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Research Article

Performance and Emission Analysis of Watermelon Seed Oil Methyl Ester and n-Butanol Blends Fueled Diesel Engine

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The impact of n-butanol, a next-generation biofuel, with watermelon methyl ester in a constant-speed diesel engine was analyzed. Methyl ester from watermelon seed oil is considered to be a promising alternative source to the standard diesel due to similar characterization. The n-butanol additive was added in small proportions as an oxygenated fuel for reducing emissions, improving thermal efficiency, and accelerating the combustion process. N-Butanol is blended with watermelon methyl ester in the form of emulsions in two different proportions (5% and 10% volume basis). Experiments were conducted with three different emulsions fuels, WME20, W20Bu5D75, and W20Bu10D70, and compared vis-à-vis standard diesel. Investigations revealed that the addition of n-butanol as an enhancer with WME20 improved characteristics owing to its inherent nature of oxygen content. The blending of WME with n-butanol improves brake thermal efficiency when compared to WME20 and slightly matches with standard diesel. The max BTE was recorded 32.79% for WME20Bu10D70 at the crest load. The peak BSFC was 0.26 kg/kWh for W20Bu10D70 at the crest load. The emissions such as CO, smoke opacity, and HC were significantly reduced, vis-à-vis diesel, and the oxides of nitrogen (NO_X) and carbon dioxide (CO_2) were decreased, relative to WME20. The maximum EGT was 354.98°C for W20Bu10D70 at the crest load. The peak CO emissions were 0.078% for W20Bu5D75 at the crest load. The blending of n-butanol with WME20 reduces the ignition delay while the combustion duration increases with an increase at full load conditions. The emulsion fuels tested in an unmodified engine did no negative impact on the engine stability.

1. Introduction

Relative to any temporal phase in human history, the twenty-first century is forecasted to register the highest energy intensity and resource consumption, by virtue of increased demand driven by hitherto unprecedented prosperity. Over the course of the succeeding decades, a transition of substantial segments of the population, especially in Asia and Africa, from poverty to the middle class, with the concomitant change in consumption patterns, will exponentially exacerbate the contemporaneous energy crisis, unless structural changes are undertaken in the energy ecosystem. The utmost salience, vis-à-vis structural changes, is the substitution of fossil fuels, which are inimical to the environment, with sustainable alternatives [1, 2]. Prudential policy-making for India, which is portended to triple its energy demand by 2040, according to its Petroleum Ministry, must focus on the vital issue of replacing fossil fuels with renewables. The Indian government's commitment under its Intended Nationally Determined Contribution (INDC) target of generating 175 GW of renewable energy by the year 2022 is a positive step in this direction, but further substantive efforts are necessary, especially in a nation where previous brushes with crises of sovereignty, such as the Balance of Payments crisis of 1990, were a direct consequence of petrol addiction. In this scenario, biodiesels have emerged as a promising prospect to achieve India's renewable energy targets [3, 4]. Multitudinous factors serve as strong arguments for renewed attention to biodiesel research, particularly in the context of its potential to substitute petroleum-based fuels. The considerable engine modification and retrofitting of vehicles constitute two of the foremost reasons for dissuasion, with reference to gravitation away from conventional petrol/diesel-based vehicles. Biodiesels obviate the need for engine modification, thus resolving a major impediment to switchover from dirty fuels, that is, upfront investment associated with migration. Additionally, the superior emission characteristics of biodiesels do not come at the cost of engine performance. Prior research with various biodiesel stocks has established the comparability of biodiesels and petroleum-based fuels, in terms of engine performance [5, 6]. Furthermore, biodiesel research is mandated by their nontoxicity, biodegradability, and ease of creating symbiotic ecosystems of agricultural production and feedstock generation. The higher BTE for butanol-diesel blends (up to 40% v/v) related to reference diesel, and BTE improved with increasing butanol content [7, 8]. The oxygen content of n-butanol improves combustion during the diffusion combustion phase [9, 10], whereas the lower CN of the blends lengthens the ignition delay, burning a larger amount of the fuel during the premixed combustion phase [9, 11]. Similar conclusions were obtained by Campos. Besides, the laminar burning velocities of butanol are higher than those of fossil diesel and contribute to higher BTE values [9, 12]. Watermelon seeds are nowadays used for oil extraction. The seeds are dried, and oil is extracted by pressing them. This practice is common in West Africa, and the watermelon seed oil is popularly known as Ootanga oil or Kalahari oil. Oil is used as frying oil in various African nations. Watermelon seed contains about 40% of oil with a high amount of unsaturated fatty acids (about 80%) predominantly linoleic acid or omega 6 fatty acid (about 45–73%). Oleic, palmitic, and stearic acid are also present in small quantities. Various researches report the positive effect of watermelon seed oil on the skin. The oil is light and consists of humectants and moisturizing properties. It is easily absorbed by the skin and helps in restoring the elasticity of the skin. Due to these attributes, this oil can be used in the cosmetic industry for the production of skincare products. The watermelon seed oil can also be used as an anti-inflammatory agent [13–17]. Methyl ester of cotton seed oil was blended with diesel and enhancer (iso-butanol) for improving the performance and reducing the emissions. CSOME10B5D95, CSOME10B10D80, CSOME20B5D75, and CSOME20B10D70 were tested along with CSOME10 and CSOME20, which further compared with standard diesel. CSOME20B5D75 and CSOME20B10D70 were tested along with CSOME10 and CSOME20, which were further compared with standard diesel. The BTE of all the blends with iso-butanol as additive was observed to be a better performer than biodiesel blends. The blend CSOME10B10D80 was found to be the higher performer with a 3% improvement in performance. The fuel consumption for the rated power output was lower for the CSOME20B10D80 blend, and more fuel was consumed for all the blends mixed with iso-butanol. EGT for all the blends was observed to be lower due to its lower calorific value. During combustion, peak pressure was recorded for CSOME20B10D80. HC emissions reach maximum when iso-butanol content was increased. CSOME20B5D80 blend was recorded with a higher value than all other blends. CSOME20B10D80 was observed to be reduced when compared with standard diesel and other blends. The addition of the iso-butanol reduces the carbon mon oxide emission. CO_2 emission was found to be decreased with an increase in the blending of methyl ester and iso-butanol. CSOME20B10D80 seems to be emitting low intensity of CO_2. Joy et al. studied emission characteristics of C.I engine using esterified palm oil and octanol blends. The fuels (POME100, O10POME90, O20POME80, O30POME70, and diesel) tested in the diesel engine show reduction in emission of exhaust gases. HC emission of all the test fuels of methyl ester was observed to be reduced when compared with standard diesel. Oxides of nitrogen for all the blends recorded lower values relative to pure methyl ester of palm oil whereas every fuel was comparably higher than diesel. CO and smoke opacity emissions were found to be lower for methyl ester and octanol blends. Based on the past decades, limited research work has been carried out on the watermelon seed oil methyl ester compared with diesel and butanol. In the current research work, investigations were conducted in a diesel engine without making any modifications for evaluating the performance and emission characteristics of the best blended fuel of watermelon methyl ester (WME20) by mixing with n-butanol additive in various proportions (5% and 10%) and compared with standard diesel with a same rated power of 5.2 KW at a constant speed of 1500 rpm. The additive (n-butanol) was mixed with a methyl ester-diesel blend for improving performance and reducing emission concentrations. The fuels tested in the diesel engine are WME20Bu5D75 and WME20Bu10D70 along with blend WME20. This work highlights the significant potential of watermelon seed oil for use as a bio-diesel blend. This could have the dual benefit of helping increase the value of by-products of the watermelon industry and decreasing the amount of agricultural waste from the watermelon consumption.

