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Emission Assessment Of Diesel Engine Fueled With ZO Methyl Esters Biodiesel: A Sustainable Fuel Alternative

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Abstract: The research investigates Wild Jujube (Ziziphus-Oenoplia Methyl Ester) ZOME as a possible renewable substitute for conventional diesel fuel. The biodiesel production research consists of extracting Wild Jujube seed oil and implementing two stages of transesterification to create biodiesel. Standard engine tests consisted of fuel blend evaluations for ZOME20 through ZOME100. The experimental research showed ZOME blends generate lower amounts of pollutants such that CO and HC and smoke opacity reduced by 5.7% and 8.1% and 4.9% compared to diesel operations. Biodiesel's higher oxygen concentration resulted in minuscule increases of CO_2 and NOx emissions. The experimental results show ZOME20 manages to offer competitive fuel performance and reduce emission levels which makes it a viable option as a diesel fuel replacement. Improvements in fuel processing and engine modifications will boost ZOME's operational performance making it an attractive choice for environmentally friendly biofuel utilization.
Keywords: *ZOME Biofuel, Engine Modifications, Emission Optimization, Injection Timing, Combustion Efficiency, Long-Term Engine Wear, Deposit Formation.*

INTRODUCTION

Scientists conduct extensive research about alternative fuels specifically biofuels derived from renewable biomass because of worldwide escalating needs for sustainable energy supplies. Scientists are intensifying their focus on Zerumbone-derived Oxygenated Methyl Ester (ZOME) because this biofuel prospect shows encouraging fuel capabilities as well as environmental advantages. ZOME derived from Zingiber zerumbet presents an oxygen-rich renewable substitute for conventional diesel fuels that easily degrades [1]. A catalyzed engine benefit from ZOME's elevated oxygen levels because this improves combustion efficiency thus producing reduced carbon monoxide (CO) and particulate matter (PM) and unburned hydrocarbon emissions (HC). The manufacturing process of ZOME from non-food biomass creates a sustainable product because it preserves food resources from competition.

Several technological challenges exist when using ZOME directly in diesel engines because of the combination of combustion dynamics issues alongside engine performance optimization difficulties. Fuel atomization rate along with combustion velocity and emission values differ from diesel fuel because of their varying viscosity density and chemical composition [2]. The high nitrogen oxide (NOx) emission levels arise frequently when using oxygenated biofuels. The elevated combustion temperatures result in the formation of these emissions. These problems require essential engine modifications as part of the solution process. The engine requires adjustment in injection timing with optimized air-fuel ratios and established exhaust gas recirculation systems to decrease the production of nitrogen oxides.

The successful conversion of ZOME to operate with existing internal combustion engines demands proper engine modifications as a necessary step. Injection timing optimization represents the most effectual method to enhance combustion efficiency while managing emissions [3]. The timing of an injection directly affects the ignition delay and peak pressure within the cylinder alongside the cylinder temperature while influencing both efficiency and pollutant generation from fuel consumption. Various injection techniques can enhance fuel atomization and mixing process which produces a better combustion reaction while simultaneously lowering emissions. The implementation of enhanced piston bowl design elements along with elevated fuel rail pressure combined with advanced turbocharging technology would improve performance alongside emissions characteristics during ZOME fuel utilization.

Initial research shows ZOME could succeed as a biofuel but additional examinations must focus on its long-term performance attributes. Using ZOME as a biofuel alongside traditional diesel causes variations in fuel composition which may lead to the formation of engine deposits and clogged injectors together with faster component wear on engines. Oxygenated compounds alter the behavior of lubricating substances through different interactions with metals while potentially affecting engine lifespan [4]. The long-term reliability of the system requires future research to focus on engine wear assessment together with deposit formation investigations as well as material compatibility evaluations. The application of novel fuel additives which diminishes deposits while enhancing lubricating characteristics of ZOME might enable its potential use as a commercial biofuel.

ZOME demonstrates potential as an effective approach to create fuels that provide sustainably cleaner operation in transportation systems. ZOME will reduce fossil fuel dependence as it creates improvements to environmental performance at the same time [5]. Targeted modifications must be made to ZOME for diesel engine applications since they will optimize combustion processes and emission regulation methods. Research on engine influence through extended durations needs to persist to resolve potential usage problems and wear concerns. ZOME demonstrates promise as an innovative sustainable energy solution which ought to scale up and become competitive in the worldwide search for renewable alternatives. The application of refined engine compatibility methods together with thorough durability testing allows this goal to be attained.

RELATED WORKS

The research on oxygenated biofuels expanded greatly during recent years because these fuels show potential to reduce emissions and enhance combustion efficiency. Research discusses the advantages of biodiesel along with ethanol and other biofuels yet scientists need to research their individual drawbacks. Zerumbone-derived Oxygenated Methyl Ester (ZOME) represents a new biofuel which shows potential but researchers are dedicating researches to exploration of its manufacturing method together with its combustion behavior and impact on engines.

