

EVALUATING A VCR ENGINE'S PERFORMANCE ENVIRONMENT PROTECTION ACT, 1986 AND EMISSIONS WITH WATERMELON SEED OIL BIODIESEL ENHANCED BY NANO ADDITIVES

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Abstract

In developing countries like India, finding the best alternative fuel oil is crucial. The high demand for SI and CI engine fuels has led to rising prices. The current research proposes an innovative approach to enhance system efficiency and reduce exhaust emissions. It focuses on predicting the emissions and performance of a variable compression ratio (VCR) engine fuelled with watermelon seed oil-based biodiesel blends. The biodiesel is produced through transesterification and mixed with nano-additives (60, 90, 120, 150 ppm) using an ultrasonicator. These blends were tested in a VCR engine at a 14:1 compression ratio under various loads. Results show that B20 biodiesel with nano-additives improved CO and HC emissions, except for NO_x. The B20 blend with 120 ppm of nano-additives achieved a brake specific fuel consumption (BSFC) of 0.32 kg/kWh, and a brake thermal efficiency (BTE) of 25.6% at full load, comparable to diesel. The mixed nano additive will be a promising solution for reduction of harmful emission in transportation sector. Addition of nano additives enhances the performance of watermelon seed oil when fuelled with VCR engine.

Keywords: Watermelon seed oil; diesel; VCR engine; combustion and emission parameters; AVL gas analyzer.

1. Introduction

Biofuels are widely recognized as renewable energy resources. Although renewable energy is predominantly utilized for electricity generation, a portion is increasingly directed toward the production of alternative fuels. Ongoing research focuses on identifying high-yield biofuel crops and improving oil productivity. However, current production levels require substantial land and freshwater resources to replace fossil fuels entirely [1]. Several studies have explored biodiesel blends and additives to improve engine performance behavior and emission response.

Studies on diesel blended with waste-cooked oil Alkyl ester have revealed noticeable effects on engine performance as well as exhaust emission characteristics [2]. In a similar vein, biodiesel produced from advanced-generation feedstocks has been reported to markedly alter combustion behavior and exhaust emissions in compression ignition engines [3].

The incorporation of ZnO nanoparticles into waste plastic oil blends (WPO20) led to reductions in smoke, CO, unburned hydrocarbons (UHC), and NO_x by 11.86%, 5.7%, 28%, and 14.93%, respectively, while maintaining BTE and BSFC values comparable to diesel [4]. Likewise, the addition of Al₂O₃ nanoparticles (500 ppm) to palm oil biodiesel blends reduced NO_x emissions by 11% [5], while cerium oxide nanoparticles optimized at 75 ppm enhanced BTE to 34.8% and reduced UBHC, CO, and NO_x emissions at full load [6].

Biodiesel blends derived from canola, safflower, and waste oils exhibited progressive increases in solidification temperature alongside marked decreases in CO, HC, and smoke emissions, though NO_x and CO₂ emissions increased notably [7]. Further research on corn oil methyl ester revealed increased BSFC at elevated injection pressures and a 22.45% rise in NO_x emissions, while CO and HC emissions declined significantly [8]. Mango seed methyl ester blends demonstrated enhanced performance, particularly when combined with 5% diethyl ether, resulting in improved BTE and reduced emissions [9–10]. Advancing injection timing and optimizing exhaust gas recirculation (EGR) rates further improved BTE by 4.54% and reduced smoke, HC, and CO emissions [11–12].

Studies on candle nut and soap nut biodiesel supplemented with nano-alumina additives identified B20 blends as the most effective, delivering enhanced engine efficiency and lower NO_x emissions [13].

Comparable emission improvements were also reported for biodiesel blends derived from papaya and watermelon seed oils [14].

Dual-fuel blends of Jatropha and turpentine oil achieved improved BTE and reduced emissions at higher compression ratios, despite a rise in CO₂ emissions [15]. Mesua ferrea linn oil blends demonstrated performance comparable to diesel with reduced CO, HC, and NO_x emissions [16].

In India, extensive wastelands are utilized for cultivating renewable bio-crops, supporting a closed carbon cycle. Watermelon seed oil, which meets ASTM standards and possesses chemical properties similar to diesel, has emerged as a promising biodiesel feedstock. Building on previous research, this research evaluates the effects of compression ratio changes on engine performance, combustion, and emissions in a VCR diesel engine fueled with a 20% watermelon seed oil biodiesel blend supplemented with MgO and ZnO nano-additives.

1.1 THE ENVIRONMENT (PROTECTION) ACT, 1986

This legislation is titled the Environment (Protection) Act, 1986. It is applicable across the entire territory of India. The Act comes into force on a date determined by the Central Government, which is announced through a notification in the Official Gazette. Different provisions of the Act may be implemented on separate dates for different regions, as specified by the Government.