2. Experimental Resources and Reagents

2.1. Watermelon Seed Oil. The seeds on a large scale from watermelon fruits were gathered and dried under the influence of sunlight for over a week for removing traces of moisture content. The dried seeds were finally allowed into the mechanical expeller for the extraction of oil. A small proportion of water, organic matter, and impurities were removed by adding 5% hexane to the raw oil and subjected to stirring for around 30 min by supplying heat at 90°C. The unwanted proportion of impurities and gum particles will reach the bottom surface of the oil and can be separated. The purified raw oil was tested for physical and chemical properties that were represented in Table 1.

2.2. Fuel Preparation. The measured watermelon oil of 3000 ml possessing an acid value of 1.13 is made to flow into the vessel of the biodiesel plant. The pictorial view of the biodiesel plant is shown in Figure 1. The oil is allowed into the vessel to get heated above 100°C for around 30 min for removing moisture content and left undisturbed for reducing temperature [18–20]. The calculated quantity of catalyst KOH is dissolved in the methanol and then added to the vessel containing watermelon oil. The chemical mixture is subjected to proper stirring over the period of 90 minutes for the reaction to happen. KOH dissolved in the yield of methanol increases with an increase in watermelon oil ratio up to 9 : 1 due to an increase in driving force for methanol adsorption. Maximum yield was found at 96.8% with 9 : 1 methanol to watermelon oil molar ratio. Beyond the molar ratio of 9 : 1, the excess amount of methanol had no substantial change in watermelon oil yield. Finally, the completed reaction is allowed into a funnel for cooling and separation of layers as top strata (methyl ester) and bottom strata (glycerol). The top strata are parted away from the lower strata. The methyl ester was held for water washing to remove entrained methanol, small traces of KOH, and glycerol.

2.3. N-Butanol. N-butanol, a colorless renewable fuel procured from propylene, is having a better solvency behavior and higher calorific value. The straight-chain isomer of n-butanol is having a molecular formula of C_4H_9OH [21, 22]. In recent times, n-butanol is considered as a partial substitute for diesel blends due to the presence of more oxygen content, higher cetane number, and higher miscibility than ethanol with lower corrosion. Characteristics of n-butanol are illustrated in Table 2. This investigation employs n-butanol having a purity level of 99%.

