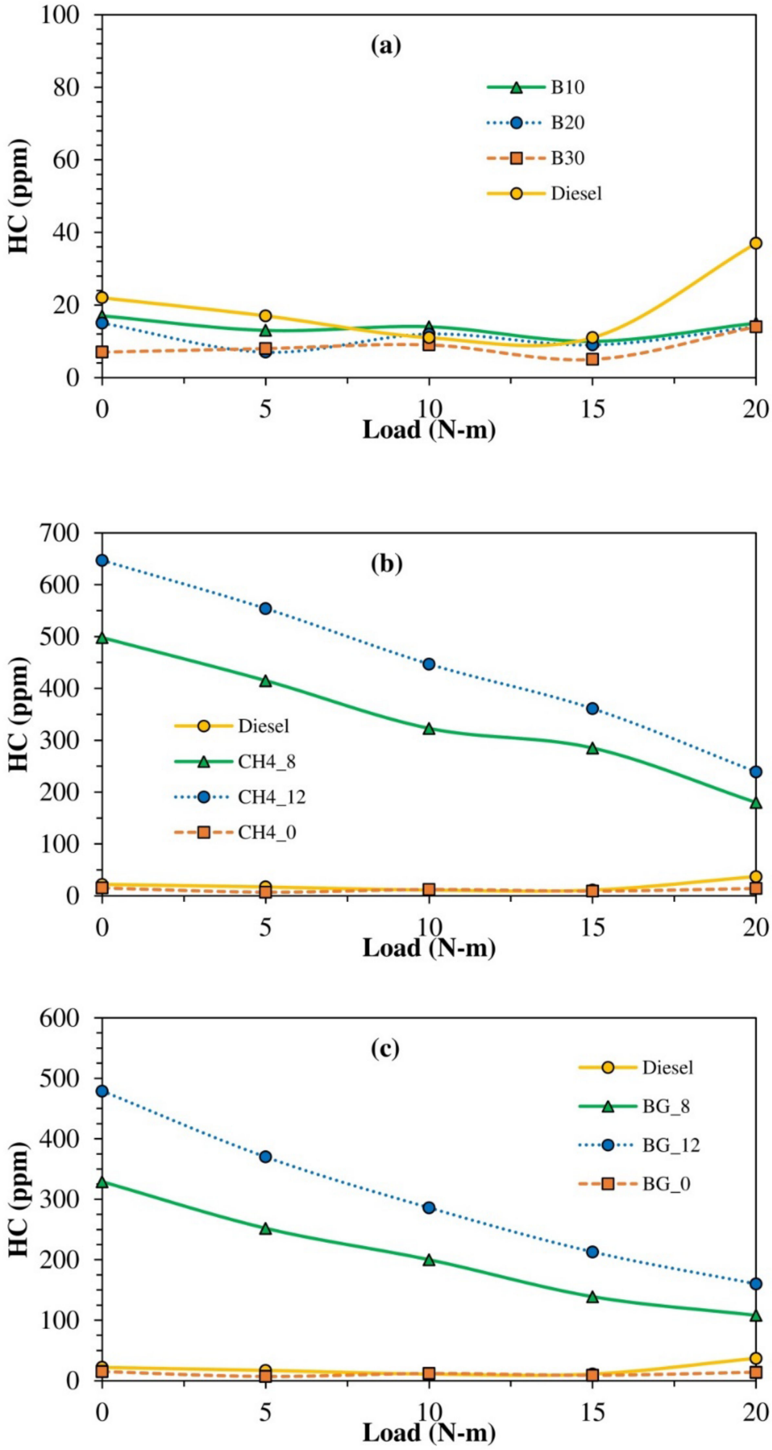

Figure 5. Variation of HC emissions with load at various (**a**) Mahua biodiesel blend, (**b**) methane flow rate and (**c**) biogas flow rate.

3.5. CO Emission

The trending behaviour of mahua blends for CO emissions is illustrated in Figure 6a. Under normal diesel mode, at 20 N-m compared to diesel, there is a substantial decrement of 14.49% in CO emissions for B30. At 100% load, B20 shows the least amount of CO emanation at 0.061%, in contrast with diesel at 0.069%. In the dual fuel condition portrayed in Figure 6b,c, the induction of methane and biogas releases obnoxious amounts of CO, with methane induction showing dominant behaviour with the maximum value reaching up to 0.378% at 12 lpm. CO emissions spiked due to increased induction of methane and biogas diminishing the oxygen content in the cylinder [22]. Biogas is considered convenient in dual fuel with the maximum value of CO, reaching only up to 0.193%. Methane with biodiesel produces more CO and HC emissions than biogas with biodiesel due to improper combustion.