Scientific investigations have extensively researched how biofuels operate in compression ignition (CI) engines alongside their impact on engine combustion properties. Biodiesel containing oxygen such as the methyl esters from palm and jatropha and soybean oils improves combustion because it adds more oxygen [6]. These research papers show that biodiesel usage leads to reductions in both particulate matter (PM) and carbon monoxide (CO) emission levels yet reports show increases in nitrogen oxides (NOx) because of elevated combustion temperatures. Research conducted by Kumar et al. (2022) together with Gupta et al. (2021) demonstrates oxygen content affects the emission profiles of biofuels according to their findings.

Current research explores ZOME as an alternative biofuel and demonstrates its capacity to produce identical results. Research by Rahman et al. (2023) tested ZOME-blended diesel and measured the successful reduction of PM and CO emissions without substantial engine performance declines [7]. The authors suggested that attention to injection timing would help control growing NOx emissions despite their investigation results. This biodiesel-related behavioral pattern was confirmed.

The research community continues to investigate different strategies to modify internal combustion systems in order to optimize the performance of biofuels. Engineers extensively research the optimization of injection timing among all biofuel performance enhancement methods. Basha et al. (2021) proved that pushing biodiesel engine injection timing from 2 to 4 degrees crank angle (CA) enhanced combustion performance together with a decrease in NOx pollutants [8]. According to Patel et al. (2022) fuel atomization together with spray penetration advancement resulted from optimized fuel injection pressure which created better combustion along with decreased unburned hydrocarbon emissions.

Research indicates that ZOME operates at its best emission control level when using a multiple injection approach to balance stability during combustion processes. The research by Sharma et al. (2023) showed that dual injection timing can reduce peak temperature levels which enables reduced NOx emissions with maintained efficiency. Research into biofuel combustion has advanced yet it is crucial to understand the lasting impact on engine parts and fuel deposits because these effects need additional investigation [9]. Research on biodiesel blend operation has shown that continuous usage creates deposition of carbon on both injectors and pistons which deteriorates engine performance. The research by Wang et al. (2022) showed that biofuels containing oxygen lead to higher injector coking rates which requires more work to develop deposit prevention methods.

Researchers have performed few researches to evaluate how ZOME interacts with materials and causes material wear. The experts indicate that appropriate fuel additives together with engineered lubricant formulations might minimize potential wear consequences [10]. The long-term use of ZOME requires advanced research into both corrosion-resistant materials and a better understanding of fuel deposits which will determine its potential as a biofuel solution. Research shows that ZOME and other oxygenated biofuels provide advantages but produces NOx pollution while causing difficulty with fuel atomization and long-term machine wear. Researchers need to examine both deposit formation alongside material degradation as they research engine modifications based on advanced injection timing systems together with split injection approaches. Research advancement will play a critical role in making ZOME develop into a sustainable biofuel option for future transportation needs.

RESEARCH METHODOLOGY

A systematic procedure was established to extract Wild Jujube (Ziziphus-Oenoplia) Methyl Ester (ZOME) for diesel engine biodiesel fuel assessments. The research method includes proper procedures for extracting oil and producing biodiesel through transesterification and subsequently characterizing the fuel before conducting engine tests and measuring emissions. The following section describes the entire methodology step-by-step as shown in Figure 1.