2.4. Engine Setup. The photographic view of the engine setup is shown in Figures 2 and 3, which illustrate the schematic diagram of the CI engine. The engine is initially made to run with standard diesel as a fuel for about half an hour to attain steady conditions. After warming up, the engine is operated with standard diesel and then switched over to watermelon-diesel blends. The time taken is calculated using a stopwatch for 10 cc of fuel consumption presented in a burette. The fuel combinations present in the fuel tank; fuel line and filter fuel pump are completely removed before switching over to start the experiment with new fuel combinations. The engine test was conducted for investigating the characteristics using standard diesel for comparison. The specification is listed in Table 3.

Table 1: Fatty acid composition and physiochemical properties of watermelon seed oil.

Fatty acid composition (%w)	Percentage
Acid value (MgNaOH/G)	2.37
Palmitic acid	11.0
Stearic acid	10.0
Oleic acid	15.0
Linoleic acid	63.0
Physiochemical properties	WSO
Kinematic viscosity at 40°C (mm^2/s)	10.2
Density at 15°C (kg/m^3)	981.7
Acid value (mg KOH/g)	1.13
Flash point (°C)	192
Calorific value (MJ/kg)	36.260

2.5. Uncertainty Analysis. The variation between the predefined result and actual value could calibrate the uncertainty. The analysis of uncertainties and errors in the test conducted during experimentations may probably arrive from reading, working conditions, observations, instruments selection, and changes in ambient conditions [23, 24].

3. Results and Discussion

3.1. Brake Thermal Efficiency (BTE). BTE is defined as the ratio of mechanical work produced to the heat energy obtained when fuel is injected. Figure 4 depicts the variation of BTE w.r.t load for WME20, W20Bu5D75, and W20Bu10D70 along with standard diesel at all conditions of load. BTE of W20Bu5D75 and W20Bu10D70 blends was improved when compared with WME20 whereas the efficiencies of all the blends are lower than standard diesel. The addition of the n-butanol additive with the WME20 diesel reduces the viscosity and calorific value of the fuel [24, 25]. The peak BTE was 32.79% for WME20Bu10D70, 34.14% for standard diesel, 32.24% for WME20Bu5D75, and 31.81% for WME20 at the crest load.

3.2. Brake Specific Fuel Consumption. BSFC is considered as the ratio of quantity (mass stream rate) of the fuel to the unit-created brake power. Figure 5 depicts the BSFC w.r.t load for W20Bu5D75, WME20, W20Bu10D70, and standard diesel. The BSFC of W20Bu5D75, WME20, and W20Bu10D70 recorded slightly higher values vis-à-vis standard diesel. The addition of the additive butanol with the

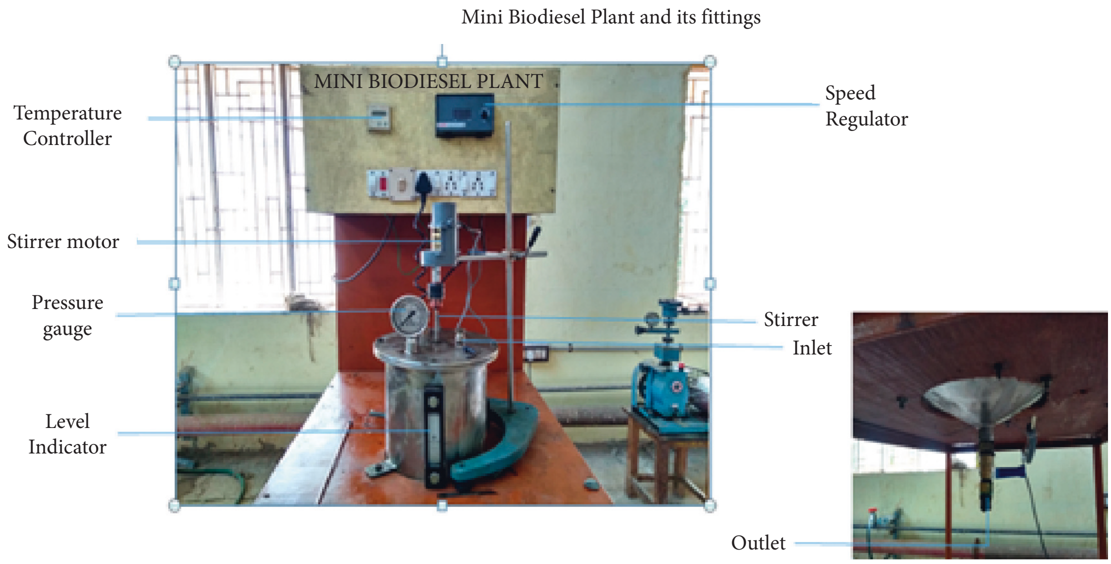


Figure 1: Mini biodiesel plant and its fittings.

Table 2: Characteristics of n-butanol.

Properties	Value
Flash point	35
Calorific value	34.33
Cetane number	25
Density at 15°C	0.81 g/cm^3
Kinematic viscosity	35 °C

Figure 2: Photographic view of the engine setup.

diesel reduces the calorific value. The performance of the diesel engine output is remains same [26, 27]. The peak BSFC was 0.26 kg/kWh for W20Bu10D70, 0.25 kg/kWh for standard diesel, 0.26 kg/kWh for W20Bu5D75, and 0.26 kg/kWh for WME20 at the crest load.