2. Materials and Methodology

2.1 Sample readiness for bio diesel

The biodiesel was obtained through a transesterification process depicted. [17]. Figure 1 depicts the seeds of watermelon, the extracted oil, a mixture of nano additives, and the resulting nano-additive blended fuel. This procedure involved mixing methanol and a NaOH catalyst at 65 °C for a duration of 60 minutes. Initially, hot water at 80 °C was produced and circulated within the biodiesel facility. Methanol and sodium hydroxide were mixed in a container with stirring for 10 minutes at a constant temperature of 60 °C using an ultrasonic machine. Within the transesterification unit, a preheating step was performed on 20 liters of watermelon seed oil, raising its temperature to 100 °C to eliminate water content. Methanol and sodium hydroxide were introduced into this unit, where preheated oil was available. A heat exchanger was utilized to recover methanol for storage. The combination remained in the transesterification unit for eight hours, following which glycerin was removed via a valve. The remaining oil for transesterification was then moved to laundry and drying units. Hot water at 80 °C from the tank was supplied to the laundry and drying unit. The oil and water were allowed to settle for 6 hours, with the first traces of glycerin being removed after this duration. Four samples of trace glycerin were collected every 6 hours. Ultimately, 13 liters of biodiesel were obtained from the washing unit and subjected to flash and fire point testing. The resultant biodiesel derived from watermelon exhibited a clear, yellow appearance. Fig. 2 shows the manufacturing plant of bio diesel. To evaluate its compatibility, different ratios of biodiesel were combined with diesel and monitored over a period of 30 days, during which no indications of separation were detected.

$$\% \text{ yield} = [\text{Grams of biodiesel produced} / \text{Grams of oil used}] \times 100$$



Fig.1 Illustration of the process of preparing the bio diesel and mixed with nano additives



Fig.2 Production plant of the bio diesel

A blend B20 consisting of 80% diesel and 20% watermelon-based biodiesel (WMB) was prepared. Additionally, various MgO and ZnO nano-composite blended fuels were created, including B20+MNA60 (B20 with 60 ppm of MgO and ZnO), B20+MNA90 (B20 with 90 ppm of MgO and ZnO), B20+MNA120 (B20 with 120 ppm of MgO and ZnO), and B20+MNA150 (B20 with 150 ppm of MgO and ZnO) as shown in Fig.3. These nano-composites were mixed with B20 utilizing an disruption unit. The nano-additives serve as catalysts to enhance efficiency and reduce emissions. Generally, nano particles possess a large outer surface area, aiding in the Perfect combustion of mixture fuel-air. The properties of the B20, B20+MNA60, B20+MNA90, B20+MNA120, and B20+MNA150 fuel samples were measured in accordance with ASTM standards and are detailed in Table 1.



Fig.3 Various blends of water melon oil with nano additives: B20, B20+MNA60, B20+MNA90, B20+MNA120, and B20+MNA150

Table 1 Features of the different fuel blends analysed

2.2 Characterization of mixed MgO and ZnO nano particles

The FT-IR spectrum of WMB (Fig. 4) exhibits characteristic bending and stretching vibrations in the range of 1014–1450 cm^{-1} , along with prominent peaks at 1739 cm^{-1} and between 2849–3002 cm^{-1} , confirming the presence of ester functional groups, particularly the carbonyl ($\text{C}=\text{O}$) group. A notable shift of the strong absorption band from 1718 cm^{-1} to 1739 cm^{-1} , when compared with watermelon seed oil, indicates successful conversion to biodiesel and the formation of organic compounds containing alkyl groups. The absorption bands observed between 2849–3002 cm^{-1} correspond to C–H stretching vibrations, while bending vibrations in the region of 1361–1458 cm^{-1} are attributed to C–H deformation modes. The strong carbonyl absorption at 1739 cm^{-1} further confirms the formation of alkyl ester compounds. Overall, these spectral features demonstrate that the MgO and ZnO structures possess the expected functional groups, indicating successful incorporation and interaction of the metaloxides.

Properties	ASTM Standards	Diesel	B20	B20+ MNA60	B20+ MNA90	B20+ MNA120	B20+ MNA150
Kinematic viscosity at ASTM D445 40 °C (Centi stoke)		3.2	3.7	3.2	3.3	3.5	3.4
Specific Gravity	ASTM D792	0.838	0.92	0.90	0.91	0.91	0.91
Flash point °C	ASTM D93	62	160	106	108	108	109
Fire point °C	ASTM D92	70	172	122	123	123	123
Calorific value (kJ/kg)	ASTM D240	44,800	38,240	39,565	39,571	39,572	39,572
Cetane number	ASTM D613	43	46	44	45	44	44
Acid value (mgKOH/g)	ASTM D664	0.06	2.3	2.1	2	2.1	2.1
Density (kg/m^3)	ASTM D975	838	827	828	828	830	831