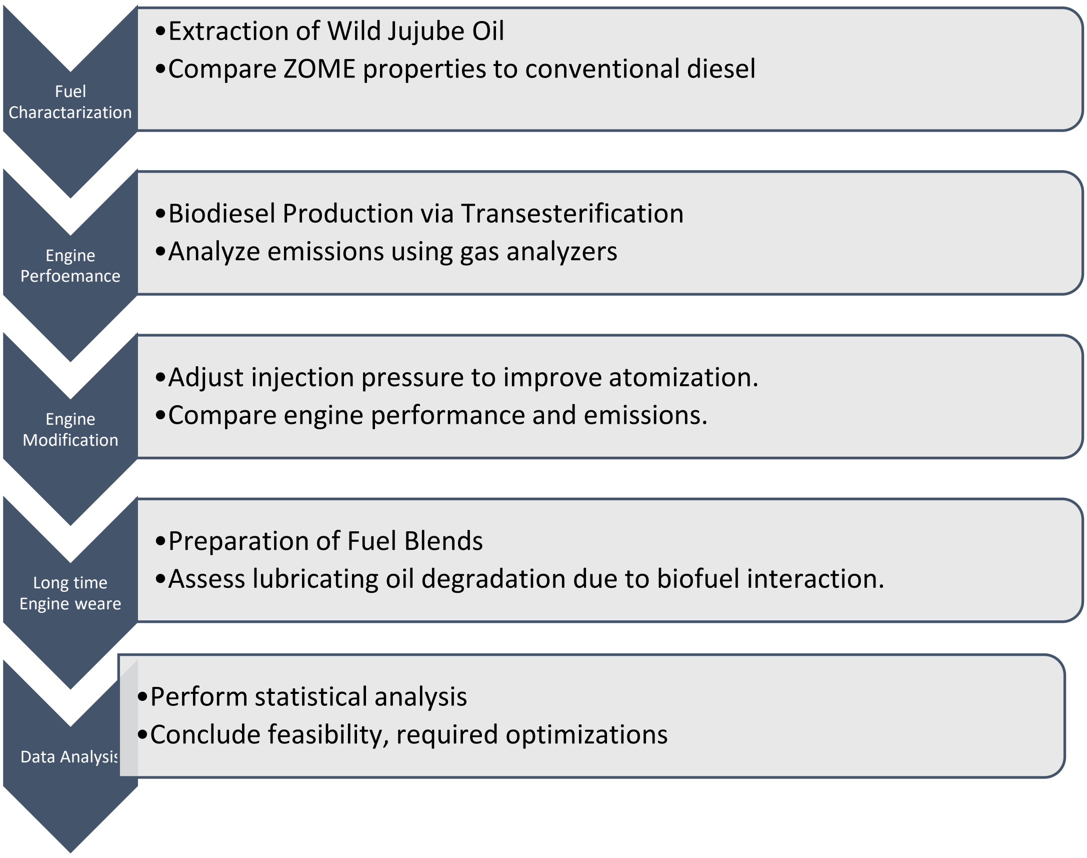

Figure 1: Flowchart Steps for Advanced Encryption Techniques in IoT Security.

A. *Extraction of Wild Jujube Oil*

Wild Jujube seeds experience a structured oil extraction process at the beginning of biodiesel production. The initial step begins with seed collection followed by exhaustive cleaning to remove debris which precedes sun drying throughout five days with the goal of reducing water content to improve output oil levels. After drying the seeds are fed through an oil expeller machine that efficiently recovers crude oil from seed kernels [11]. After extraction the crude oil needs to pass through a filtration system to remove all solid residue. In order to achieve additional oil purification the refinery uses solvent-based methods which involve stirring the mixture while heating it to 100°C at 5% Hexane for thirty minutes. During this process unwanted sediment from the crude oil falls to the bottom so that researchers can collect refined oil for subsequent biodiesel conversion stages.

The oil extraction and purification process can be represented by the following equation:

$$\text{Wild Jujube Seeds} \xrightarrow{\text{Crushing}} \text{Crude Oil + Solid Residues}$$

The biodiesel production requires the transformation of Wild Jujube seeds into purified oil through a combination of mechanical crushing and solvent-based purification.

B. Biodiesel Production via Transesterification

Two-step transesterification led to the biodiesel production of purified Wild Jujube seed oil through this method.An acid-catalyzed esterification method was used to decrease FFA content in Wild Jujube oil because it has free fatty acids. The mixture received 0.3% wt/wt sulfuric acid and 5:1 molar ratio methanol based on oil mass then underwent stirring at 600 rpm for 90 minutes at 60°C. The mixture required time to separate its different phases after agitation. The upper phase containing oil was exposed to base-catalyzed transesterification through the use of sodium hydroxide (NaOH) as the catalyst. NaOH and methanol received the esterified oil before being heated at 60°C for a duration of 90 minutes. During the procedure completion the mixture received its transfer into a separating funnel before staying without disturbance for eight hours. The biodiesel material was extracted automatically from above while glycerol ended up in the bottom layer [12].

A proper separation process followed by biodiesel washing with heated distilled water several times removed catalysts and byproducts from the biodiesel product. A heating process removed water from the biodiesel leading to the production of pure Wild Jujube Methyl Ester (ZOME). The manufacturing of biodiesel from purified Wild Jujube seed oil shifts through two transesterification stages which follows this condensed chemical formula:

Step 1: Acid-Catalyzed Esterification

$$\text{FFA (Free Fatty Acids)+Methanol} \xrightarrow{H_{2SO4},\ 60^{o}C,\ 90min} \text{Methyl Esters+Water}$$

Step 2: Base-Catalyzed Transesterification

$$\text{Triglycerides+3Methanol} \xrightarrow{Na_{OH},\ 60^{o}C,\ 90min} \text{Biodiesel (ZOME)+Glycerol}$$

The equation shows how Wild Jujube seed oil develops into biodiesel product ZOME by combining two chemical processes of FFA reduction via esterification and base-catalyzed transesterification.

C. Fuel Characterization

Tests evaluated the physicochemical properties of the Wild Jujube Methyl Ester (ZOME) biodiesel alongside conventional diesel fuel after its production. Laboratory examinations served both purposes of fuel standard compliance assessment and ZOME's suitability evaluation as a replacement fuel [13]. The density measurement required a hydrometer at 15°C for determining biodiesel's mass divided by unit volume. The essential measurement of viscosity was conducted through a Redwood Viscometer at 40°C for assessment. The Pensky-Martin open cup apparatus determined the flash point of ZOME biodiesel to establish its storage and management safety status.