3.3. Exhaust Gas Temperature. Figure 6 depicts the EGT w.r.t load for W20Bu5D75, WME20, W20Bu10D70, and standard diesel at full load. EGT of WME20, W20Bu5D75, W20Bu10D70registered higher values vis-à-vis standard diesel. The lower IDP, efficient combustion, and lower calorific value of the standard diesel could be the prevailing reasons for indicating a trend for the samples of watermelon [28, 29]. The maximum EGT was 352.63°C for W20Bu5D75, 347°C for standard diesel, 351.19°C for WME20, and 354.98°C for W20Bu10D70 at the crest load.

3.4. CO Emissions. Figure 7 depicts the CO w.r.t load for WME20, W20Bu5D75, W20Bu10D70, and standard diesel at full load. CO emissions of WME20, W20Bu5D75, and W20Bu10D70 registered lower values relative to standard diesel. CO recorded lower values for WME20, W20Bu5D75, and W20Bu10D70 blends vis-à-vis standard diesel at all load conditions. The surplus availability of oxygen in WME and blends indorses lower emissions of CO [30, 31]. The peak CO emissions were 0.078% for W20Bu5D75, 0.088% for diesel, 0.083% for WME20, and 0.075% for W20Bu10D70 at the crest load.

3.5. Hydrocarbon (HC) Emission. Figure 8 depicts the HC w.r.t load for W20Bu5D75, WME20, W20Bu10D70, and standard diesel at full load. HC emissions of WME20, W20Bu5D75, and W20Bu10D70 recorded lower values relative to standard diesel. The lower IDP, efficient combustion, and lower calorific value of the standard diesel could be the prevailing reasons for indicating the trend for the samples of watermelon with additive n-butanol indorses lower HC emission [32, 33]. The peak HC emissions were 45 ppm for W20Bu5D75, 49 ppm for standard diesel, 48 ppm for WME20, and 42 ppm for W20Bu10D70 at the crest load.

3.6. Carbon Dioxide (CO_2) Emission. Figure 9 depicts the CO_2 w.r.t load for W20Bu5D75, WME20, and W20Bu10D70 along with standard diesel at full load. CO_2 emissions of WME20, W20Bu5D75, and W20Bu10D70 recorded higher vis-à-vis standard diesel. The lower IDP, efficient

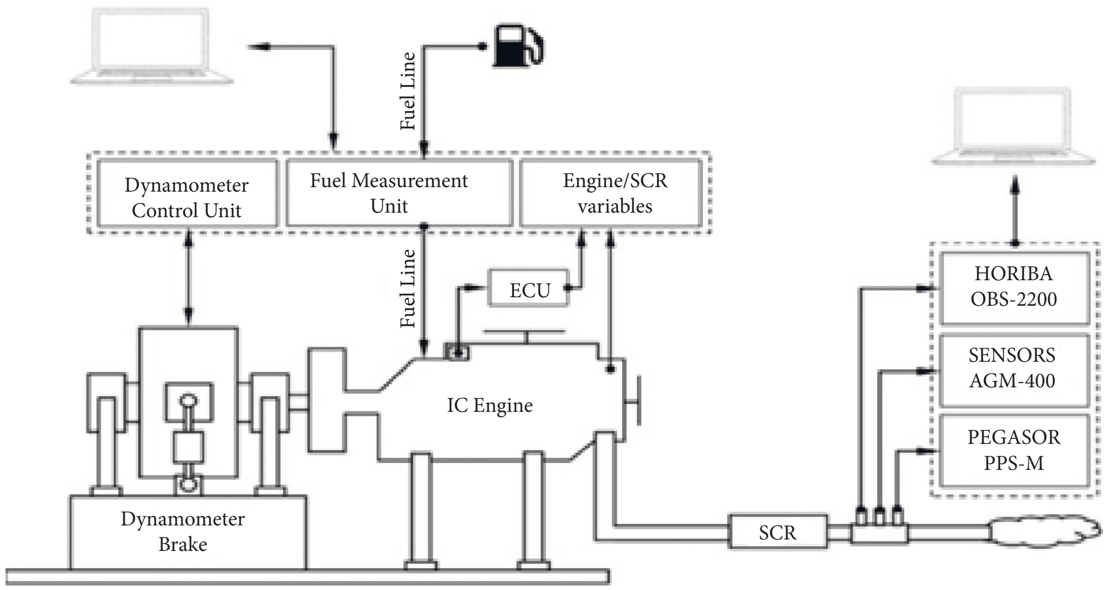


Figure 3: Schematic diagram of CI engine.

Table 3: Specification of experimental setup.

