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Editorial

Evaluating the influence of diethyl ether on performance and emission outputs in KIRLOSKAR TV-I engines fueled with pumpkin seed oil biodiesel

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Abstract: This investigation examines the performance and emission characteristics of the KIRLOSKAR TV-I engine utilizing pumpkin seed oil (Cucurbita pepo L) methyl ester blended with 5% diethyl ether (DEE). Various blends containing 10%, 20%, 30%, 40%, and 50% pumpkin seed oil biodiesel were analysed for their chemical and physical properties, including viscosity, density, flash point, cetane number, and oxidation stability, in compliance with ASTM standards. Gas Chromatography-Mass Spectrometry (GC-MS) was employed to determine the fatty acid composition of the biodiesel. Experimental results revealed that the 20% biodiesel blend exhibited superior performance, combustion, and emission characteristics, making it a viable substitute for conventional diesel with minimal engine modifications. Emission analysis of the 20% blend showed a 0.65% reduction in carbon monoxide (CO), a 10.3% decrease in carbon dioxide (CO2), and a 21.1% reduction in nitrogen oxide (NOx) compared to diesel. Notably, blends without additives also demonstrated significant reductions in NOx (25.83%), CO (14.3%), and CO2 (13.8%) emissions, highlighting the environmental benefits of these biodiesel formulations.

1. Introduction

The global community faces significant challenges stemming from an increasing reliance on fossil fuels, escalating crude oil prices, and the detrimental environmental effects of these energy sources, particularly

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their contribution to atmospheric pollution [1]. The adoption of alternative energy sources, such as biodiesel fuel, plays a crucial role in reducing CO2 emissions [2, 3]. Biodiesel has garnered widespread recognition as a sustainable alternative to diesel, owing to its compatibility with existing diesel engines without the need for modifications [4]. As an oxygenated fuel, biodiesel enhances combustion efficiency and reduces engine emissions.

However, several studies have shown that biodiesel's dense structure, lower carbohydrate content, and higher viscosity, when used as a replacement for diesel in internal combustion (IC) engines, may result in decreased engine durability and thermal efficiency [5, 6]. To address these issues, blending biodiesel with diesel in varying ratios has become a common practice. This approach aligns the properties of the blended fuel more closely with those of standard diesel fuel. Additionally, the application of specific fuel additives has shown promise in improving the quality and usability of biodiesel, making it a more viable substitute for conventional diesel.

Qi et al. [7] investigated the effects of enhancing biodiesel blends with ethanol and diethyl ether (DEE). Their findings demonstrated that adding 5% DEE reduced emissions of carbon monoxide (CO) and brake-specific fuel consumption (BSFC) while increasing hydrocarbon (HC) and nitrogen oxide (NOx) emissions. These changes were attributed to the superior volatility of DEE, which improved air-fuel homogeneity and combustion efficiency. Sivalakshmi and Balusamy [8] similarly noted that integrating 5% DEE into neem-based biodiesel enhanced brake thermal efficiency (BTE) and BSFC while reducing CO and smoke emissions. This improvement was attributed to better spray atomization and a more uniform air-fuel mixture, which diminished the rich zones within the cylinder and lowered CO emissions. Tudu et al. [9] examined the role of DEE in proportions of up to 4% within a 60% diesel blend. They observed a 25% reduction in NOx emissions and a 6% reduction in BSFC during peak load operation compared to diesel alone. Barik et al. [10] evaluated a dual-fuel engine injecting 2%, 4%, and 6% DEE while operating on a biogas and Karanja biodiesel blend. At maximum load, their results showed a 2.3% increase in BTE and a 5.8% drop in BSFC, although NOx emissions increased by approximately 12.7% compared to conventional BDFM24.5. Similarly, Murat et al. [11] found that adding 10% DEE to cottonseed biodiesel and diesel blends reduced HC, CO2, and NOx emissions but increased BSFC and reduced BTE.

Further research by Devaraj et al. [12] explored the effects of blending recyclable plastic pyrolysis oil with 5% and 10% DEE in a single-cylinder diesel engine. Venu et al. [13] investigated the impact of DEE injection on biodiesel blends containing ethanol and methanol, finding that adding up to 10% DEE reduced NOx and CO emissions while improving BTE from 28% to 29%. Patil et al. [14] examined the effects of blending DEE, diesel, and kerosene across various volumes (2%–25%). Their results showed that DEE-diesel blends increased fuel consumption and reduced both BTE and NOx emissions. Rakopoulos et al. [15] analyzed several diesel blends supplemented with 8%, 16%, and 24% DEE, noting reduced CO, NOx, and smoke emissions but increased hydrocarbon emissions and fuel consumption. Similarly, Lee et al. [16] found that DEE addition to diesel (10%, 25%, and 50% ratios) lowered CO and hydrocarbon emissions while increasing NOx emissions due to its higher cetane number and lower boiling point, which enhanced combustion efficiency.

Despite extensive research on biodiesel and additives, studies on the application of pumpkin seed oil (Cucurbita pepo L) biodiesel in KIRLOSKAR TV-I engines remain limited. This study aims to evaluate the performance and emission characteristics of KIRLOSKAR TV-I engines using biodiesel derived from pumpkin seed oil methyl ester blended with 5% DEE. The investigation focuses on assessing the impact of varying operating loads on engine performance and emissions, highlighting the potential of pumpkin seed oil as a viable biodiesel feedstock.

2. Experimental Methods

2.1. Biodiesel Characterization

Pumpkin oil extraction, though limited in social markets and discontinued in commercial production in Greece, holds potential for biodiesel production. The process of biodiesel synthesis is primarily influenced by two critical quality parameters: free fatty acids (FFAs) and water content [17]. The transesterification process was used to produce biodiesel from pumpkin seed oil. For each blend containing 10%, 20%, 30%, 40%, and 50% biodiesel, the procedure involved mixing 1 liter of raw pumpkin oil with 15 grams of potassium hydroxide (KOH) and 100 ml of methanol. Additionally, a separate set of blends included 5 ml of diethyl ether as an additive. Oil procurement and biodiesel production were conducted on a laboratory scale following standardized protocols for both additive-enhanced and non-additive biodiesel production. Initially, the raw material was refined into grain powder of specified granularity, followed by a drying phase at 100°C for two hours. The biofuel was then extracted continuously using a Soxhlet extractor, with KOH serving as the catalyst. The Soxhlet extractor was maintained at an operating temperature between 65°C and 70°C for 24 hours. In the final phase, the biodiesel was separated from the organic solvent using a rotary vacuum evaporator. This process was performed at a temperature of 60°C under desiccation to ensure complete extraction and refinement of the biodiesel.

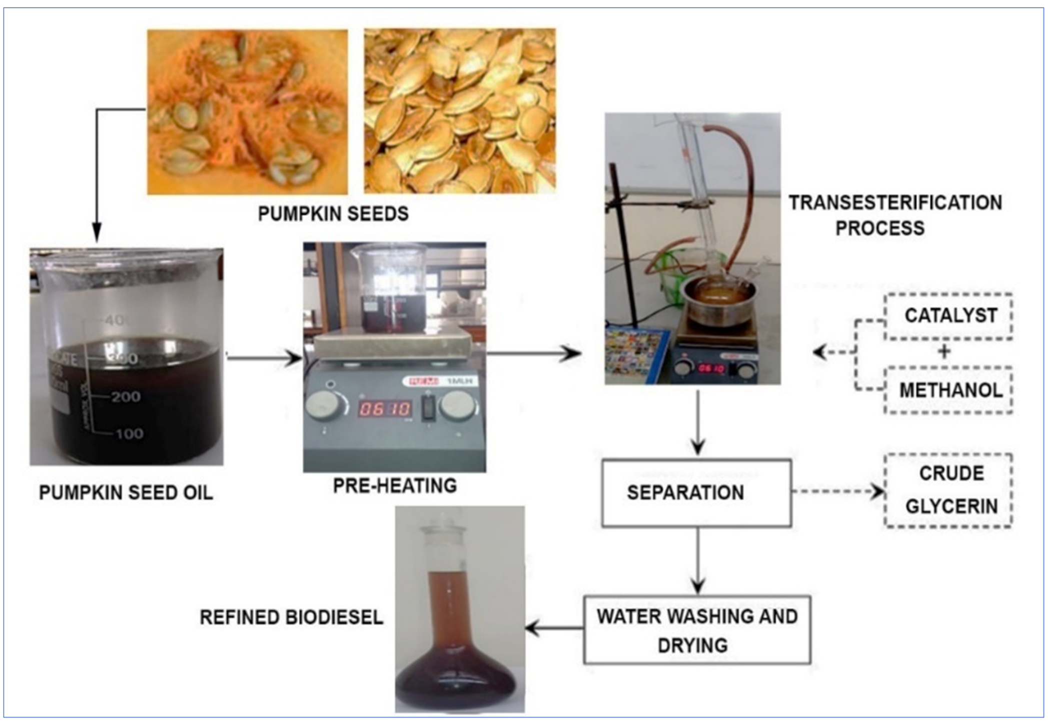


Figure 1. Block diagram for the production of biodiesel (Centinkaya et al., 2004) [18].