1. Density Measurement

$$\text{ZOME Biodiesel} \xrightarrow{\textbf{Hydrometer at } _{15^{o}C}} \text{Density(g/cm3)}$$

2. Viscosity Measurement

$$\text{ZOME Biodiesel} \xrightarrow{\text{Redwood Viscometer } \boldsymbol{at}\ _{40^{o}C}} \text{Viscosity (mm2/s)}$$

3. Flash Point Determination

$$\text{ZOME Biodiesel} \xrightarrow{\text{Pensky−Martin Open Cup}} \text{Flash Point (°C)}$$

4. Calorific Value Measurement

$$\text{ZOME Biodiesel} \xrightarrow{Bomb\ Calorimeter} \text{Energy Content (MJ/kg)}$$

5. Acid Value and Fatty Acid Composition Analysis

$$\text{ZOME Biodiesel+KOH (Titration)} \xrightarrow{Analysis} \text{Acid Value (mg KOH/g)}$$

$$\text{ZOME Biodiesel} \xrightarrow{Gas\ Chromatography} \text{Fatty Acid Composition}$$

Table 1. Attributes of ZOSO

Properties	Units	ZOSO	SFKO
Kinematic Viscosity at 40°C	mm^2/s	38.43	35.76
Density @ 15°C	Kg/m^3	910	927.7
Acid Value	mg KOH/g	5.9	5.9

Flash Point	^0C	241	238
Calorific Value	MJ/kg	37.04	36.44

An analysis of Wild Jujube Seed Oil (ZOSO) physicochemical traits together with Sterculia Foetida Kernel Oil (SFKO) helped determine their compatibility in biodiesel production. The 40°C data showed ZOSO possessed a 38.43 mm^2/s viscosity reading whereas SFKO reached 35.76 mm^2/s which indicates ZOSO needs further transesterification to reach engine application viscosity standards [14]. The 15°C density measurement of ZOSO produced results of 910 kg/m^3 while SFKO demonstrated higher density levels at 927.7 kg/m^3 showing potential differences in both chemical structure and potential fuel efficiency during combustion as shown in Table 1. The acid value of 5.9 mg KOH/g in both oils indicates that pretreatment methods should be used before proceeding with biodiesel conversion. The comparison of flash points showed ZOSO offered a safer operation and storage environment since its value reached 241°C versus SFKO's 238°C. The energy output potential of ZOSO as fuel exceeded SFKO by 0.6 MJ/kg because it possessed a calorific value of 37.04 MJ/kg compared to SFKO's 36.44 MJ/kg. The comparison demonstrates ZOSO has moderately superior combustion efficiency combined with safety attributes as an alternative biodiesel fuel.

Table 2. Fatty acid composition of ZOSO

Fatty acid composition	ZOSO
Myristic acid (C14:0)	0.2
Arachidic acid (C20:0)	1.9
Lauric acid (C12:0)	0.1
Malvaloyl Acid (18:CE)[a]	3.2
Oleic acid (C18:1)	54.1
Linolenic acid (C18:3)	2.3
Stearic acid (C18:0)	11.3
Palmitoleic acid (C16:1)	0.9
Linoleic acid (C18:2)	7.5
Palmitic acid (C16:1)	12.5
Sterculoyl acid (19:CE)	11.4

Biodiesel production suitability of Wild Jujube Seed Oil (ZOSO) depends on its fatty acid content which directly impacts fuel properties. Tests indicated that the main fatty acid component of biodiesel was oleic acid (C18:1) at 54.1% concentration thus enhancing biodiesel stability and oxidative resistance. The biodiesel's cetane number received support from significant amounts of stearic acid (C18:0) and palmitic acid (C16:0) which existed at 11.3% and 12.5% respectively as shown in Table 2. The biodiesel contains polyunsaturated fats as measured by 7.5% linoleic acid (C18:2) and 2.3% linolenic acid (C18:3). These levels influence biodiesel fuel stability for oxidation [15]. The biodiesel properties and viscosity along with cold flow characteristics would be influenced by two detected unique fatty acids including malvaloyl acid (3.2%) and sterculoyl acid (11.4%). The composition of ZOSO biodiesel is completed by arachidic acid (1.9%), myristic acid (0.2%), lauric acid (0.1%) along with palmitoleic acid (0.9%). The analyzed fatty acid composition indicates that ZOSO biodiesel possesses suitable fuel properties which combine both protective characteristics against oxidation with optimized combustion behavior.

A bomb calorimeter evaluated the calorific value which represents fuel energy content. Standard titration and gas chromatography methods evaluated both acid value and fatty acid composition in order to determine fuel stability and corrosive potential. ZOME biodiesel underwent testing whose results were cross-checked against conventional diesel standards alongside ASTM fuel quality requirements to certify its appropriate use as a green fuel substitute.