Type	Kirloskar
Cooling system	Water
Stroke (L)	110 mm
Bore diameter (D)	87.5 mm
Injection timing	24°bTDC
Rated power	5.2 KW
Cylinder	Single
Rated speed	1500 rpm
Stroke	4
Injection pressure	210 bar
Load	Eddy current dynamometer
Compression ratio	17.5 : 1

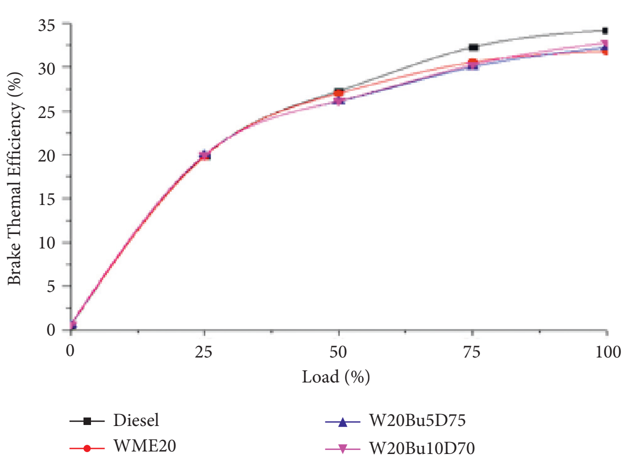


Figure 4: Variation of BTE.

combustion, and lower calorific value of the standard diesel could be the prevailing reasons for indicating the trend for the samples of watermelon with additive n-butanol indorses lower HC emission [34–36]. The CO_2 emissions were 5% for W20Bu5D75, 5.19% for standard diesel, 5.23% for WME20, and 4.7% for W20Bu10D70 at the crest load.

3.7. NO_X Emissions. Figure 10 depicts the NO_X w.r.t load for W20Bu5D75, WME20, and W20Bu10D70 along with standard diesel at full load condition. NO_X emissions of W20Bu5D75 and W20Bu10D70 registered lower relative to standard diesel. Generally, methyl esters exhibit a rich amount of NO_x relative to standard diesel owing to the enriched concentration of oxygen [37, 38]. The peak NO_X emissions were 2139 ppm for W20Bu5D75, 2140 ppm for diesel, 2183 ppm for WME20, and 2112 ppm for W20Bu10D70 at the crest load.

4. Smoke Opacity Emissions

Figure 11 depicts the smoke opacity w.r.t load for W20Bu5D75, WME20, and W20Bu10D70 along with standard diesel at full load. Smoke emissions of WME20, W20Bu5D75, and W20Bu10D70 recorded lower vis-à-vis standard diesel. The effective atomization for the droplets and better vaporization of methyl esters of watermelon along with additive n-butanol could be the reason for low recorded values vis-à-vis standard diesel. In addition, the rich content of oxygen in methyl esters of watermelon along with additive n-butanol indorses lower smoke emission [39, 40]. The peak smoke emissions were 48.9% for W20Bu5D75, 63.4% for standard diesel, 50.5% for WME20, and 43.9% for W20Bu10D70 at the crest load.

5. In-Cylinder Pressure (ICP)

ICP predicts the cycle of combustion in the diesel engine. The variation of ICP for WME20, WME20Bu5D75, and WME20Bu10D70 along with standard diesel at full load with injection timing (23BTDC) is depicted in Figure 12. The peak cylinder pressure for WME20, W20Bu5D75, and

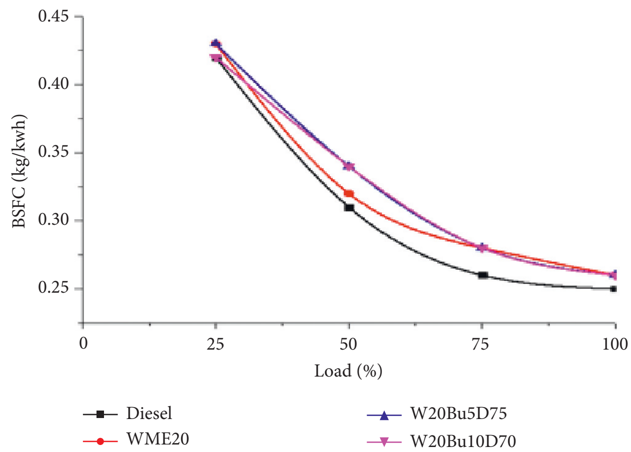


Figure 5: Variation of BSFC.

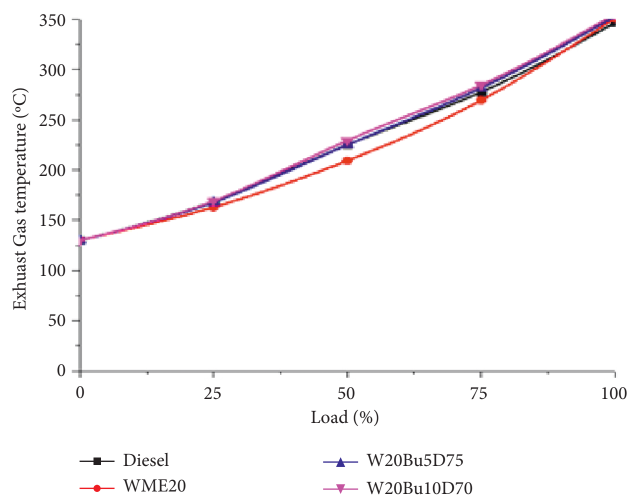


Figure 6: Variation of EGT.