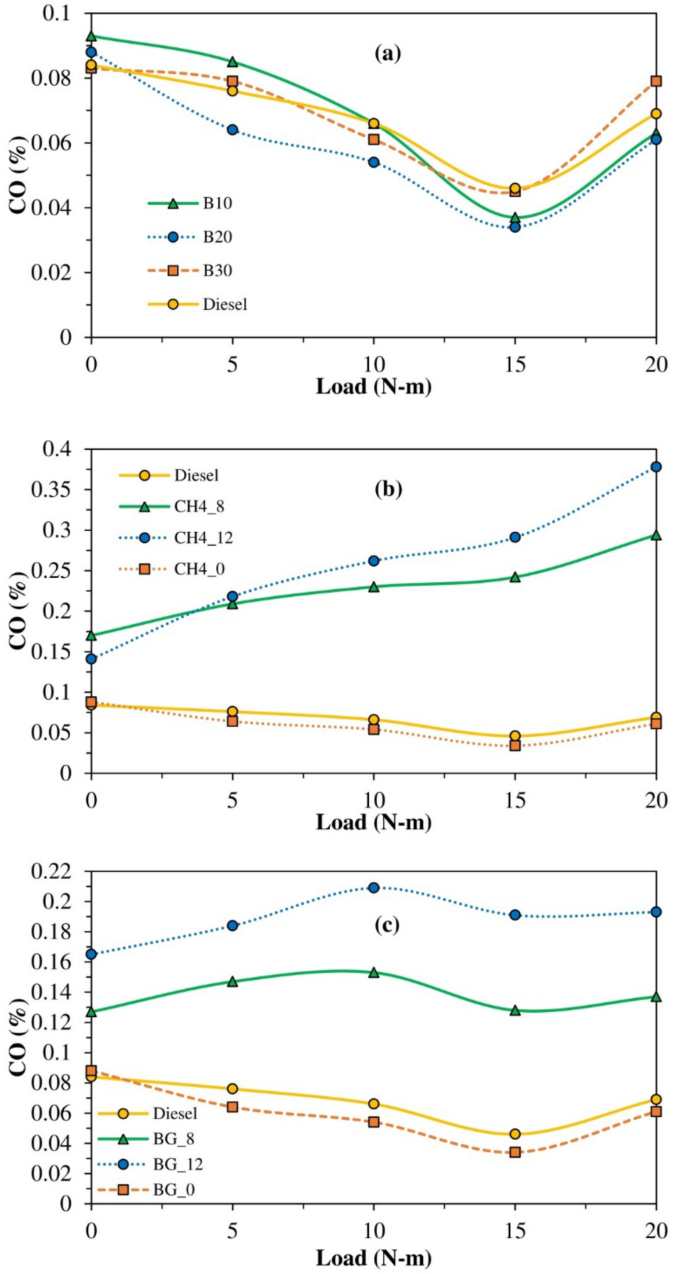

Figure 6. Variation of CO emissions with load at various (**a**) Mahua biodiesel blend, (**b**) methane flow rate and (**c**) biogas flow rate.

3.6. Combustion Characteristics

Figure 7a,b shows cylinder pressure data and heat release rate, respectively. The addition of biogas (BG_8) reduces diesel consumption and provides lower cylinder pressure. The maximum pressure is observed as 51 bar and 49.5 bar in dual fuel for biogas flow rate 12 lpm and 8 lpm, respectively. In total, a 2 to 10% decrease in pressure is recorded in most of the cases at high biogas flow rate. This is due to the replacement of diesel. The same trend is visible in the heat release rate also. The maximum heat release rate is observed as 33 J/°CA and 30 J/°CA bar in the dual fuel mode for biogas flow rate 8 lpm and 12 lpm, respectively. In total, a 8 to 18% decrease in HRR is recorded in most of the cases. These scenarios are confirmed with high HC and CO emissions at high biogas and methane flow rates (Refer Figures 5 and 6). Improper or late combustion is observed at a high biogas flow rate.