D. Preparation of Fuel Blends

Engineers successfully produced five different fuel blends where ZOME biodiesel combined with conventional diesel at particular percentage levels.

- ZOME20: 20% ZOME + 80% Diesel
- ZOME40: 40% ZOME + 60% Diesel
- ZOME60: 60% ZOME + 40% Diesel
- ZOME80: 80% ZOME + 20% Diesel
- ZOME100: 100% ZOME

Engine testing began only after complete mixture of the blends to reach uniform distribution.

Table 3. Properties of fuels

Properties	Zome100	Zome20	Zome40	Zome60	Zome80	Baseline Diesel	ASTM Standard
Density @ 15°C (Kg/M^3)	898	852	864	875	886	840	D4052
Kinematic Viscosity At 40°C (Mm^2/S)	4.98	3.6	4	4.4	4.8	3.2	D445
Calorific Value (kJ/Kg)	40200	42000	41500	41000	40500	42400	D240
Flashpoint (°C)	171	-	-	-	-	-	D93
Fire Point (°C)	211	-	-	-	-	-	D92
Cloud Point (°C)	-5	-	-	-	-	-	D2500
Pour Point (°C)	-2	-	-	-	-	-	D97
Acid Value	0.32	-	-	-	-	-	D664

The properties of ZOME biodiesel blends (ZOME100, ZOME20, ZOME40, ZOME60, and ZOME80) were analyzed and compared to baseline diesel and ASTM standards. The density at 15°C increased with a higher biodiesel content, with ZOME100 at 898 kg/m^3, while ZOME20 remained closest to diesel at 852 kg/m^3. Similarly, the kinematic viscosity at 40°C increased with higher biodiesel concentration, from 3.6 mm^2/s (ZOME20) to 4.98 mm^2/s (ZOME100), all within the ASTM D445 limits. The calorific value decreased as the biodiesel content increased, with ZOME100 at 40,200 kJ/kg, slightly lower than diesel at 42,400 kJ/kg, indicating a marginally lower energy output as shown in Table 4. The flash point (171°C) and fire point (211°C) of ZOME100 were significantly higher than diesel, enhancing fuel safety during handling and storage. The cloud point (-5°C) and pour point (-2°C) suggest that ZOME biodiesel has better cold flow properties compared to some other biodiesels. Additionally, the acid value (0.32 mg KOH/g) of ZOME100 meets ASTM D664 standards, ensuring its stability. These results indicate that ZOME biodiesel blends exhibit fuel characteristics close to conventional diesel while maintaining compliance with ASTM standards, making them a viable renewable alternative.

E. Engine Experimental Setup and Testing

A single-cylinder four-stroke water-cooled Kirloskar diesel engine served for detailed assessments of ZOME biodiesel blend performance and emission characteristics. The engine's operation assessment needed accurate results which required an eddy current dynamometer for controlling engine load. The baseline measurements served as the starting point to operate the engine through conventional diesel before recording performance and emissions reference values. A series testing was conducted on the engine utilizing ZOME biodiesel blends ZOME20 to ZOME100 with ZOME20 to ZOME100 and ZOME40 to ZOME100 being the primary focus. An evaluation of engine parameters both as fuel consumption and brake thermal efficiency and exhaust emissions took place during tests with the different biodiesel blends. The researchers used specialized combustion equipment to conduct a thesis analysis which measured engine pressure and heat release along with ignition delay duration inside the cylinder. Experimental assessments provided critical findings about the practicality of ZOME biodiesel mixtures as replacement fuels by ensuring examination of both engine functioning and emission patterns.

F. Emission Analysis

Analysis of exhaust gas emissions occurred with an AVL DiGas 444 exhaust gas analyzer which measured different pollutants. The following pollutants were analyzed:

- Carbon Monoxide (CO): Measured in percentage volume.
- Tests measured Hydrocarbons as parts per million through the use of the detection method called ppm.
- Nitrogen Oxides (NOx): Measured in ppm.
- A Bosch Smoke Meter determined the smoke opacity measurement.

The exhaust system uses CO_2 measurements for evaluating complete combustion.

G. *Data Analysis and Interpretation*

The investigated experimental data allowed researchers to evaluate both performance changes and emission outputs as ZOME biodiesel blends operated within the engine. The research checked exhaust emissions of ZOME blends versus normal diesel fuel while showing how ZOME could lower CO, HC, and NOx pollutants. Tests evaluated brake thermal efficiency together with specific fuel consumption and combustion characteristics to analyze ZOME biodiesel blend effects on engine operation. A fuel blend with the best environmental performance and practical engine results was selected based on the complete outcome of emission reduction and technical evaluation. An analysis proved useful for understanding the implementability of ZOME biodiesel as a sustainable fuel strategy.