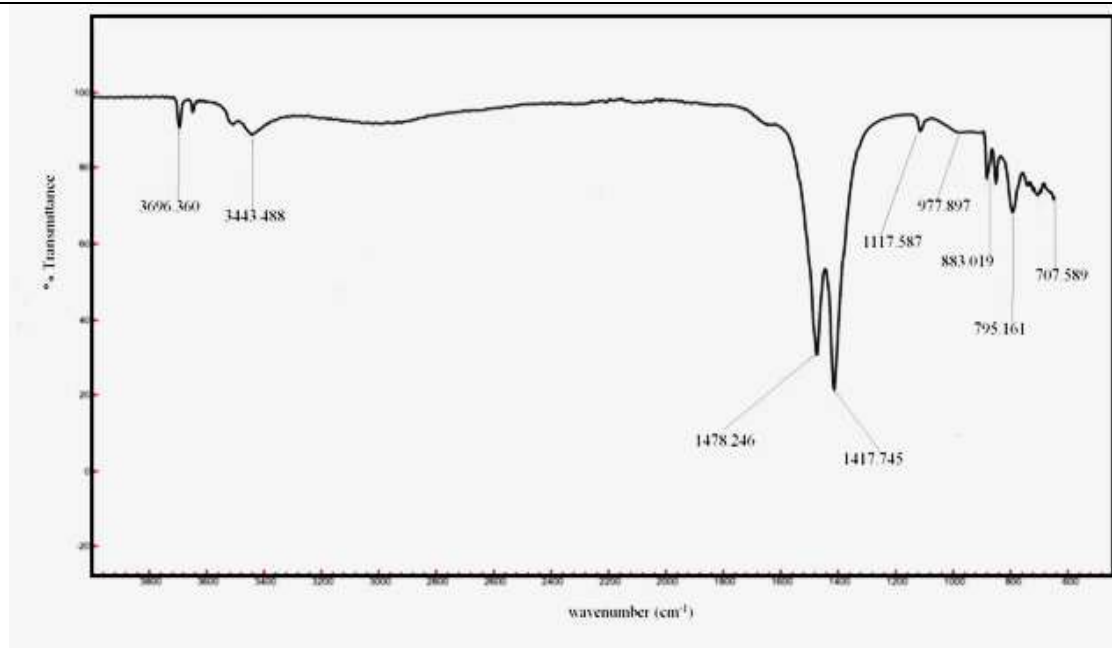


Fig.4 FT- IR spectra of MgO and ZnO nano particles

3. Investigation setup and Test procedure

The experimental setup of the VCR engine is illustrated in Fig. 5. Initially, the engine operated for 15 minutes, during which cooling water was supplied at a flow rate of 100 L/h. After preparing the dynamic fuel blends, the engine was allowed to stabilize for 10 minutes before data collection. To ensure uniform emulsification, an ultrasonicator operating in the frequency range of 60–100 kHz was used. The fuel blends containing MgO and ZnO nanoparticles were subjected to ultrasonic stirring for 10 minutes to improve dispersion and enhance interaction between the nanoparticles and the base fuel. Fuel injection was mechanically performed at 200 bar with a timing of 23° before TDC, while HC, CO, CO₂, and NO_x emissions were measured using an AVL DI Gas 444N analyzer and the results were recorded through a computerized data acquisition system. The specifications of the VCR engine are provided in Table 2.



Fig. 5 Photographic view of the experimental setup for a variable compression ratio engine

Table 2 Specifications of the variable compression ratio engine

Particulars	Specifications
Model and Make	Kirloskar TV1
Engine Type	Single cylinder, Water-cooled, 4-Stroke diesel engine
Compression ratio range	12:1 to 18:1
Cylinder bore	87.5 mm
Cylinder stroke	110 mm
Exhaust gas calorimeter	Shell and Tube, K type thermocouple, cooling water
Injection pressure	200 bar
Maximum load	10 kg
Pressure sensor	Piezoelectric
Rated engine power	3.5kW
Rated engine speed	1500rpm
Software	“Engine soft” Analysis software
Start of Injection	23° bTDC
Details Emission analyzer	
Model and Make	AVL 444N Di-Gas analyser

Measurement principle of CO	Infrared method
Measurement principle of NO _x	Electrochemical method
Air humidity	90% max., Non-condensing

4. Results and Discussion

4.1 Properties of the engine performance

4.1.1 Brake thermal efficiency

Figure 6 illustrates the variation of brake thermal efficiency (BTE) with load for diesel and B20-based fuel blends. BTE increased with load for all fuels, reaching 28% for diesel. The BTE values for B20, B20 + MNA60, B20 + MNA90, B20 + MNA120, and B20 + MNA150 were 26.6%, 27.1%, 25.6%, and 26.8%, respectively. An increase in BTE was observed with higher nano-additive concentration up to B20 + MNA120.