2.2. Characterizing Parameters of Pumpkin Seed Oil

Pumpkin seed oil was extracted through a step-by-step process, and its chemical and physical properties were analyzed to evaluate its suitability as a raw material for biofuel production. These parameters were compared against those of diesel, Juliflora biodiesel, and blends, providing a comprehensive assessment for automotive applications. Table 1 summarizes the key physical properties of *Cucurbita pepo* L.

Table 1. Physical parameters of *Cucurbita pepo L.*

Property	**Diesel**	**Juliflora**	**Pumpkin Juliflora**	**B20 Blend with DEE**	**Pumpkin Seed Oil**	**Test Method**
Kinematic Viscosity (40°C) (mm²/s)	2.87	5.120	4.960	3.388	4.410	EN ISO 3104
Density (15°C) (kg/m³)	825	873	778	830	921.6	EN ISO 3675
Flash Point (°C)	065	074	098	072	>230	EN 22719
Sulphated Ash Content (wt%)	0.001	0.002	0.001	0.002	<0.01	EN ISO 6245
Water Content (µg/g)	0.003–0.100%	0.82	0.75	0.665	584	EN ISO 20846
Sulphur Content (µg/g)	1	3	2	1	2	EN ISO 20846
Iodine Number	120	152	132	162	115	EN 14111
KOH (mg/g)	0.7–1.0	0.56	0.8	0.65	0.55	EN 14104
Carbide Residue (wt%)	0.2524	0.3624	0.2869	0.36694	0.1754	EN ISO 10370
Pour Point (°C)	-5 to 10	-2	-10	-4	-12	ASTM D 97
Gross Calorific Value (kJ/kg)	128062	11715.2	131265.4	121365.4	390012	IP12

These findings highlight the favorable properties of pumpkin seed oil, such as its high calorific value, low sulphur content, and satisfactory viscosity, which align with biodiesel standards. The data indicates that*Cucurbita pepo* L oil is a viable candidate for biodiesel production, particularly in blends with additives like diethyl ether to enhance performance.

2.3. Transesterification Process

The first step in the transesterification process involved heating the vegetable oil to 100°C to eliminate any moisture present in the Juliflora pumpkin oil. The heated oil was then placed on a magnetized stirrer and allowed to cool gradually to 65°C. Methanol was added to the oil in the presence of potassium hydroxide (KOH) as the catalyst, maintaining a methanol-to-oil molar ratio of 6:1. This ratio is critical to ensuring the effectiveness of the transesterification reaction [19]. The reaction was carried out for one hour at 65°C, as described in studies by Jagtap et al. (2020) and Tomasevic et al. (2003) [20]. These conditions significantly improved the fuel properties of the biodiesel, achieving high purity levels [21]. During the process, glycerol and methanol, by-products of the reaction, were removed. Methanol was separated using deionized water, while any residual pollutants were neutralized with a small amount of sulfuric acid (H_2SO_4).

The final purification step involved using heat-treated sodium sulfate, rinsed with diethyl ether, to eliminate impurities. Solid traces of diethyl ether were subsequently removed through a filtration process. A rotary vacuum evaporator was employed to remove alcohol from the biodiesel, maintaining a temperature of 90°C during this phase. At the completion of the transesterification process, different combination ratios

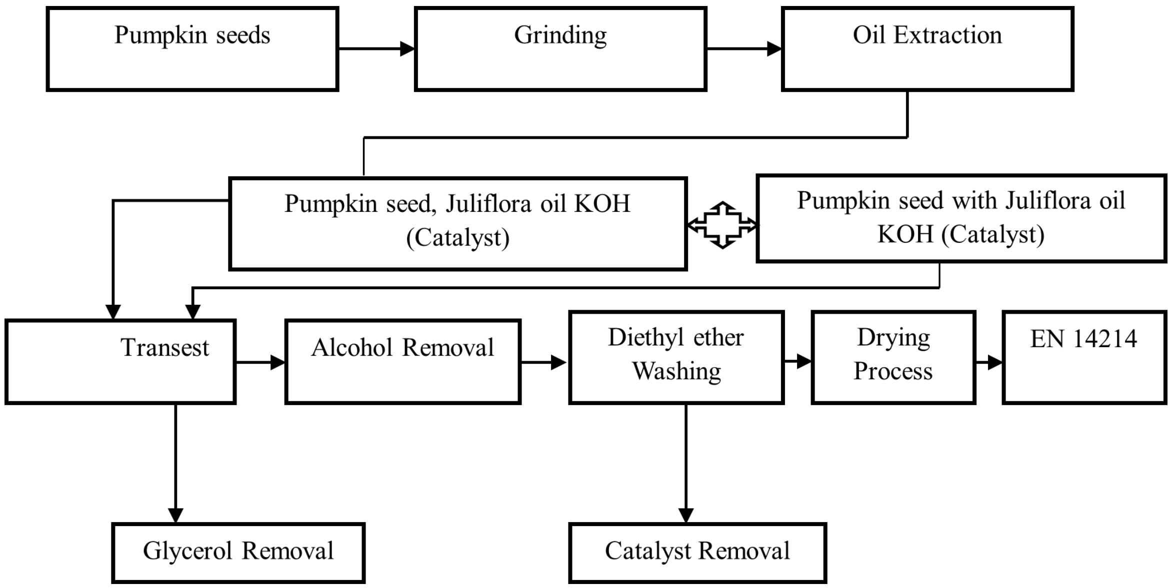


Figure 2. Transesterification process flow diagram.

were converted into glycerol and diethyl ether decanters. The glycerol layer was allowed to separate over a 24-hour period, ensuring complete stratification.

2.4. Fatty Acid Properties

Fatty acids enhanced through the chemical reaction with diethyl ether were analysed, and their compositions are summarized in Table 2. The fatty acid profile of pumpkin seed oil indicates a high content of unsaturated fatty acids, particularly linoleic and oleic acids, which contribute to its suitability as a biodiesel feedstock.

Table 2. Composition of Fatty Acids *(Schinas et al., 2009)* [22].

Fatty Acid	Structure	Formula	Composition (%)
Stearic	C18:0	C18H32O2	5.22
Palmitic	C16:0	C16H32O2	11.51
Oleic	C18:1	C18H32O2	36.07
Linoleic	C18:2	C18H32O2	41.72
Linolenic	C18:3	C18H32O2	0.22
Lignoceric	C24:0	C24H32O2	0.08

The high content of linoleic acid (41.72%) and oleic acid (36.07%) suggests that pumpkin seed oil biodiesel could exhibit favourable combustion and emission characteristics, making it a promising candidate for sustainable energy applications.

3. Experimentation

3.1. Experimental Setup

The performance and emission characteristics of pumpkin seed oil biodiesel were evaluated using a KIRLOSKAR TV-I engine. This engine is widely employed in small-scale industrial applications, such as agricultural operations, farm machinery, and low-capacity power generation units [23]. A schematic layout of the experimental setup is shown in Figure 3, which illustrates the engine configuration. The test setup included a load cell integrated with an electrical dynamometer to apply load to the engine's motor. Engine performance was monitored using a Kistler piezoelectric data acquisition system (model 5395A), comprising an amplifier, encoder, and computer interface. Data were collected using a 23-channel signal analyser, transmitted through Ethernet, and archived for detailed analysis. Fuel consumption was measured using a solenoid controller, while a pressure sensor gauge monitored air input efficiency near the combustion area. A surge tank was employed to stabilize the air intake manifold system, ensuring consistent airflow.