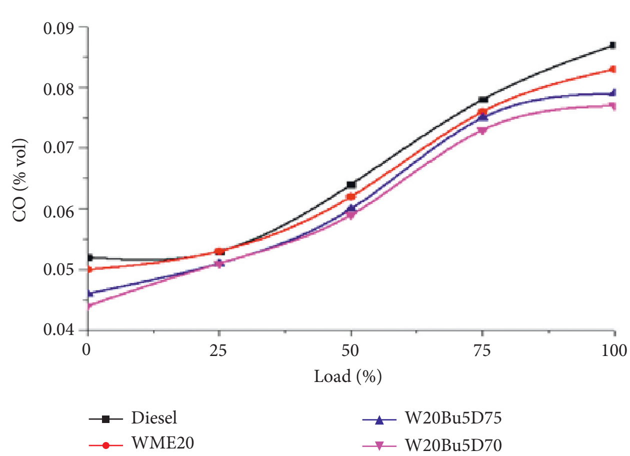


Figure 7: Variation of CO.

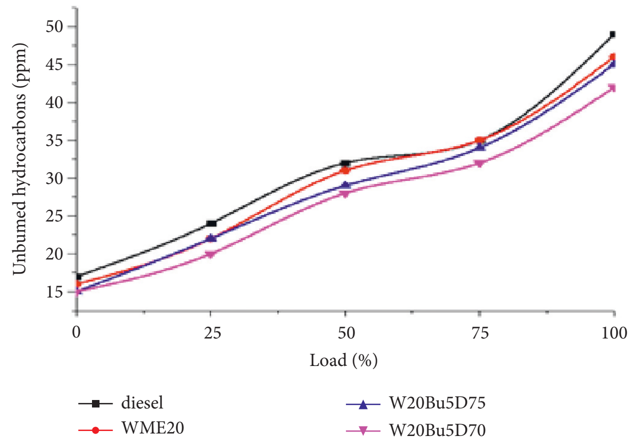


Figure 8: Variation of HC.

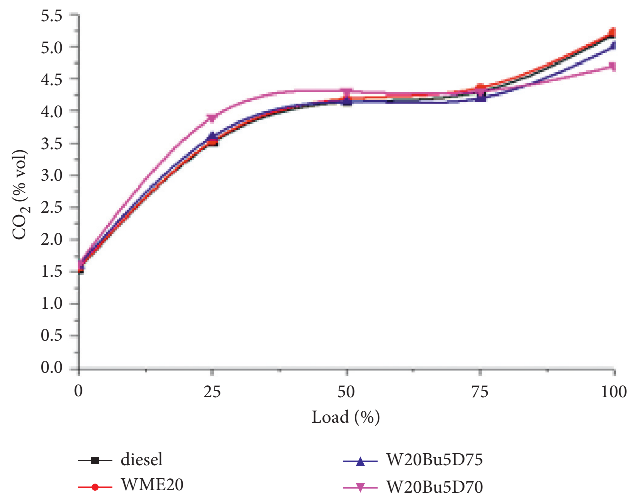


Figure 9: Variation of CO_2.

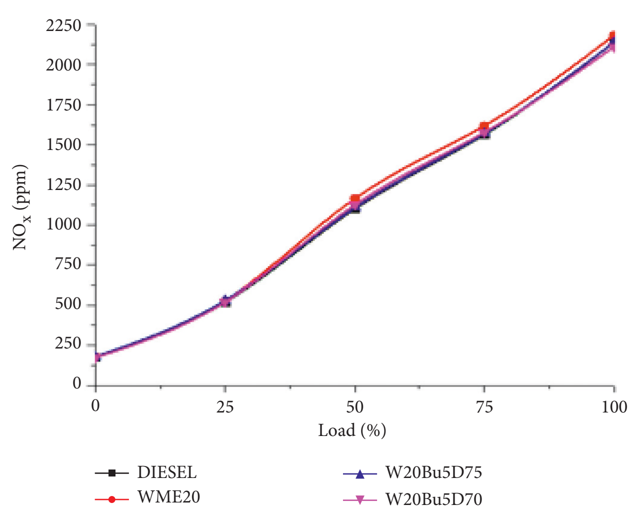


Figure 10: Variation of NO_X.

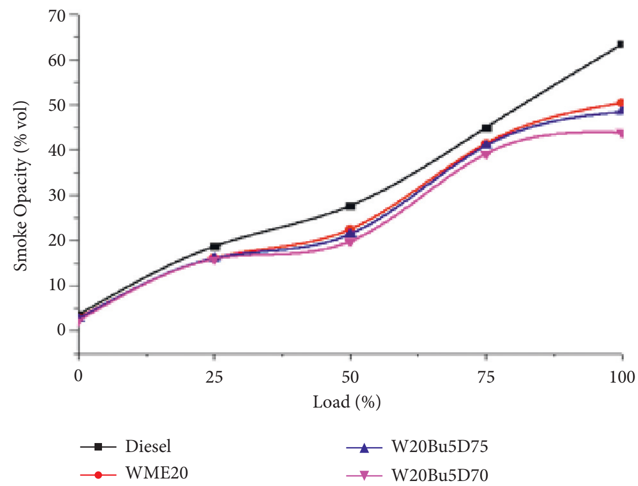


Figure 11: Variation of smoke opacity.