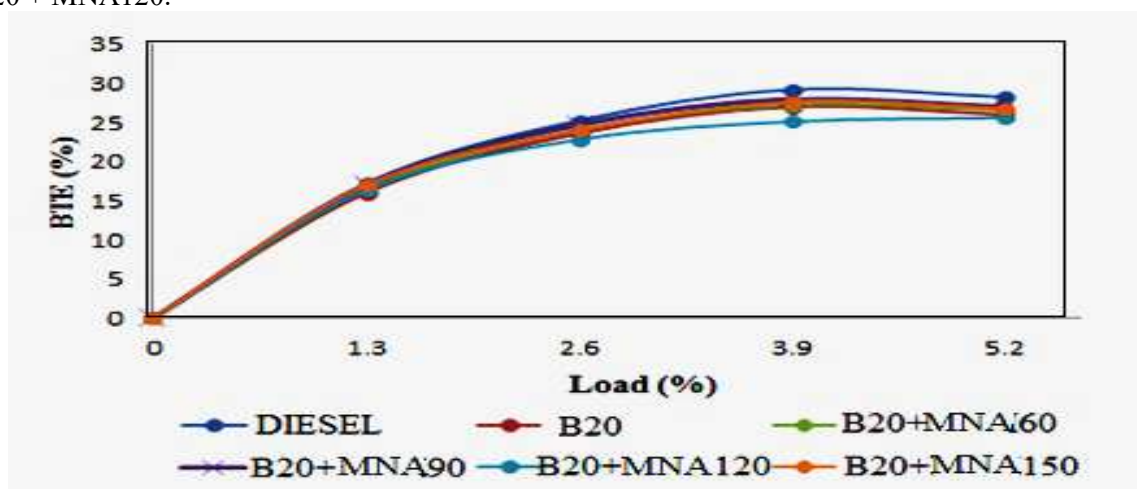


Fig.6 Distribution of brake thermal efficiency with respect to load

4.1.2 Brake specific fuel consumption

Figure 7 shows the Distribution of brake fuel consumption with respect to load, and B20 blends with different MNA concentrations. BSFC decreased with increasing load for all fuels. Diesel exhibited a BSFC of 0.28 kg/kW·h, while B20, B20+MNA60, B20+MNA90, B20+MNA120, and B20+MNA150 recorded values of 0.29, 0.30, 0.28, 0.32, and 0.28 kg/kW·h, respectively. Although B20 showed higher fuel consumption, the addition of MNA reduced BSFC up to MNA120, beyond which BSFC increased. Hence, B20+MNA120 was identified as the optimal blend in terms of fuel efficiency and power output.

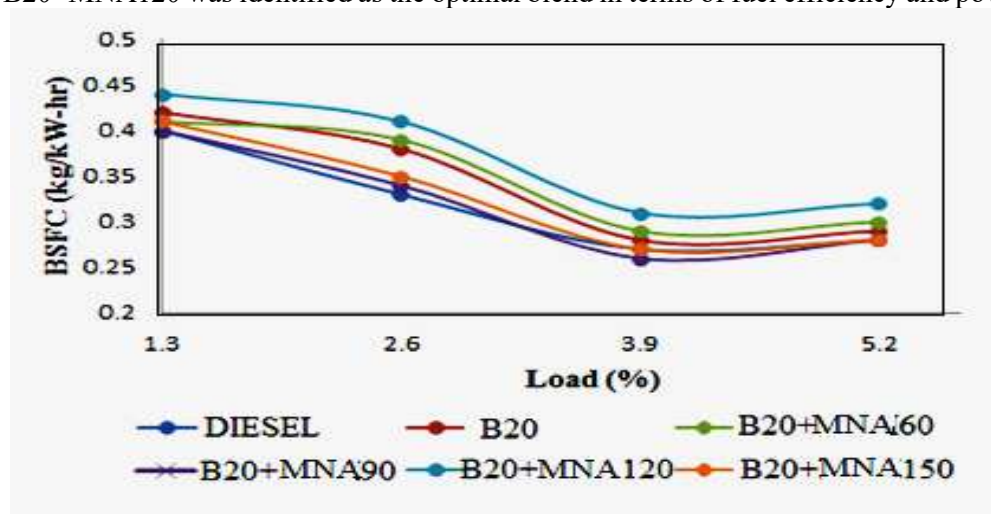


Fig.7 Distribution of brake fuel consumption with respect to load

4.1.3 Exhaust Gas Temperature

Figure 8 illustrates the Distribution in exhaust gas temperature (EGT) with load for all fuel blends. EGT increased with load for all fuels; however, at full load, B20 and MNA-blended fuels exhibited lower EGTs (311–353 °C) compared to diesel (367 °C). This reduction in EGT indicates improved heat utilization and supports the higher brake thermal efficiency (BTE) observed for the blended fuels.