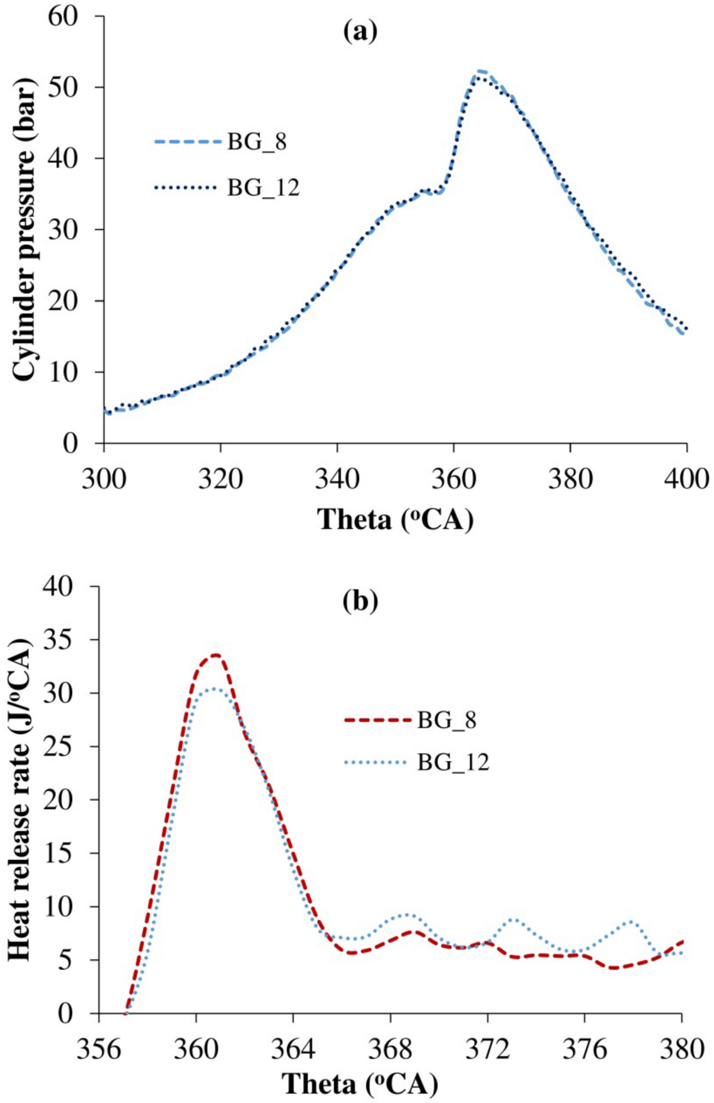

Figure 7. (**a**) Cylinder pressure data and (**b**) heat release rate for various biogas flow rates at 10 N-m.

4. Conclusions

The effects of the mahua biodiesel blend and biogas are studied for various performance, combustion and emission characteristics in the dual fuel mode. Percentage of biodiesel in diesel, biogas composition, biogas flow rate and load are varied. Brake thermal efficiency, brake specific energy consumption, HC, NO_x, CO and smoke emissions, cylinder pressure data and heat release rate are calculated. B20 (20% biodiesel in diesel) showed better performance and emission characteristics compared to diesel-only mode. In the dual fuel mode, biogas with 8 lpm flow rate had better emissions than other combinations of biogas. Based on the investigation, detailed conclusions have been drawn and are summarised below:

- Addition of biodiesel (B20) showed more than 5% improvement in brake thermal efficiency. Purified biogas (100% methane) showed lower efficiency compared to raw biogas (60% methane). Biogas with 8 lpm flow rate with B20 showed substantially better BTE (32.39%) at high load. Increase in biogas flow rate reduced liquid fuel consumption and lead to improper combustion at low loads.
- Addition of biodiesel in diesel reduced HC, CO and NO_x emissions. B20 exhibits better emissions compared to B10 and B30. B20 dominated in portraying lower values of HC (14 ppm) and CO emissions (0.061%).
- Dual fuel mode showed high HC and CO emissions. Biodiesel-blended pilot fuel reduces HC and CO emissions due to better combustion.
- Huge reduction in NO_x emissions is possible in the dual fuel mode. More than 50% reduction is possible through the addition of biogas at high load.

Among the biodiesel blends, B20 was the most effective, showing superlative performance and diminishing emissions. In the dual fuel mode, methane and biodiesel added to the benefit by lowering NO_x and smoke to as low as 358 ppm and 59.1%, respectively. In the dual fuel mode, biogas at 8 lpm proved to be more effective than methane due to a lower increment in HC and CO and gave a better BTE.

Author Contributions: Conceptualization, F.M.; Methodology, A.S.K., P.T., S.M., T.M.Y.K., S.D.A.K., M.M. and F.M.; Formal analysis, A.S.K., P.T., S.M., T.M.Y.K., S.D.A.K., M.M. and F.M.; Investigation, A.S.K., P.T. and F.M.; Resources, S.M. and F.M.; Data curation, A.S.K., P.T., S.M., T.M.Y.K., Shaik Dawood, Abdul Khadar, M.M. and F.M.; Writing—original draft preparation, A.S.K., P.T., T.M.Y.K. and F.M.; Writing—review and editing, S.M., T.M.Y.K., S.D.A.K., M.M. and F.M.; Supervision - F.M. and T.M.Y.K. Project administration, S.M., T.M.Y.K., S.D.A.K., M.M. and F.M.; Funding acquisition - T.M.Y.K., S.D.A.K., M.M. All authors have read and agreed to the published version of the manuscript.

Funding: The authors extend their appreciation to the Deanship of Scientific Research at King Khalid University for funding this work through the research groups program under grant number (R.G.P 1/221/41).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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