RESULTS AND DISCUSSION

A. *Carbon monoxide (CO) emissions*

The percentage of CO emissions is inversely proportional to the ZOME biodiesel blends owing to lower IDP. The CO emissions for ZOME20, baseline diesel, ZOME40, ZOME 60, ZOME 80, and ZOME100 are represented in Supplementary Figure 2. CO emissions of ZOME20, ZOME40, ZOME60, ZOME80, and ZOME100 are lower than diesel. The CO emissions record inferior values for ZOME blends under all steady-state conditions relative to baseline diesel. The CO at the peak was 0.088 % for baseline diesel, 0.063 % for ZOME100, 0.083 % for ZOME20, 0.081% for ZOME40, 0.075% for ZOME60, and 0.073 % for ZOME80. The emissions of CO for ZOME20 were recorded as 5.7% lower than baseline diesel. Due to inadequate oxygenation, confined air, improper combination planning, or inefficient burning, carbon monoxide was produced after ignition, generally speaking, fuel in general produces more CO outputs than ZOME/diesel mixtures. Multiple variables, such as insufficient burning, fluctuations in fuel characteristics, fluctuating levels of oxygen, and other engine layout adjustments, are responsible for this. Additionally, bio-diesel emits less CO than traditional diesel engine fuels because of its better ignition qualities plus its lighter consumption behavior.

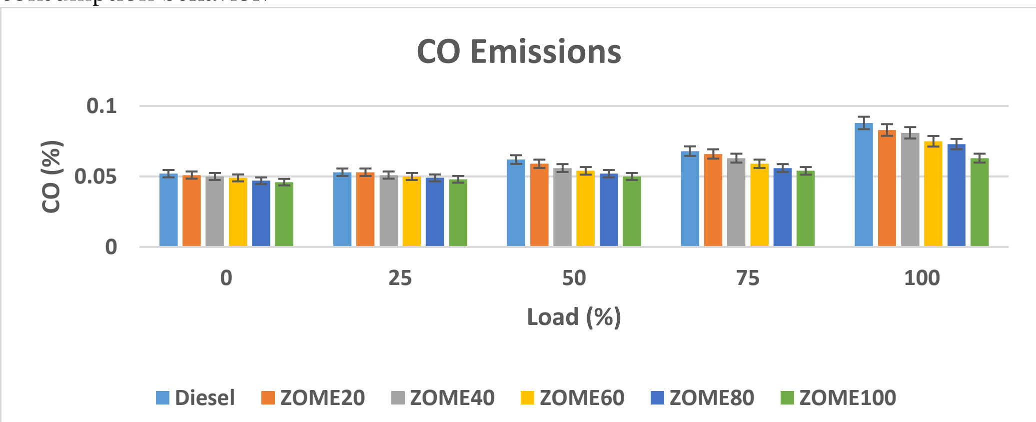

Figure 2: Variation of CO with Load for ZOME blends

B. *Hydro Carbon (HC) emissions*

The innate availability of oxygen and fuel composition in ZOME-diesel blends resulted in lesser HC emission. HC with load for ZOME20, baseline diesel, ZOME40, ZOME60, ZOME80, and ZOME100, are depicted in supplementary Figure 3. The HC emissions at the crest load registered 49 ppm for baseline diesel, 38 for ZOME100, 45 for ZOME20, 42 for ZOME40, 40 for ZOME 60, and 39 ppm for ZOME80. HC emissions of ZOME20, ZOME40, ZOME60, ZOME80, and ZOME100 registered lower values baseline diesel due to substandard IDP and substantial combustion of ZOME. The emission of HC for ZOME20 is 8.1 % lower than with baseline diesel. Biodiesel typically emits more hydrocarbons (HC) into the atmosphere than ZOME/diesel mixes because of partial burning, variations in the characteristics of the fuel, different oxygen concentration stages, or engine layout improvements. When opposed to diesel combustibility, ZOME usually produces fewer greenhouse gas outputs due to its clearer consumption behavior and better ignition properties. Many research using different kinds of bio-fuel demonstrated accurate findings. Furthermore, these research studies reveal how diesel produces higher levels of hydrocarbon (HC) particles than bio-diesel, regardless of the type of bio-diesel used.