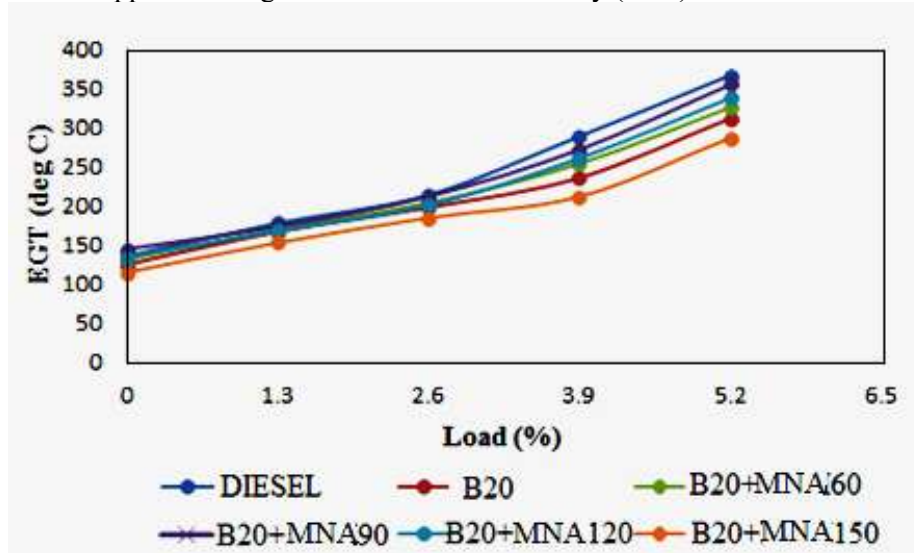


Fig.8 Distribution of exhaust temperature with respect to load

4.1.4 Ignition delay period

Ignition delay was determined as the time interval between fuel injection and the onset of combustion and is strongly influenced by fuel properties and in-cylinder conditions. Fuels with higher cetane numbers exhibited shorter ignition delays, particularly biodiesel and its blends. Figure 9 shows the ignition delay values for diesel, B20, B20+MNA60, B20+MNA90, B20+MNA120, and B20+MNA150 as 10, 11, 10, 10.4, 11, and 10.7 ms, respectively.

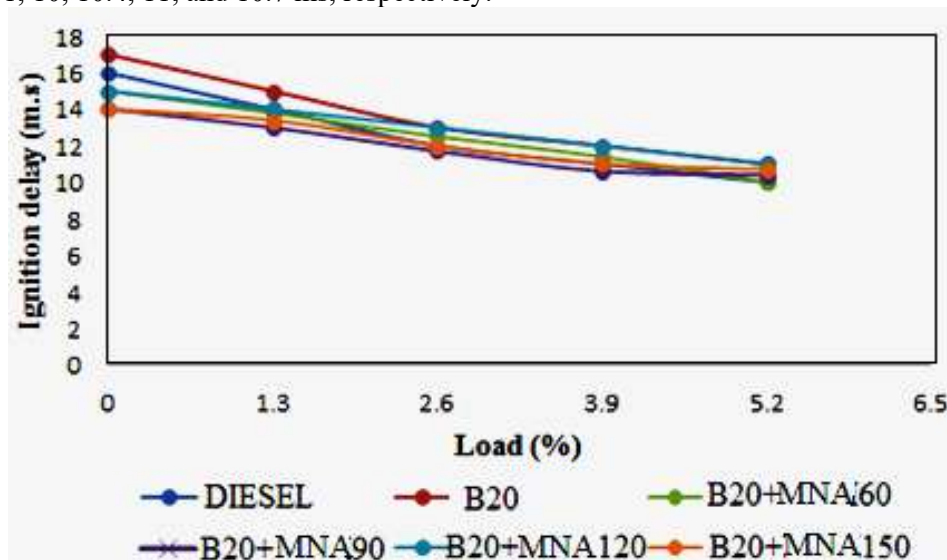


Fig.9 Distribution of ignition delay with respect to load

4.1.5 Combustion duration

The combustion length refers to the distance between the onset and completion of combustion. Fig. 10 illustrates that the examination of biodiesel, diesel-blend fuels, and their shorter combustion durations are attributed to the chemical composition of these fuels, facilitating a more efficient combustion process and thereby accelerating combustion, notably shortening the diffusion combustion phase. The

combustion length decreased sequentially for biodiesel and blends at each engine load, as the chemical element content and volatility increased in the order of biodiesel and MNA.