3.2. Engine Specifications

The KIRLOSKAR TV-I engine is a water-cooled, four-stroke, single-cylinder model with a 661-cc displacement and a compression ratio of 17.5:1. The engine can generate a maximum power output of 6 kW at 1800 rpm. Throughout the testing process, the engine operated under varying load conditions—20%, 40%, 60%, 80%, and 100%—while maintaining a constant speed of 1800 rpm. The fuel injector pressure was set at 200 bars, and the ambient temperature was held steady at 60°C. Detailed engine specifications are provided in Table 3.

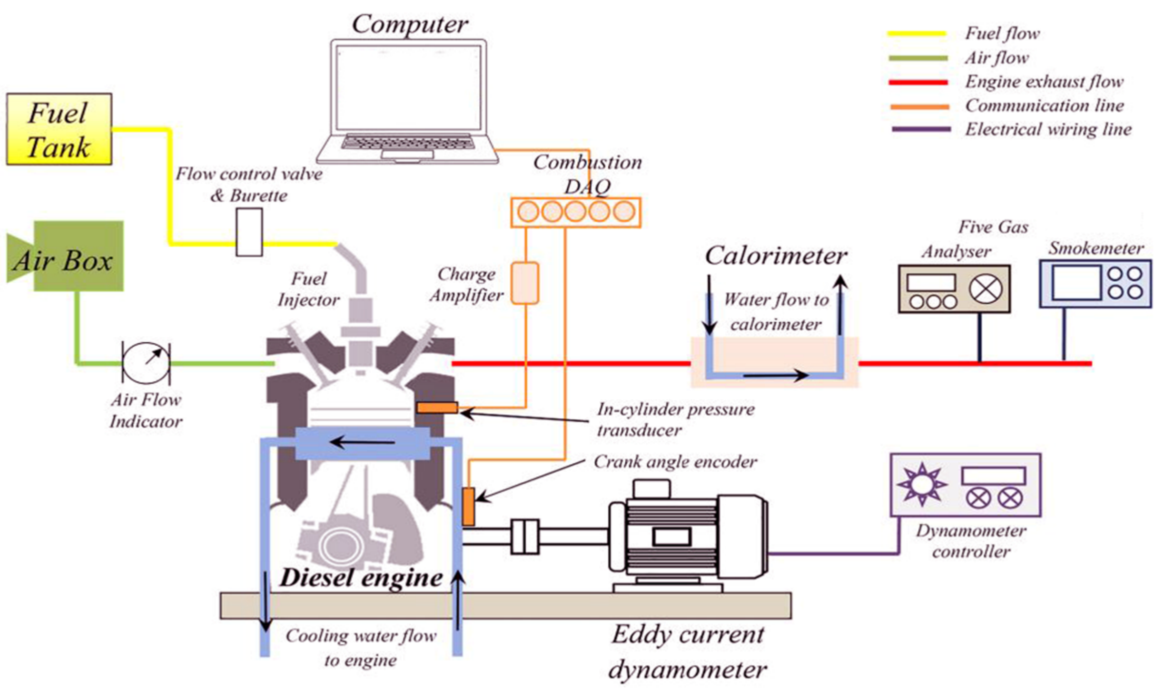


Figure 3. Experimental layout of the KIRLOSKAR TV-I engine.

3.3. Measurement and Control

To ensure accurate measurements of engine speed, a non-contact sensor was attached to the nearest flywheel. Continuous airflow was regulated to cool the sensor and maintain stable operating temperatures. The sensor determined the crank angle using the crankshaft, while data-predictive software monitored combustion-related parameters, including pressure, heat exchange rates, and ignition delays.

Table 3. Engine Configuration

Configuration	Specifications
Type	Kirloskar TV1
Process	Vertical, Direct Injection, Water-cooled
No. of Cylinders/Strokes	1/4
Compression Ratio	17.5:1
RPM	1500
Fuels	H.S Diesel
Ignition Type	Compression Ignition
Speed	1500 RPM
Rated Power	5.2 kW
Nozzle Hole	3
Fuel Injector Opening Diameter	0.3 mm
Injector Timing/Pressure	220° (bTDC)/210 bar
Dynamometer Model	Technomech Pvt. Ltd.
Dynamometer Type	Eddy Current
Cooling	Water-cooled
Pressure Sensor	Piezoelectric Sensor
Data Acquisition System	Kistler (2614C11)
Crank Angle Encoder	USB Multifunctional I/O Device, 16AI; 4DI; 4DO
Load Cell	Sensortronics (Model 606001)
Airflow Measurement	WIKA (Model SL1)

The KIRLOSKAR TV-I engine's robust build allowed it to withstand high pressures, making it ideal for evaluating the combustion and emission properties of biodiesel blends. The experiments provided valuable insights into the performance of biodiesel blends under diverse operating conditions.

3.4. Error Analysis

This method quantifies the potential inaccuracies associated with the instrumentation and procedures used. Table 4 lists the equipment specifications and their corresponding measurement ranges for exhaust emissions.

Table 4. Equipment Specifications for Monitoring Exhaust Emissions

Machinery Name	Model	Characteristics
Exhaust Analyzer	AVL DI-GAS 444 Analyzer	Measures CO (0–10% by volume), HC (0–2000 ppm), and NO_x (0–5000 ppm).
Smoke Meter	AVL 417 Free Accelerometer Smoke Meter	Measures smoke density, range: 0–100 (HSU).

The total uncertainty (UUU) was calculated using the following formula:

$$U = \sqrt{(U_{BP})^2 + (U_{TSF})^2 + (U_{BSFC})^2 + (U_{BTE})^2 + (U_{EGIT})^2 + (U_{CO})^2 + (U_{HC})^2 + (U_{NOx})^2 + (U_{Smoke})^2 + (U_{Pressure})^2} \quad (1)$$

Substituting the individual uncertainties:

$$U = \sqrt{(1)^2 + (0.2)^2 + (1)^2 + (1)^2 + (0.2)^2 + (0.1)^2 + (0.2)^2 + (1)^2 + (0.15)^2 + (1)^2} = \pm 2.25\%$$

Table 5 outlines the practical uncertainties associated with the measurement apparatus, highlighting the possible deviations during the experimental process.

Table 5. Practical Uncertainty of Measurement Instruments

Property	Measurement Apparatus	Correctness	Deviation Error
Fuel	Liquid Volume Gauging	± 0.1 cm^3	± 1
Temperature	Temperature Sensor	± 1°C	± 0.15
Crank Angle	Electromagnetic Velocity Sensor	± 1°	± 0.2
Pressure	Electromagnetic Velocity Sensor	± 0.1 kg	± 0.1
Time	Timer	± 0.1 s	± 0.2
Load	Pressure Transducer	± 10 N	± 0.2
Manometer	Hydrostatic Pressure Measurement	± 1 mm	± 1
CO	NDIR	± 0.02% volume	± 0.2
HC	NDIR	± 10 ppm	± 0.1
NOx	NDIR	± 12 ppm	± 0.2
Smoke	Opacimeter	± 1 HSU	± 1
Speed	Electromagnetic Velocity Sensor	± 10 rpm	± 0.1

Error analysis is crucial in identifying and quantifying uncertainties that may arise during experimentation. Table 5 highlights the sources of potential inaccuracies, which include improper maintenance of measuring equipment, human errors during operation, and environmental factors. The overall experimental error was calculated to be ±2.25%. After completing the biodiesel tests, the engine was switched back to diesel operation. Before the transition, the engine was stopped and the injection system flushed to remove any residual testing fuels, ensuring consistent performance during subsequent experiments.