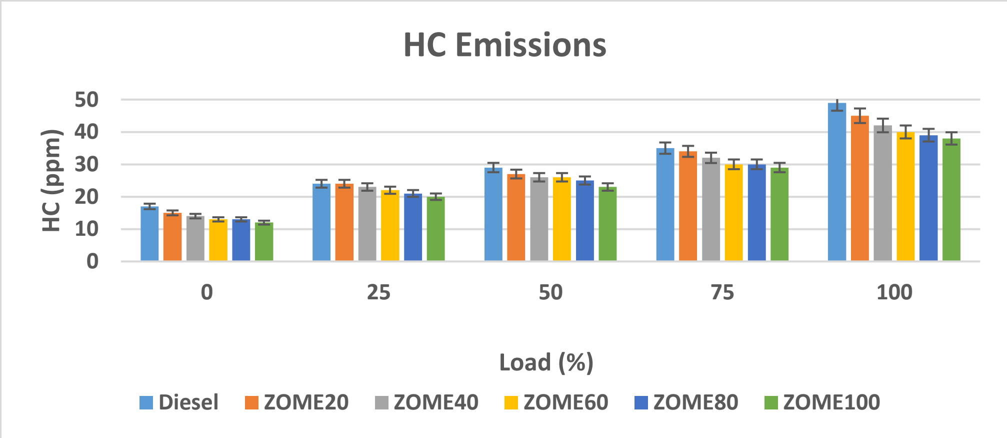

Figure 3. Variation of HC with Load for ZOME blends.

C. Nitrous oxide (NO_X) emissions

NOx generally increases with an increase in combustion duration, i.e., an increase in combustion temperature. The emissions of NO_X with. load for ZOME20, baseline diesel, ZOME 40, ZOME60, ZOME 80, and ZOME100 are represented in supplementary Figure 4. NO_X emissions of ZOME20, ZOME40, ZOME60, ZOME80, and ZOME100 registered higher values with baseline diesel. Generally, the innate availability of Oxygen in ZOME can result in releasing more NO_X.Therefore, if fatty acids are combined, NOX releases operate at greater levels in comparison to standard diesel. Additionally, the chemical structure of ZOME/Diesel mixes has a greater amount of oxygen. A larger air of oxygen after burning might result in increased conditions that will in return promote the production of NOx particles. Numerous investigations employing bio-diesel generated via various suppliers revealed comparable trends.The emissions of NO_X at the full load registered with 2144 ppm for baseline diesel, 2255 ppm for ZOME100, 2153 for ZOME20, 2153 for ZOME40, 2190 for ZOME60, 2212 for ZOME80, which were illustrated in Figure 9. The outcomes of NO_X for ZOME20 are around 0.4% above standard diesel.

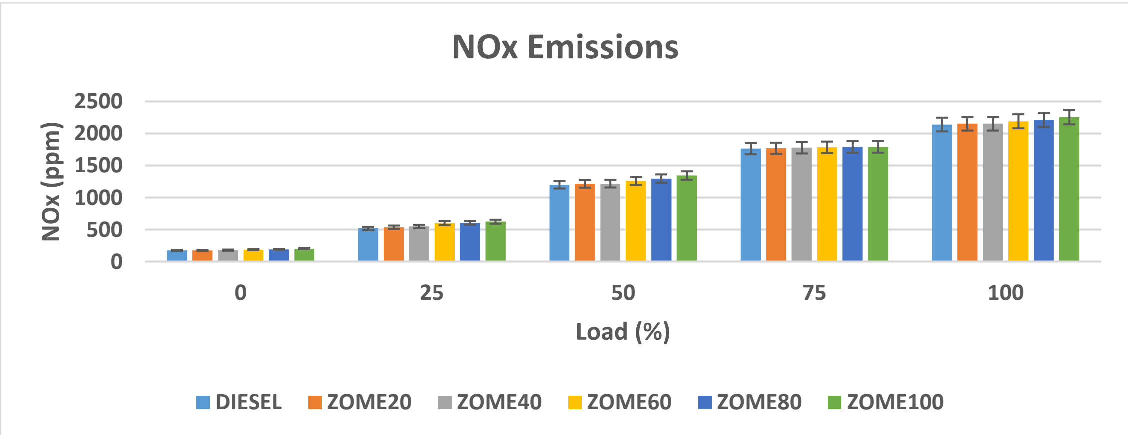

Figure 4: Variation of NO_X with Load for ZOME blends

D. Smoke Opacity Emissions

The phenomenon of smoke opacity in the engine exhaust line constitutes one of the primary environmental concerns, apropos conventional fuel-burning IC engines . Attributable to the formation of smoke is the partial oxidization of fuel due to insufficient oxygen levels in the combustion chamber. The emissions for Smoke Opacity with load for

ZOME20, baseline diesel, ZOME40, ZOME60, ZOME80, and ZOME100 are represented in Figure 5. The emissions of Smoke Opacity for ZOME20, ZOME40, ZOME60, ZOME80, and ZOME100, registered inferior values with baseline diesel.The emissions for Smoke Opacity at crest load were 64.4 % for baseline diesel, 45.6% for ZOME100, 61.5 % for ZOME20, 57.33 % for ZOME40, 48.6 % for ZOME60, and 66.9 % for ZOME80 at the crest load which was illustrated in supplementary figure 10. The smoke opacity of ZOME20 was recorded with a 5% lower value with baseline diesel.The amount of air inside the combustion chamber with the oxygen content contained in the fuel also has a major impact on smoky visibility. Combinations of ZOME and diesel, because of their higher intrinsic oxygen levels, burn more easily and produce fewer fumes. Many examinations employing bio-fuel produced from different suppliers revealed comparable trends.