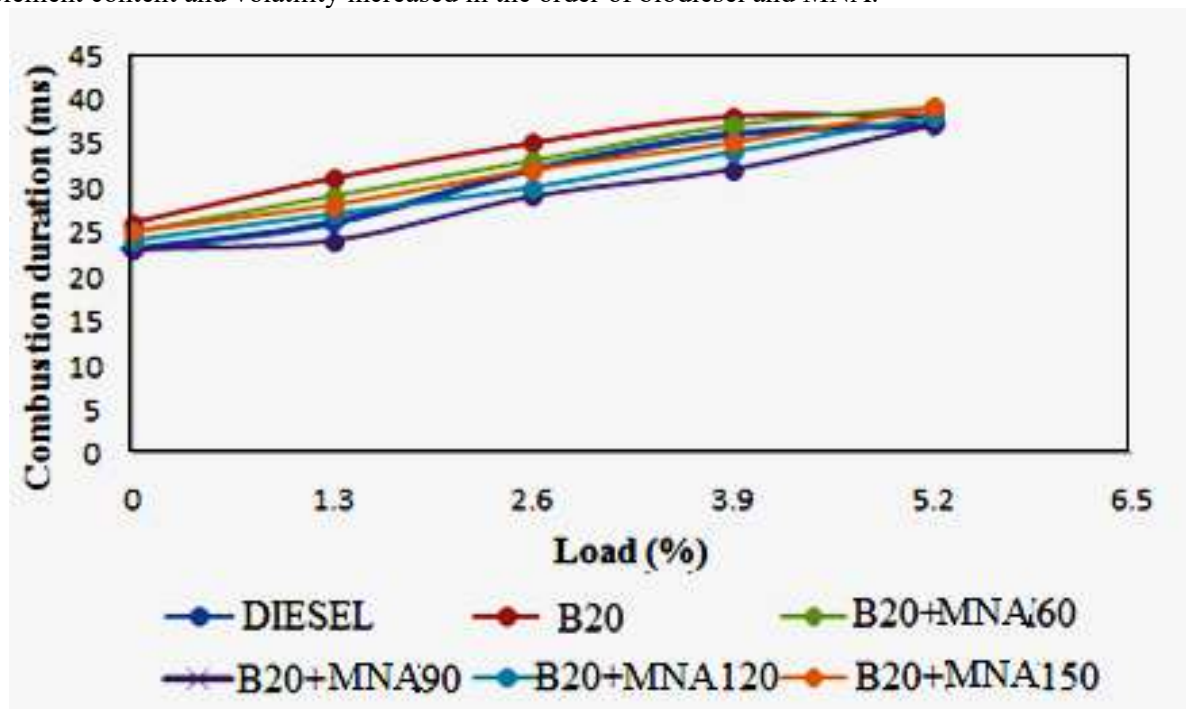


Fig.10 Variation of combustion duration with load

4.2 Characteristics of the emission

4.2.1 CO emissions

Fig.11 illustrates the difference in CO emissions concerning load for diesel, B20, and B20 with MNA. At full load conditions, diesel emitted 0.32%, B20 emitted 0.27%, and B20+ MNA60, B20+ MNA900, B20+ MNA120, and B20+ MNA150 emitted 0.19%, 0.17%, 0.13%, and 0.13% by volume, respectively. The shorter flame temperature and the improved fuel-air mixture ratio are key factors contributing to CO emissions from diesel engines. However, elevated CO emissions come at the expense of engine efficiency. Various factors may contribute to CO generation, such as insufficient residence time and extremely little or elevated similarity ratios. The superior properties of fluid flow of untainted B20 lead to lower blend development, resulting in incomplete combustion and higher CO emissions compared to diesel under all load conditions. Additionally, disturbances caused by the reaction of CO to carbon dioxide could also contribute to the increase in CO emissions.