4. Results and Discussion

The performance and emission characteristics of pumpkin seed oil biodiesel enhanced with *Juliflora* were evaluated in a Kirloskar engine and compared to conventional diesel. To further improve the performance features of the biodiesel, 5 ml of diethyl ether was added to mixtures of pumpkin seed oil and *Juliflora* biodiesel in varying concentrations (10% to 50%). Potassium hydroxide (KOH) was used as a catalyst during the transesterification process. The investigation included a detailed analysis of engine emissions for various fuel types. Key emissions measured were oxygen (O), carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), and nitrogen oxides (NO_x). Additionally, smoke emissions were assessed and quantified using Hartridge Smoke Units (HSU). This comprehensive evaluation provided insights into the impact of biodiesel blends on engine performance and emission reduction compared to regular diesel, highlighting their potential as a cleaner and more sustainable alternative.

4.1. FTIR Spectrum

Fourier Transform Infrared (FTIR) spectroscopy was employed to identify the functional groups present in the biodiesel samples. This analytical method provides detailed insights into the chemical composition and structural characteristics of the synthesized biodiesel. The analysis was conducted over a wavelength range of 4000–600 cm^{-1} with a resolution of 4 cm^{-1}, enabling precise detection of vibrational transitions of chemical bonds. A prominent peak observed at 3452 cm^{-1} corresponds to the O–H stretching vibration. This feature indicates the presence of hydroxyl groups, which may arise from residual water or alcohol intermediates formed during the transesterification process. The use of methanol as a reactant is likely responsible for this peak, emphasizing the need for effective removal of residual methanol during purification. Similarly, the C–H stretch vibration at 3012.54–3011.54 cm^{-1} shows aromatic C–H stretching, indicative of aromatic compounds in the biodiesel. These compounds typically originate from fatty acid methyl esters (FAMEs) derived from unsaturated fatty acids such as oleic and linoleic acids. The peak's intensity reflects a high level of unsaturation, aligning with the fatty acid profile presented in Tables 5 and 6.

As resulting, the stretching vibrations found for aliphatic C–H bonds at 2865–2768 cm^{-1} in this region denote aliphatic (C–H) bonds in the long carbon chains of fatty acids. These peaks are characteristic of saturated fatty acids, such as palmitic and stearic acids, which contribute significantly to the combustion properties of pumpkin seed oil biodiesel. Their prominence indicates a considerable proportion of aliphatic hydrocarbons in the fuel. Furthermore, the carbonyl (C=O) stretch at $\sim$1700 cm^{-1} corresponds to the carbonyl group, a hallmark of ester functional groups formed during the transesterification process. The presence of this peak confirms the successful conversion of triglycerides into biodiesel. The high intensity of the carbonyl peak suggests efficient conversion with minimal unreacted triglycerides. Similarly, the nitrogen–oxygen (N–O) vibrations at 1500–1600 cm^{-1} within this range indicate the presence of nitrogen–oxygen compounds, potentially arising from impurities or residual catalysts like potassium hydroxide (KOH) used in transesterification. These residues, if not fully neutralized, could affect biodiesel purity and necessitate improved purification techniques. The bending vibrations detected around 700 cm^{-1} are associated with terminal methyl groups and alkene (C=C) groups in unsaturated fatty acids. These functional groups contribute to the overall unsaturation levels in biodiesel, primarily due to linoleic acid.

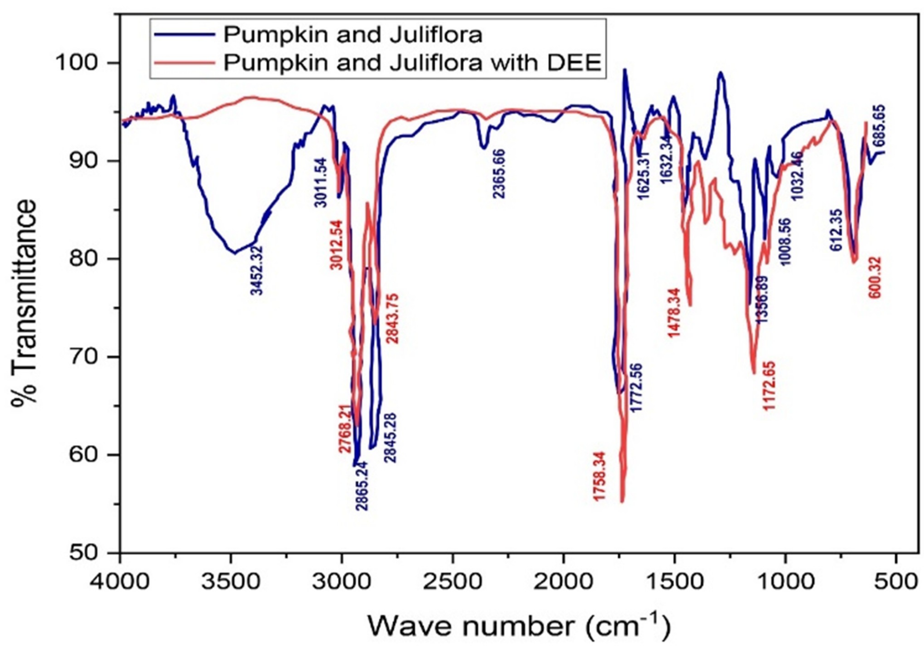


Figure 4. FTIR analysis of *Pumpkin Juliflora Biodiesel.*

The presence of aromatic and aliphatic C–H stretching peaks suggests a significant concentration of unsaturated fatty acids, including oleic and linoleic acids. These components enhance combustion efficiency but may slightly compromise oxidative stability. The strong carbonyl (C=O) peak at $\sim$1700 cm^{-1} highlights successful transesterification, with triglycerides efficiently converted into methyl esters. The absence of significant residual triglycerides underscores a well-optimized reaction process. The O–H stretch vibration may be attributed to trace water content or intermediate alcohols produced during the reaction. Residual methanol, if not adequately removed, can also contribute to this peak. Enhanced post-reaction purification techniques are recommended to minimize hydroxyl content, ensuring improved biodiesel quality. Nitrogen–oxygen vibrations in the spectrum imply incomplete removal of the KOH catalyst. Introducing advanced neutralization methods, such as thorough washing with sulfuric acid, can mitigate these residues and enhance biodiesel purity. The robust aliphatic and aromatic C–H peaks reflect the structural stability of the biodiesel, essential for enduring thermal and oxidative stresses during combustion. This stability is vital for ensuring reliable fuel performance in practical applications.

4.2. Effect of Proposed Biofuels Analysis by GC-MS Techniques

Gas Chromatography–Mass Spectrometry (GC–MS) analysis was performed to evaluate the molecular composition of pumpkin seed oil and its derivatives with diethyl ether (DEE). The GC–MS technique provided detailed insights into the chemical structure and distribution of fatty acids present in the biodiesel blends, highlighting their suitability for energy applications. The results, as shown in Figure 5, demonstrate the chromatographic profile of the biofuel blend.

The primary fatty acids identified in the pumpkin seed oil are listed in Table 2, with their corresponding molecular structures, formulas, and concentrations. The GC–MS analysis revealed a substantial proportion of unsaturated fatty acids, with linoleic acid (41.72%) and oleic acid (36.07%) being the most prominent. These unsaturated compounds enhance combustion properties by improving fuel atomization and reducing particulate emissions. The low presence of linolenic acid (0.22%) is particularly advantageous, as it minimizes oxidative instability, thus extending the biodiesel's shelf life. Palmitic acid, a saturated fatty acid, contributes to the thermal stability and improved cetane number of the biodiesel. However, excessive saturation could increase viscosity, emphasizing the need for blending to achieve optimal fluidity and performance. As a polyunsaturated fatty acid, linoleic acid plays a crucial role in enhancing the oxygen content in biodiesel, facilitating more complete combustion. This results in reduced CO and HC emissions, making its high concentration a pivotal factor in the biodiesel's superior performance.