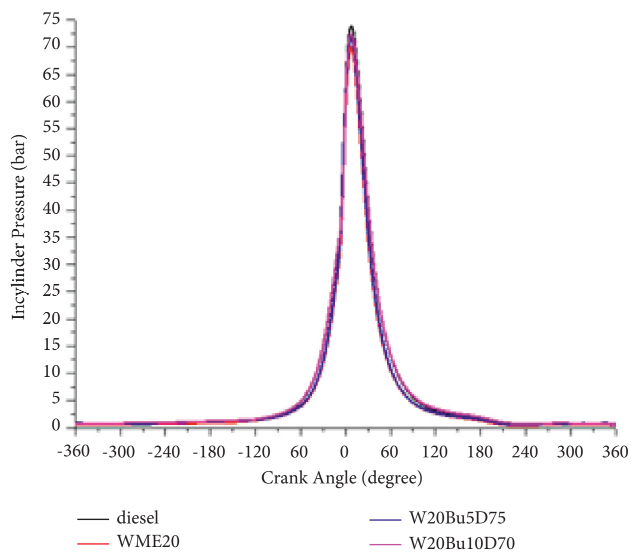


Figure 12: Variation of ICP.

W20Bu10D70 along with standard diesel was recorded as 71.56, 74.02, 72.71, 72.52 bar, respectively. Standard diesel had a higher in-cylinder pressure amid stall tested fuels owing to its longer ignition delay and greater calorific value as compared to all other tested fuels. The addition of enhancers in 5% and 10% increased the ICP but slightly recorded lower visa standard diesel [41, 42]. The combustion happened burning phase of diffusion for WME20, W20Bu5D75, and W20Bu10D70 owing to the innate contribution of oxygen available in both biodiesels and n-butanol vis-à-vis standard diesel. The significant causes for the high in-cylinder temperature with high butanol were better fuel atomization and better combustion of fuel.

6. Heat Release Rate (HRR)

The heat release profiles may provide numeric info about combustion development. HRR brings up the fuel release rate of chemical energy through combustion. The HRR basis on the pressure values of the cylinder [41–44]. Figure 13 depicts the HRR against crank angle diagram at full load condition for WME20, standard diesel, WME20Bu5D75, and WME20Bu10D70. The HRR for standard diesel registered a higher value among blends WME20, standard diesel, W20Bu5D75, and W20Bu10D70. This is due to a longer IDP and greater calorific value. W20Bu5D75 and W20Bu10D70 generate higher HRR than WME20. The addition of butanol at 5% and 10% volume improves the HRR relative to WME20. This is due to improved mixing and evaporation with reduced viscosity at increased inlet fuel temperature [23, 28]. Due to duction in viscosity, the fuel was atomized into finer droplets which might have enhanced the combustion process resulting in higher peak HRR [45–48].

7. Numerical Validation

Model-based experimental design techniques are extremely reliable for rapid improvement and better process models.

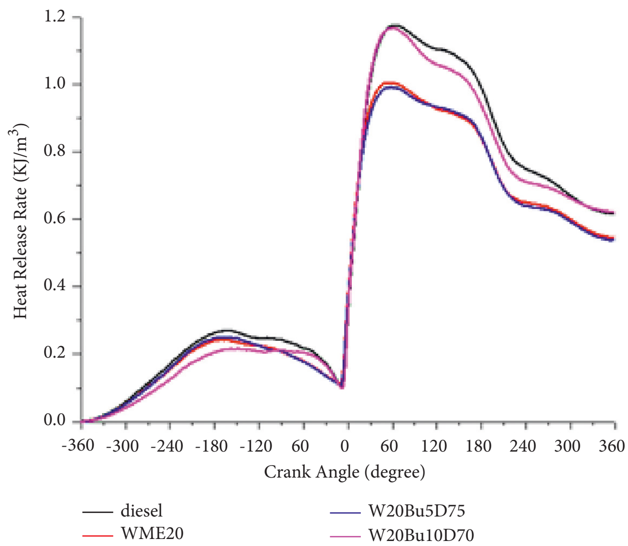
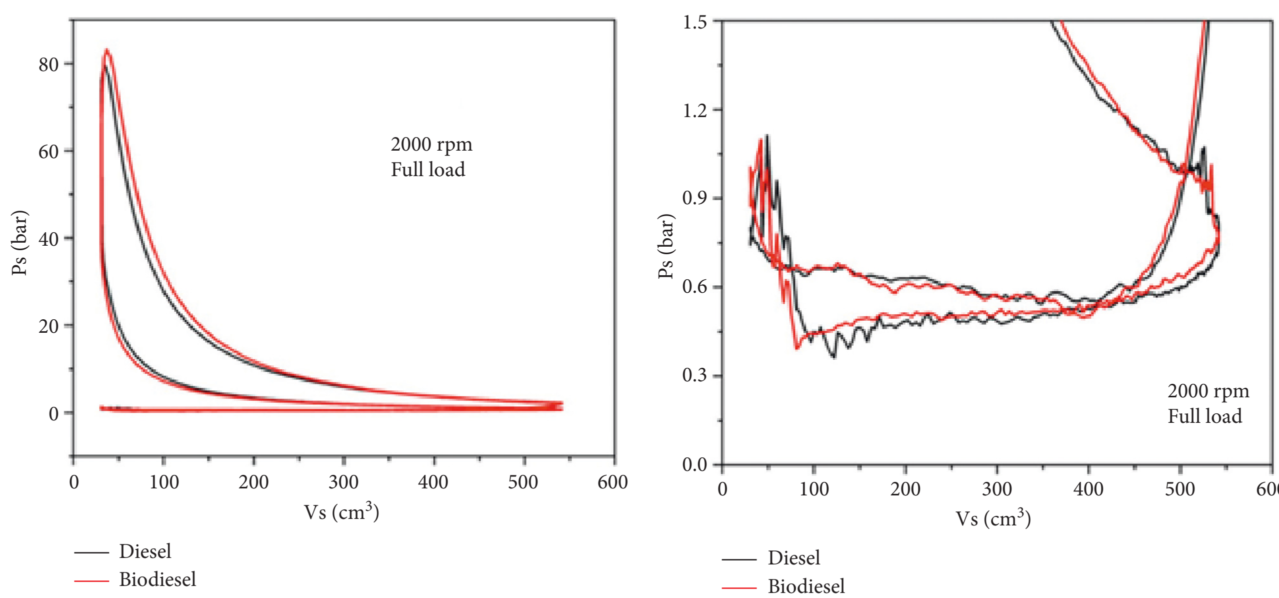