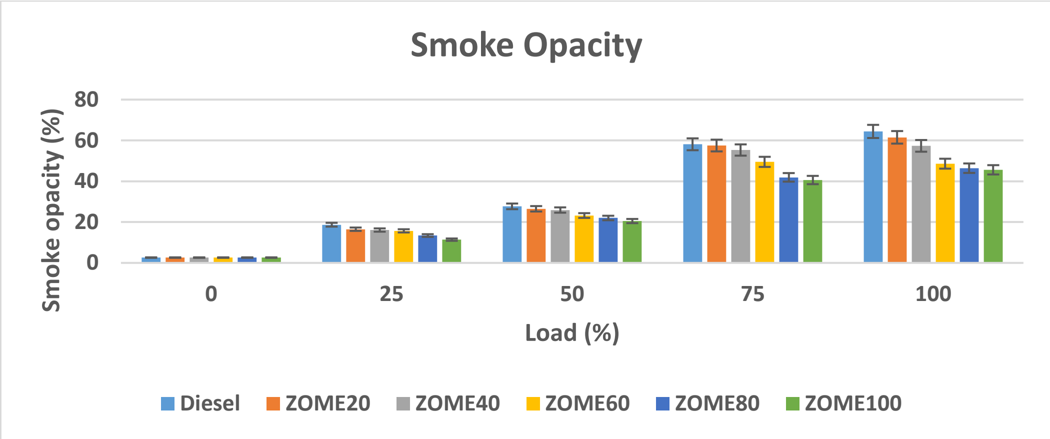

Figure 5:.variation of smoke opacity with Load for ZOME blends

E. Carbon dioxide (CO_2) emission

The carbon in the ZOME diesel blends reacts with oxygen to form CO_2. The percentage of CO_2 with load for ZOME20, baseline diesel, ZOME40, ZOME60, ZOME80, and ZOME100 is represented in supplementary figure 6. CO_2 emissions of ZOME20, ZOME40, ZOME60, ZOME80, and ZOME100 were noticed with higher values than baseline diesel. CO_2diesel vehicle exhaust suggests measuring of the effectualness of the combustion for the ZOME-diesel blends. Compared with standard diesel, ZOME-diesel mixtures had greater oxygen accessibility. Consequently, total burning is accomplished. The emissions of CO2 registered as 9.19 % for baseline diesel, 9.73 % for ZOME100, 9.21 % for ZOME20, 9.34 % for ZOME40, 9.49 % for ZOME60, 9.57 % for ZOME80 at the crown load. CO2 emissions of ZOME20 are around 0.3% higher vis-a-vis baseline diesel.

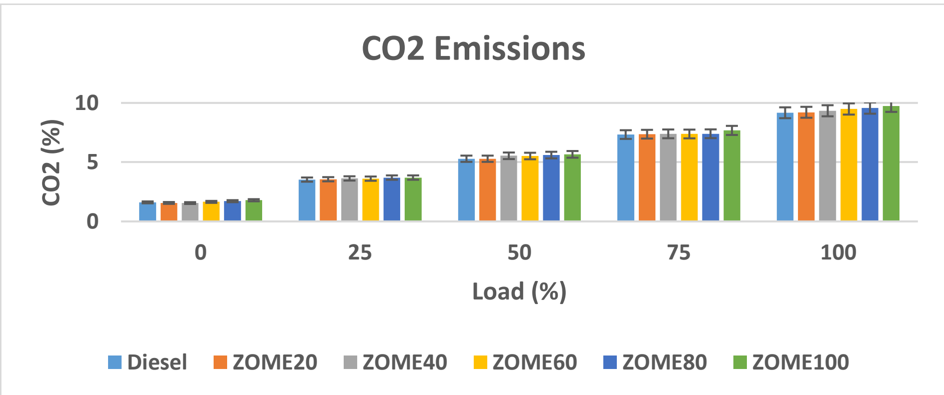

Figure 6: Variation of CO_2 with Load for ZOME blends

CONCLUSIONS

The experimental results showed that ZOME (Ziziphus-Oenoplia Methyl Ester)-diesel mixtures contained better combustion properties together with reduced emissions than pure diesel fuel. ZOME20 produced the most optimal performance results because it reduced CO by 5.7% and HC by 8.1% and smoke opacity by 4.9% while matching diesel engine efficiency. The higher oxygen levels in biodiesel caused a modest escalation of NOx and CO_2 emissions. ZOME20 shows potential as an excellent biofuel replacement because it enables sustainable operation and environmental improvements. Future research should concentrate on improving biodiesel production methods as well as making engine modifications to achieve better performance together with minimized NOx emissions. Widespread commercial implementation of ZOME biodiesel requires both long-term durability analysis and economic research of its feasibility. The collected observations make essential contributions to creating cleaner fuel alternatives with sustainable features.

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