The analysis indicates that a 25% blend of pumpkin seed oil biodiesel with diethyl ether (DEE) and 75% diesel meets ASTM standards. The balanced ratio of saturated and unsaturated fatty acids in this blend ensures a combination of high thermal efficiency, improved combustion quality, and reduced emissions. The high volatility and oxygenated nature of DEE improve the uniformity of the fuel–air mixture, leading to more efficient combustion. This is reflected in the reduced emissions observed during performance evaluations. DEE acts as a combustion promoter by reducing the prevalence of heavier hydrocarbon chains, as shown in the GC–MS results. This enhances ignition quality and minimizes combustion delay, further supporting efficient energy release. The inclusion of DEE facilitates the breakdown of longer hydrocarbon chains during combustion. This is evidenced by the reduced smoke and particulate emissions observed in the experimental tests, highlighting its role in improving environmental sustainability. The GC–MS analysis validates the potential of pumpkin seed oil biodiesel as a renewable energy source, particularly when enhanced with diethyl ether. The high concentrations of linoleic and oleic acids ensure efficient combustion, while DEE improves fuel atomization and reduces emissions. The 25% blend emerges as an optimal composition, adhering to ASTM standards and demonstrating its suitability for biodiesel applications under controlled conditions.

4.3. Performance Analysis of KIRLOSKAR TV-I Engine

The performance analysis of biodiesel blends derived from pumpkin seed oil was carried out using the KIRLOSKAR TV-I engine, emphasizing the critical influence of free fatty acid (FFA) and water content on biodiesel quality. Studies by Karthickeyan et al. (2019) [24] and Haas et al. (2005) highlight that optimal biodiesel production requires FFA content below 1.0 mg g^{-1} and water content under 0.3%, thresholds that were successfully met in this study. The pumpkin seed oil biodiesel enhanced with diethyl ether (DEE)

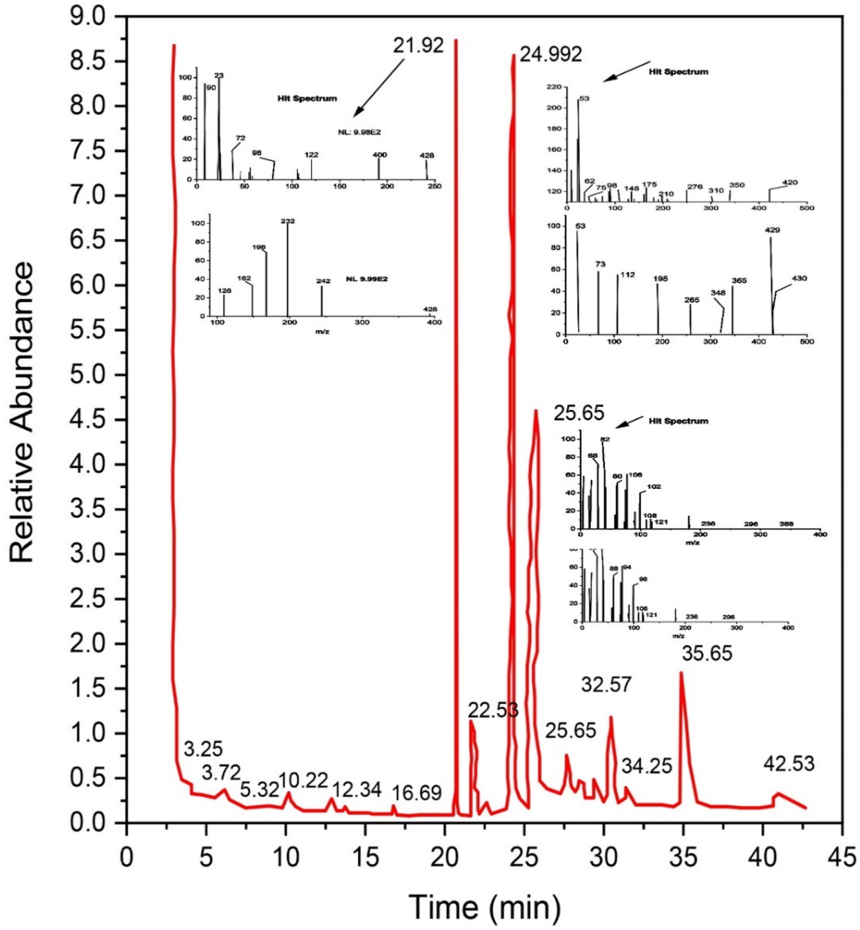


Figure 5. GC-MS chromatogram of pumpkin seed oil with diethyl ether.

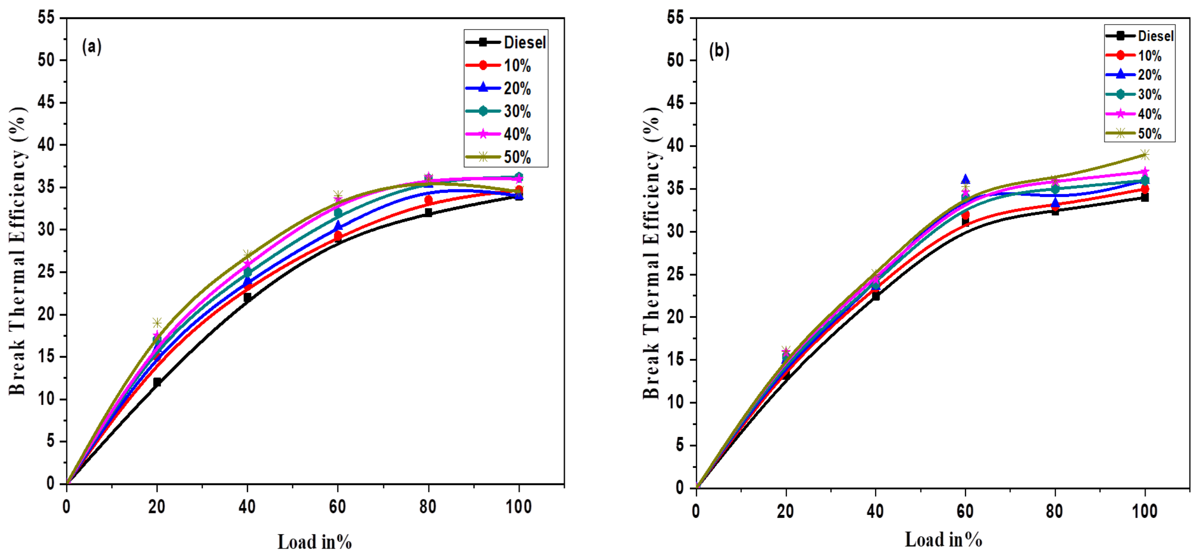
exhibited an acid value of 0.26% and water content of 500 μg g^{-1}, ensuring effective transesterification and superior combustion performance. The use of potassium hydroxide (KOH) as a catalyst, combined with a methanol-to-oil molar ratio of 6:1, ensured high conversion efficiency and minimized post-reaction impurities. The chemical stability of the biodiesel blends was further improved through the balanced composition of saturated and unsaturated fatty acid chains, supporting favorable combustion properties and adherence to EN 14214 standards.

The biodiesel blends, particularly the 20% pumpkin seed oil biodiesel with DEE, demonstrated superior performance by achieving higher brake thermal efficiency (BTE) and reduced specific fuel consumption (SFC) compared to conventional diesel. DEE's role as an oxygenated additive significantly enhanced atomization and combustion efficiency, resulting in lower emissions of carbon monoxide (CO) and hydrocarbons (HC). However, blends exceeding 30% displayed reduced efficiency due to increased viscosity and decreased volatility, underscoring the importance of blend ratio optimization. Despite challenges related to oxidative stability, the 20% blend with DEE emerged as the most balanced formulation, offering a combination of high efficiency, low emissions, and commercial viability, making it a suitable alternative to conventional fuels for industrial and environmental applications.

4.4. Effect of Emission Characteristics

The emission characteristics of biodiesel blends derived from pumpkin seed oil, with and without the addition of diethyl ether (DEE), were thoroughly analyzed using the KIRLOSKAR TV-I engine under varying loads (20%, 40%, 60%, 80%, and 100%). The results demonstrated a significant enhancement in the engine's Brake Thermal Efficiency (BTE) and a reduction in Specific Fuel Consumption (SFC) due to the inclusion of DEE, along with notable improvements in emission profiles. The maximum observed BTE values for diesel, diesel with *Juliflora* oil, and pumpkin seed oil with *Juliflora* and DEE were 34%, 36.45%, and 39%, respectively, at a maximum load of 100%, as shown in Figure 6(a–b). The improvement in BTE can be attributed to the oxygen-rich properties of both biodiesel and DEE, which enhance combustion efficiency by ensuring better oxidation of unburnt fuel residues. DEE's high cetane number also plays a crucial role in reducing ignition delay, thereby facilitating smoother and more complete combustion.