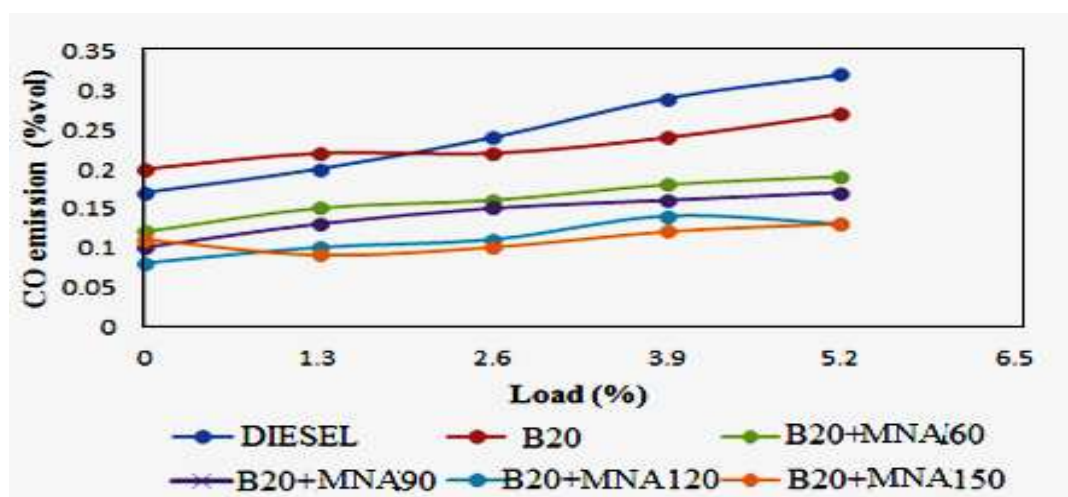


Fig.11 Distribution of CO emissions with respect to load

4.2.2 Unburned hydro carbon emissions

Fig. 12 depicts the difference in unburned hydrocarbon (UBHC) emissions concerning brake power (BP) for diesel, B20, and B20 with MNA. At full throttle conditions, diesel emitted 51 ppm of UBHC, while B20 emitted 55 ppm. For B20+MNA60, B20+MNA90, B20+MNA120, and B20+MNA150, UBHC emissions were measured at 51 ppm, 44 ppm, 55 ppm, and 42 ppm, respectively. It is evident that the addition of the inhibitor slightly increased UBHC emissions. Generally, UBHC emissions showed a slight increase with the addition of any inhibitor to biodiesel, as the inhibitor reduced the quantity of peroxy and peroxide radicals. The decrease in free radicals significantly affected the formation of OH extremists in the reactions of HC and CO. The engine load rise led to additional fuel consumption; however, the shorter burning time of the fuel caused in unfinished combustion and led to emission of HC. The formation of UBHC in diesel engines is attributed to two main reasons: (1) improper air-fuel mixture during ignition delay and (2) having a fuel-air mixture significantly richer than the thin combination limit. UBHC exists in several positions, including vapor, fuel droplets, or fuel products of fuel later thermal degradation. The UBHC pollutants contribute to air pollution and can react with chemically active compounds, potentially leading to the formation of pollutants.

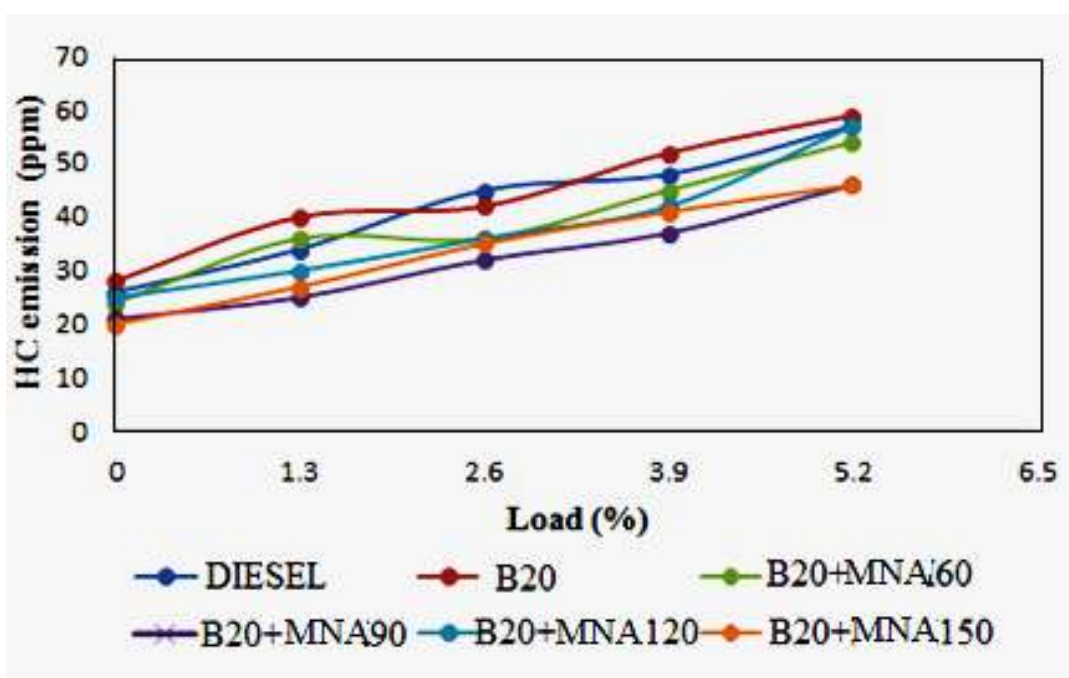


Fig.12 Distribution of hydro carbon emissions with respect to load

4.2.3 NOx emission

Fig.13 illustrates the difference in NOx emissions concerning brake power (BP) for diesel, B20, and B20 with MNA. NOx is the most harmful exhaust gas during combustion. The development of NOx is influenced by reactions occurring within the combustion process, the compounds involved, their concentrations, elevated combustion chamber temperature, prolonged burning duration, and adequate internal oxygen concentration. The results indicate that NOx production increases with load due to heightened fuel consumption, leading to elevated temperatures. Under full-load conditions, diesel emitted 912ppm of NOx, while B20 emitted 934ppm. For B20+MNA60, B20+MNA90, B20+MNA120, and B20+MNA150, NOx emissions were measured at 939ppm, 974ppm, 831ppm, and 416ppm, respectively. Significant reductions in NOx emissions were observed for B20 with MNA150 at most loads compared to diesel. The combination of MNA and B20 resulted in decreased NOx emissions, possibly due to the anti-oxidation property of MNA.