Figure 13: Variation of HRR.



(a)

(b)

Figure 14: (a) Comparison of p-V diagrams for diesel and biodiesel fuels. (b) Comparison of the charge change process for diesel and biodiesel fuels.

Also, numerical analysis helps in estimating the results and times and reducing experimental costs. Numerical simulations were created with the developed numerical model. It predicts the possible problems that may arise in the combustion of diesel engines. The numerical values are validated with the experimental results such as brake thermal efficiency. Figure 14(a) illustrates the comparison of p-V diagrams for diesel and biodiesel fuels. Figure 14(b) demonstrates the comparison of the charge change process for diesel and biodiesel fuels. The numerical method demonstrates the validity of this approach. The method that predicts the best results is identified for in-cylinder pressure and mass fraction burned. The experimental and numerical results for cylinder pressure and mass fraction burned are close to each other. It could be said that the difference is probably due to the difference in pumping losses, friction losses, and heat losses. Experimental and numerical results confirmed that the numerical model is consistent [49, 50].

8. Conclusion

(i) The BTE for diesel is 34.22%, WME20 is 31.81%, W20Bu5D75 is 32.24%, and W20Bu10D70 is 32.89%. BTE was improved by adding 5% and 10% n-butanol when compared with WME20, and on the whole, the results obtained were recorded at lesser values relative to standard diesel.

(ii) NO_X emission for the blends W20Bu5D75 and W20Bu10D70 was greatly reduced when compared to standard diesel. The addition of 5% and 10% n-butanol in the blend of WME20 decreased it by 0.1% and 1.3%, respectively.

(iii) In this study, NO emissions show the same trend as NOX emissions and represent 93%, 95%, and 93% of the total NOX emissions observed.

(iv) Smoke opacity, CO, and HC emissions are predominantly decreased when WME20 was blended with diesel along with n-butanol.

(v) CO_2 emission for the blends W20Bu5D75 and W20Bu10D70 was 3.6% and 9.4% lower than the standard diesel.

(vi) Exhaust gas temperature rises with an increase in the percentage blending of diesel in watermelon methyl ester.

(vii) The pattern for in-cylinder pressure (bar) registered rise for the blends of watermelon along with additive n-butanol (bar). In-cylinder pressure (ICP) for standard diesel is 72.52 bar, and in-cylinder pressure for W20Bu5D75, W20Bu10D70, and WME20 is 74.02, 72.71, and 71.56 bar.

(viii) The heat release rate (kJ/m^3) with respect to the crank angle (degree) for standard diesel is higher and followed by W20Bu10D70.

The blending of n-butanol as an enhancer in WME20 improves the performance and reduces the emissions. Normally, when biodiesels are used as fuels in diesel engine, it releases more NO_X and CO_2 emissions. These emissions were reduced significantly by adding n-butanol to the methyl ester-diesel blends. The blending of n-butanol with WME20 reduces the ignition delay while the combustion duration increases with an increase at full load conditions.

Abbreviations

WME:	Watermelon methyl ester
WME20:	20% WME + 80% diesel
W20Bu5D75:	20% WME + 5% n-butanol + 75% diesel
BD20Bu10D70:	20% WME + 10%n-butanol + 70% diesel;
HRR:	Heat release rate
PCP:	Peak cylinder pressure
CI:	Compression ignition
IDP:	Ignition delay period.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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