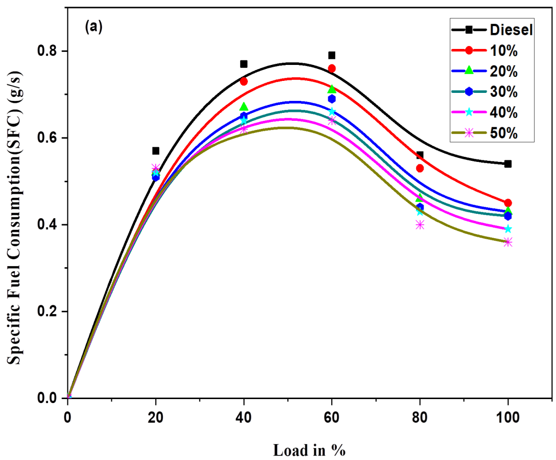
Furthermore, the higher combustion chamber temperature induced by DEE promotes better thermal energy utilization, reducing heat loss and enhancing energy transfer, as noted in studies like Rizwanul et al. (2013) [25]. The use of potassium hydroxide (KOH) as a catalyst during transesterification further ensures the production of biodiesel with minimal impurities, contributing to its thermal stability and combustion efficiency. However, at blend levels exceeding 30%, increased viscosity and density counteract these benefits, leading to reduced atomization and less homogeneous combustion.



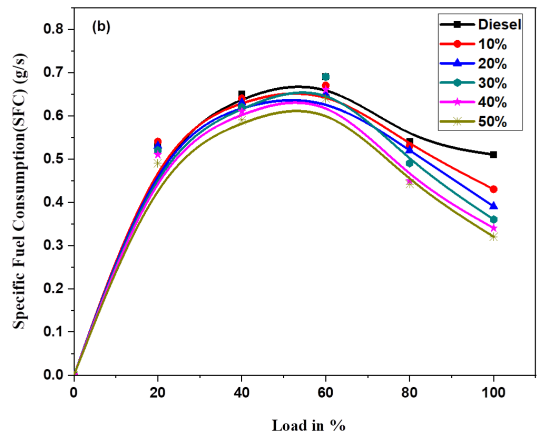
(a) **(b)**

Figure 6. Shows the Break thermal efficiency (a) Pumpkin with Juliflora (b) Pumpkin with Juliflora with DEE.

The Specific Fuel Consumption (SFC) showed a marked decrease with increasing load, as illustrated in Figure 7(a-b). At maximum load (100%), the SFC values for biodiesel blends with DEE were recorded as 0.43 g/s, 0.39 g/s, 0.36 g/s, 0.34 g/s, and 0.32 g/s for blends of 10%, 20%, 30%, 40%, and 50%, respectively. This reduction in SFC is primarily attributed to DEE's high volatility and oxygenating properties, which enhance fuel-air mixture uniformity and reduce the ignition delay, consistent with findings by Rizwanul Fattah et al. (2013) [25]. Additionally, higher combustion chamber temperatures under increased loads improve fuel atomization and evaporation, further reducing SFC. Blends with DEE also exhibit lower kinematic viscosity compared to non-additive biodiesel blends, leading to smoother injector performance and better atomization, while the slightly higher calorific value of the biodiesel-DEE blend ensures efficient energy extraction. However, blends above 40% exhibit slightly increased SFC due to the counteracting effects of higher viscosity and density, emphasizing the need for optimal blend ratios.



(a)



(b)

Figure 7. Shows the Specific Fuel Consumption (SFC) (a) Pumpkin with Juliflora (b) Pumpkin with Juliflora with DEE.

Among all tested blends, the 20% blend with DEE demonstrated the best performance, achieving a balance between reduced SFC and improved BTE, making it the most efficient and economically viable formulation. The inclusion of DEE not only enhances combustion but also significantly reduces emissions, making biodiesel-DEE blends a promising and sustainable alternative to conventional diesel fuels.

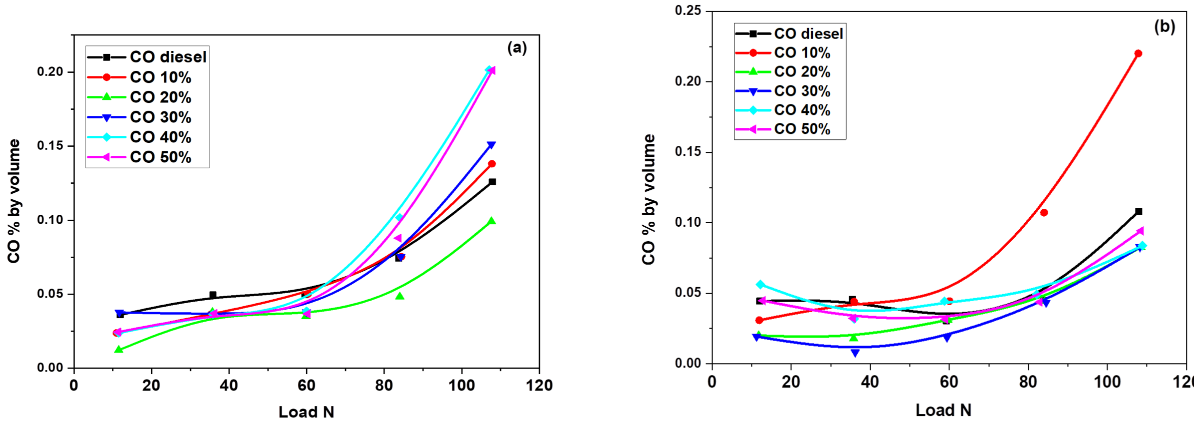
4.5. Combustion Characteristics

The combustion characteristics of the tested biodiesel blends, including pumpkin seed oil with *Juliflora* and diethyl ether (DEE) additives, were examined in detail using the KIRLOSKAR TV-I engine under varying loads (20%, 40%, 60%, 80%, and 100%). This section explores the emissions of carbon monoxide (CO), carbon dioxide (CO_2), hydrocarbons (HC), nitrogen oxides (NO_x), oxygen (O_2), and smoke density. These characteristics are discussed to elucidate the effectiveness of DEE in enhancing combustion and reducing emissions while maintaining high engine performance.

4.5.1. Carbon Monoxide (CO) Emissions

Figure 8(a–b) highlights the CO emissions for diesel, pumpkin seed oil with *Juliflora*, and DEE-based blends under different engine loads. CO emissions are a result of incomplete combustion, which occurs due to insufficient oxygen, improper fue

The reduced CO emissions in DEE-enhanced blends can be attributed to the additive's ability to improve combustion homogeneity through enhanced fuel atomization and air-fuel mixing. DEE, with its high cetane number, reduces ignition delay, allowing for more complete combustion. Furthermore, the oxygen-enriched nature of DEE ensures better oxidation of carbon atoms, converting CO into CO2 efficiently. Schinas et al. (2009) confirmed that pumpkin seed oil meets EN 14214 standards, ensuring its compatibility for combustion applications and contributing to reduced emissions when blended with DEE. The slight increase in CO at higher loads is attributed to the enriched fuel supply, which momentarily surpasses the available oxygen for complete combustion.