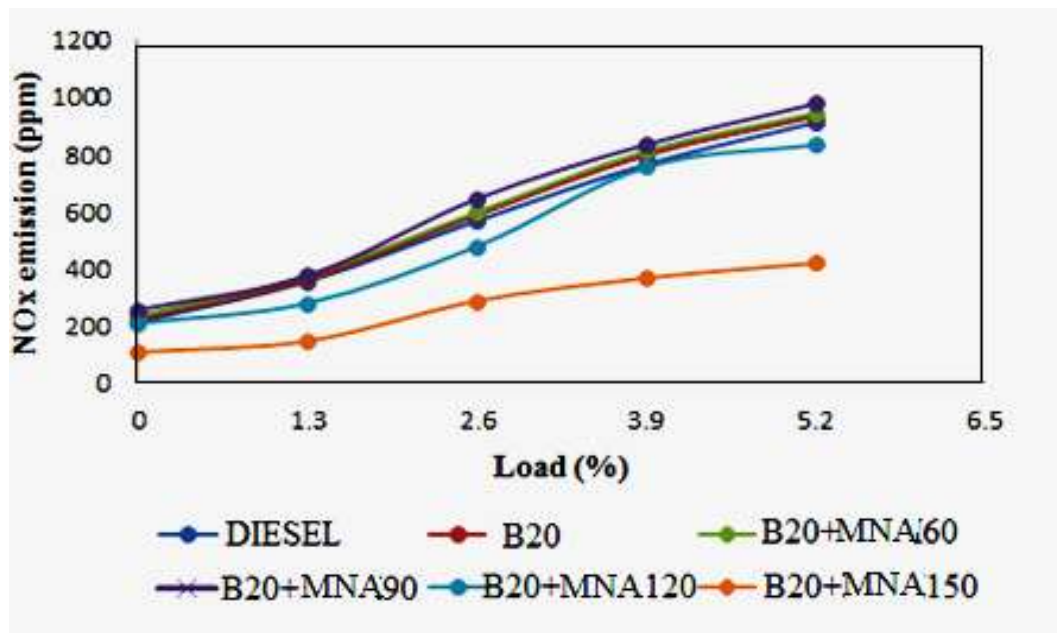


Fig.13 Distribution of NOx emissions with respect to load

5. Conclusion

Investigations were conducted into the properties, performance, and combustion of watermelon biodiesel combined with varied nano additives. From the experimental investigation, the following conclusions can be summarized:

1. The addition of mixed nano-additives (MNA) to B20 fuel generally enhances BTE, peaking at B20 + MNA120 with 27.8%, due to improved combustion efficiency from better fuel-air mixing and catalytic effects. The addition of MNA to B20 generally reduces BSFC, with B20 + MNA90 (0.28 kg/kW-h) showing the best performance. B20 + MNA120 represents the optimal blend.
2. EGTs for B20 and its blends with MNA are: B20 (311 °C), B20 + MNA60 (323 °C), B20 + MNA90 (353 °C), B20 + MNA120 (336 °C), and B20 + MNA150 (287 °C). Diesel has the highest EGT at 367 °C.
3. A higher cetane number typically results in a shorter ignition delay. The addition of MNA to B20 maintains or slightly reduces the ignition delay, enhancing combustion efficiency. Biodiesel and its blends with MNA show shorter combustion lengths compared to pure diesel, with combustion durations decreasing sequentially as the content of biodiesel and MNA increases.
4. Diesel, B20, and B20 with various MNA concentrations show different CO emissions at full load: Diesel (0.32%), B20 (0.27%), B20+MNA60 (0.19%), B20+MNA90 (0.17%), and B20+MNA120/B20+MNA150 (0.13%).
5. At full throttle, diesel emitted 51 ppm of UBHC, while B20 emitted 55 ppm. For B20+MNA, emissions were: MNA60 (51 ppm), MNA90 (44 ppm), MNA120 (55 ppm), and MNA150 (42 ppm).
6. Under full-load conditions, NOx emissions for diesel were 912 ppm, B20 at 934 ppm, and B20+MNA: MNA60 (939 ppm), MNA90 (974 ppm), MNA120 (831 ppm), and MNA150 (416 ppm).
7. The combined MgO and ZnO nanoparticles were found to be in the anatase phase, with an average size of 30–40 nm, according to FT-IR analysis. Compared to other fuel blends, the B20+MNA120 blend performed better overall, indicating its potential to replace traditional diesel.

Declaration of Competing Interest

The authors confirm that there are no known financial or personal conflicts of interest related to this study.

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Nomenclature

Name	Abbreviation
ASTM	American Society of testing and materials
B	Blend
B20	80% Diesel + 20% biodiesel
B20 +MNA 60	80% Diesel + 20% biodiesel +60ppm (MgO + ZnO)
B20 +MNA 90	80% Diesel + 20% biodiesel + 90ppm (MgO + ZnO)
B20 +MNA 120	80% Diesel + 20% biodiesel +120ppm (MgO + ZnO)
B20 +MNA 150	80% Diesel + 20% biodiesel + 150ppm (MgO + ZnO)
bTDC	Before top dead centre
BSFC	Brake Specific Fuel Consumption
BTE	Brake Thermal Efficiency
CA	Crank angle
CO	Carbon monoxide
CR	Compression ratio
EGT	Exhaust gas temperature
HRR	Heat release rate
ID	Ignition delay
MNA	Mixed nano additive
MgO	Magnesium oxide
NO _x	Nitrogen Oxide
UBHC	Unburned Hydrocarbon
ZnO	Zinc Oxide