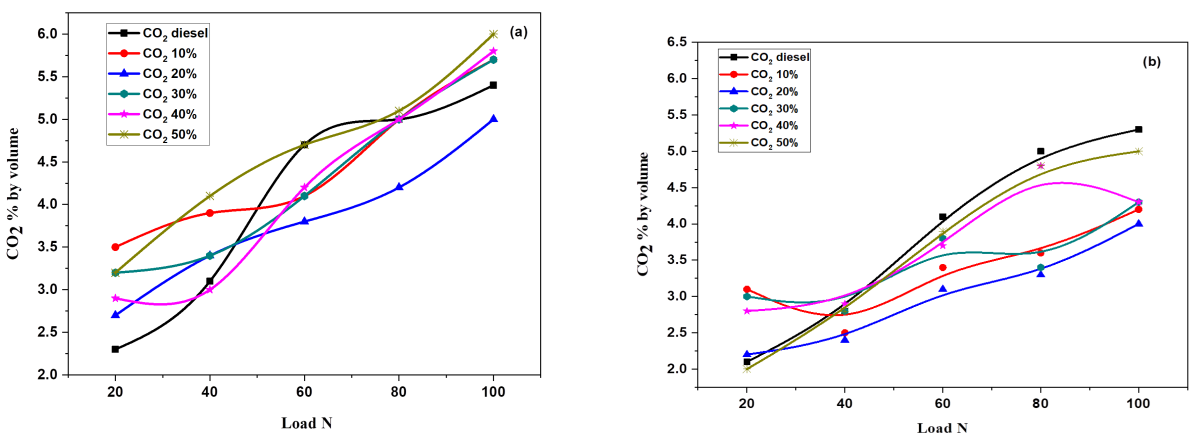


(a) **(b)**

Figure 8. CO emissions (a) Pumpkin with Juliflora (b) Pumpkin with Juliflora with DEE.

4.5.2. Carbon Dioxide (CO_2) Emissions

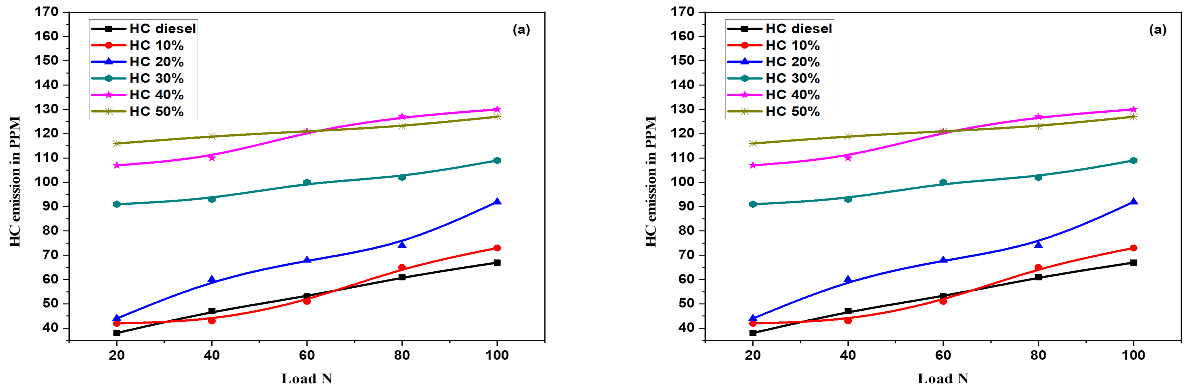
Figure 9(a–b) illustrates the CO_2 emissions under varying loads. CO_2 emissions arise from complete combustion, where carbon in the fuel fully oxidizes to CO_2 in the presence of sufficient oxygen. For the DEE-blended biofuels, the CO_2 emissions were observed at 5.4%, 5%, 5.7%, 5.8%, and 6% for increasing loads. In comparison, the biofuel blends without DEE produced CO_2 emissions of 5.3%, 4.2%, 4%, 4.3%, and 5%.



(a) **(b)**

Figure 9. CO_2 emissions (a) Pumpkin with Juliflora (b) Pumpkin with Juliflora with DEE.

The slightly higher CO_2 emissions in DEE blends reflect their improved combustion efficiency. DEE's oxygen content promotes complete combustion, converting carbon to CO_2 rather than intermediate compounds like CO. However, CO_2 emissions remain lower than diesel, which aligns with the lower carbon content and calorific value of the biodiesel blends. The reduced calorific value necessitates burning more fuel to achieve the same energy output, leading to higher CO_2 emissions at higher loads. The decrease in CO_2 emissions for non-additive blends is indicative of incomplete combustion, further validating the effectiveness of DEE in ensuring complete fuel oxidation [26].



(a) **(b)**

Figure 10. CO_2 emissions (a) Pumpkin with Juliflora (b) Pumpkin with Juliflora with DEE.

4.5.3. Hydrocarbon (HC) Emissions

Figure 10(a-b) depicts the HC emissions for various fuel blends. Hydrocarbon emissions occur when unburned fuel escapes the combustion chamber due to inadequate temperatures, poor air-fuel mixing, or insufficient oxygen near the combustion chamber walls. HC emissions for the DEE-enhanced blend were recorded as 44 ppm, 60 ppm, 68 ppm, 74 ppm, and 92 ppm for increasing loads, while biodiesel without DEE showed slightly higher emissions of 43 ppm, 52 ppm, 66 ppm, 78 ppm, and 87 ppm. The reduction in HC emissions in DEE blends is primarily due to the improved combustion chamber temperatures and oxygen availability facilitated by DEE. DEE's low boiling point enhances evaporation, promoting a uniform air-fuel mixture and reducing the presence of rich zones near the cylinder walls. Senthil Kumar et al. (2013) [27] highlighted that higher cylinder wall temperatures near the exhaust manifold reduce HC emissions, a phenomenon observed in the current study. The increased emissions at higher loads result from greater fuel quantities being introduced, leading to marginally incomplete combustion at peak operating conditions.

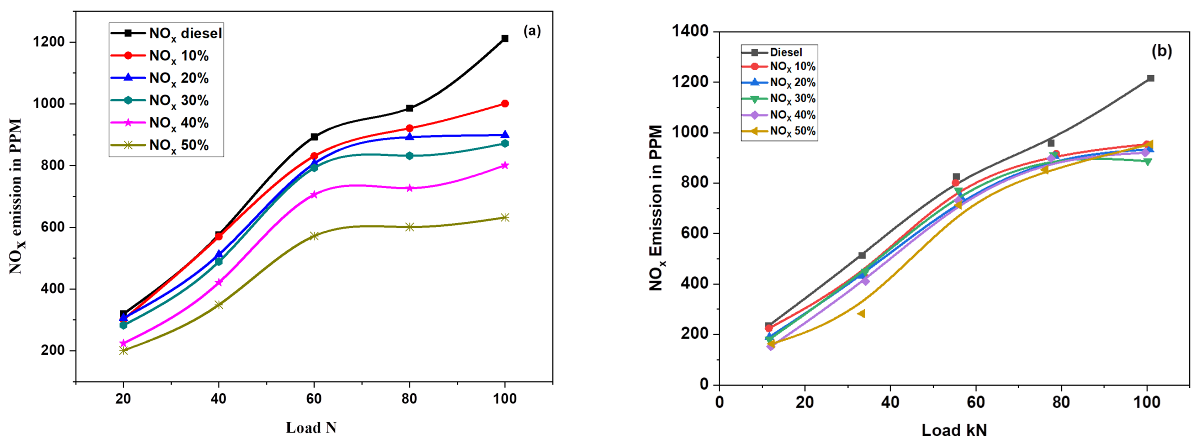
4.5.4. Nitrogen Oxides (NOx) Emissions

Nitrogen oxide emissions, depicted in Figure 11(a-b), are a byproduct of high-temperature combustion, where nitrogen in the air reacts with oxygen. NOx emissions for DEE-enhanced biodiesels were measured as 632 ppm, 801 ppm, 872 ppm, 899 ppm, and 1001 ppm, significantly lower than non-additive blends, which ranged from 942 ppm to 1237 ppm [19].

The lower NOx emissions in DEE blends are due to the optimized combustion temperatures achieved with the high cetane number of DEE. The enhanced ignition quality shortens the ignition delay and air-fuel mixing time, reducing peak combustion temperatures. Additionally, DEE's oxygenating properties ensure a controlled burn, limiting localized high-temperature zones where NOx formation peaks. Yilmaz et al. (2017) [28] observed a similar trend in their study, demonstrating that additives like di-tertiary-butyl peroxide (DTBP) effectively reduce NOx emissions in biodiesel blends.

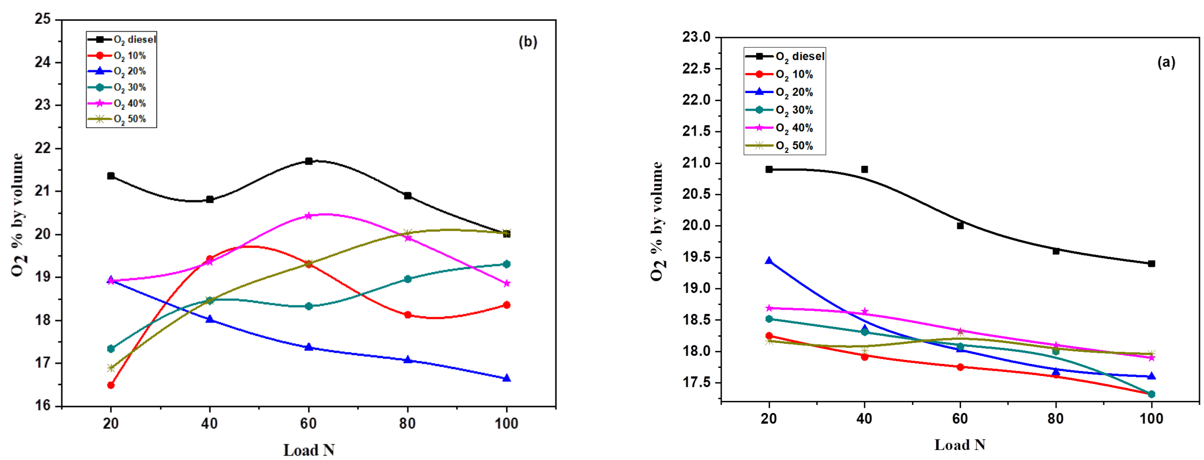
4.5.5. Oxygen (O_2) Emissions

Figure 12(a-b) presents oxygen emissions under varying load conditions. Oxygen emissions were slightly lower for DEE blends, recorded as 17.32%, 17.6%, 17.6%, 17.32%, 17.9%, and 17.96%, compared to non-additive blends, which exhibited emissions ranging from 16.64% to 20.03%. The lower oxygen emissions for DEE blends indicate better utilization of oxygen in the combustion process, corroborating the enhanced combustion efficiency observed with DEE additives.



(a) **(b)**

Figure 11. NO_x (a) Pumpkin with Juliflora (b) Pumpkin with Juliflora with DEE



(a) **(b)**

Figure 12. (a) Pumpkin with Juliflora (b) Pumpkin with Juliflora with DEE.

5. Smoke Density

Smoke emissions, shown in Figure 13, were significantly lower for DEE-enhanced blends, measured at 60.8 HSU, 74.2 HSU, 78 HSU, 80 HSU, and 88 HSU, compared to non-additive blends, which ranged from 85.3 HSU to 95.3 HSU. Smoke density reductions are attributed to the improved atomization and combustion facilitated by DEE. Karthickeyan et al. (2017) [29] highlighted that biodiesel blends with enhanced oxygen content reduce smoke emissions by minimizing the formation of soot precursors. The higher temperatures in the combustion chamber due to DEE also aid in the oxidation of soot particles, leading to lower smoke levels.

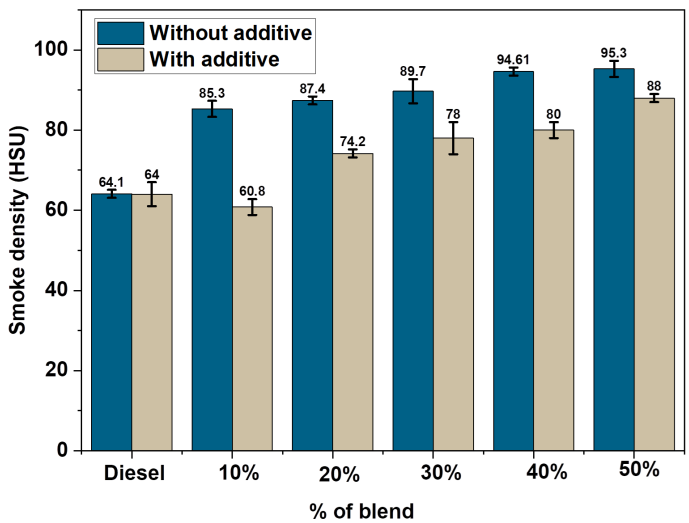


Figure 13. Smoke Density for prepared biofuel from pumpkin seed oil.

The incorporation of DEE into pumpkin seed oil biodiesel significantly improves combustion characteristics by reducing CO, HC, NOx, and smoke emissions while maintaining high thermal efficiency and minimizing oxygen and CO2 emissions. The 20% biodiesel-DEE blend emerged as the optimal formulation, offering an excellent balance between performance and environmental benefits. These results underscore the potential of DEE-enhanced biodiesels as a sustainable and efficient alternative to conventional diesel fuels [30].

6. Conclusions

The primary objective of this research was to evaluate the feasibility of utilizing pumpkin seed oil as a viable feedstock for biodiesel production. A thorough examination and comparative analysis of the physicochemical properties of pumpkin seed oil, Juliflora, and their blends with diethyl ether (DEE) against conventional diesel revealed that these formulations align with standard biodiesel criteria. The operational efficiency and emissions profiles of both the pure pumpkin seed oil and its blends with DEE were meticulously assessed, highlighting their potential as sustainable alternatives to diesel.

1. **Efficiency of DEE in Refinement:** The refining process utilizing DEE proved effective in reducing free glycerol content when distilled water was employed, ensuring enhanced fuel quality and stability.
2. **Specific Fuel Consumption (SFC) Performance:** In the KIRLOSKAR TV-I engine, pumpkin seed oil blends with Juliflora and DEE demonstrated a notable reduction in SFC compared to diesel and

non-additive blends. This improvement was attributed to the higher calorific value and enhanced combustion facilitated by DEE additives.

3. **Break Thermal Efficiency (BTE):** Blends containing DEE, particularly those derived from pumpkin Juliflora oil, exhibited superior BTE due to better oxidation and combustion processes, driven by DEE's oxygen-rich properties and high cetane number.
4. **Emissions Reductions:** The 20% pumpkin seed oil blend with DEE showed significant reductions in CO_2 emissions (14.2%) and CO emissions (15.4%) at higher loads. These improvements were a direct result of enhanced combustion efficiency and reduced incomplete oxidation.
5. **Improved Combustion Efficiency:** The addition of DEE resulted in increased BTE and decreased SFC compared to standard diesel, indicating better utilization of the fuel's energy content.
6. **Hydrocarbon (HC) Emissions:** The 10% and 20% biodiesel blends with DEE demonstrated HC emissions comparable to diesel, with the 20% blend achieving reductions in CO and O_2 emissions due to superior combustion characteristics.
7. **Nitrogen Oxides (NOx) Emissions:** While higher NOx emissions were observed in most biodiesel blends due to elevated chamber temperatures and oxygen content, the 20% DEE blend exhibited a balanced performance, maintaining lower emissions compared to other additive-free blends.

Based on these findings, the 20% pumpkin seed oil biodiesel blend with DEE emerged as the most promising formulation. It offered an optimal balance of enhanced performance, reduced SFC, and significantly improved emissions characteristics compared to conventional diesel. This study underscores the potential of pumpkin seed oil, combined with DEE, as a sustainable and efficient biodiesel source, paving the way for further advancements in alternative fuel technologies.

Scope for Further Research

Future studies could focus on exploring the efficacy of various catalysts in the biodiesel production process and the influence of DEE incorporation on emissions and combustion characteristics in diverse biodiesel fuels. This would provide deeper insights into optimizing the biodiesel production process and improving its performance characteristics.

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Author contributions:

1. T. G. Sakthivel: Conceptualization of the study, overall supervision, and manuscript review.
2. S. Senthilkumar: Methodology development, data collection, and analysis.
3. T. Gopalakrishnan: Literature review and drafting of the manuscript.
4. A. Parthiban: Data visualization and statistical interpretation.
5. R. Manikandan: Project administration, funding acquisition, and final manuscript editing (corresponding author).
6. R. Manimegalai: Validation of results and technical inputs on experimental design.

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