Vol. 08, No. 2 (2026) 781-794, doi: 10.24874/PES08.02.016

Proceedings on Engineering Sciences

www.pesjournal.net

TOWARDS GREEN MOBILITY: INVESTIGATION OF CI ENGINE CHARACTERISTICS POWERED WITH NOVEL BLEND OF ARGEMONE MEXICANA BIODIESEL AND DIESEL

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Received 27.01.2026.
Revised 19.05.2026.
Accepted 01.06.2026.

Keywords:

Biodiesel, Argemone mexicana, Transesterification, DI engine, Performance characteristics, Emission analysis

A B S T R A C T

The continuous rise in global population and the pursuit of higher living standards have led to a steady increase in energy demand across all regions. Traditionally, this demand has been met by petroleum-based fuels; however, the depletion of fossil fuel reserves and growing environmental concerns have encouraged researchers to explore alternative energy sources. Biodiesel, particularly from non-edible feedstocks, has emerged as a promising option. This study examines the potential of Argemone mexicana as a biodiesel feedstock, focusing on its thermal performance and emission characteristics when used in a four-stroke compression-ignition engine. Oil extracted from Argemone mexicana seeds yielded approximately 31% (by weight), and the optimal transesterification conditions were achieved at 60 °C for 1 hour using KOH as the catalyst. The resulting biodiesel blends were evaluated for key engine performance parameters, including brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), exhaust gas temperature (EGT), and emissions of CO2, HC, CO, and NOx. Results showed that the thermal performance of the biodiesel blends was comparable to that of conventional diesel, with significant reductions in CO, HC, CO2, and NOx emissions. Overall, the findings suggest that Argemone mexicana methyl ester is a viable and sustainable alternative to conventional fossil fuels, offering the potential to meet future energy demands while minimizing environmental impact.

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1. INTRODUCTION

Between 1965 and 2023, energy consumption per capita in India, encompassing electricity, transportation, heating, and cooking, increased dramatically from 1,000 kWh to 7,000 kWh, representing a sevenfold rise (Ritchie et al., 2022). Over the same period, primary energy consumption soared from 619 TWh to 9,841 TWh, representing a near fifteenfold surge (Bhattarai et al., 2024; Lau et al., 2024). This rapid rise in energy demand, coupled with the harmful effects of fossil fuel pollution (Tan et al., 2017), has compelled nations to seek alternative energy sources to ensure a healthier and more sustainable future (Prabu et al., 2017). Options such as biomass, wind power, small hydropower (Sharma et al., 2013), and solar energy have gained traction (Mahida, 2024). Notably, the underlying impetus for adopting alternative fuels is their potential to mitigate pollution

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and reduce the impacts of global warming. To address these concerns, researchers are exploring biofuels as a viable alternative to conventional fuels. Biodiesel is generally made with one mole of glycerol and three moles of fatty acid (Gopinath et al., 2015). It has low emission characteristics and is biodegradable, making it an environmentally friendly option (Ayoub & Abdullah, 2012). Biodiesel can be classified into two categories: primary and secondary (Yaşar, 2020). Primary biofuels are derived from burning woody and cellulosic fuels, as well as dry animal waste. According to the EASAC Report 2012, secondary biofuels can be categorized into three generations, with the fourth generation being generated from manufactured biological tools (Dharani et al., 2024). However, all have the same origin and are renewable. Many researchers have begun working on biofuel production to increase its potential use. A detailed study on vegetable oil-based bio-diesel blends was presented by Murugesan et al., where the authors evaluated engine performance, emission profiles, and transesterification processes. The findings suggest that B20 blends yield improved brake thermal efficiency and lower CO and HC emissions (Murugesan et al., 2009). Benemann (1978) surveyed the potential use of biofuel from biomass and its various conversion processes, as well as energy farming applications. The author primarily discusses the types of biomass, including municipal, agricultural, and forestry waste, as well as their potential for biofuel production. The authors also addressed the impact of oil derivatives or raw materials on transportation costs and their potential yield. (Ramalingam & Mahalakshmi, 2020) conducted a comprehensive experimental study on the influence of high-pressure fuel injection and advanced injection timing on the performance, combustion, and emission characteristics of a CRDI-assisted diesel engine fueled with Moringa Oleifera methyl ester (MOME) and its blends. The study underscores the potential of MOME as a viable biodiesel feedstock and highlights the critical role of injection parameters in optimizing engine performance and reducing emissions, except for NO_x, which remains a challenge. Gowen (1989) analyzed the economic viability of biofuels compared to fossil fuels in developing nations, focusing on aspects like production expenses, economies of scale, and financial support mechanisms. The study also examined how fuel price fluctuations affect the appeal of these energy sources across various sectors. Kulkarni (2024) investigated biodiesel from a blend of *pongamia* oil, animal fat (*beef tallow*), and waste cooking oil, then evaluated its performance in a single-cylinder diesel engine. The authors optimized the transesterification processes and performance of biodiesel blends in CI engines, demonstrating improved emissions and comparable efficiency, which guided this study's approach and blend formulation. Raheman & Phadatare (2004) conducted a study to investigate the fuel characteristics of *Karanja* methyl ester and its multiple blends with diesel, focusing on volumetric ratios ranging from 20% to 80%. Their research assessed the performance of a diesel engine powered by these fuels, measuring parameters such as torque, power output, specific fuel consumption, and emissions, including carbon monoxide, smoke density, and nitrogen oxides NO_x. Anjum et al. (2019) investigated the potential for transforming crude *Argemone mexicana* (AM) oil into biofuel by a two-step transesterification method. The author found that the best yield of 94% was achieved using a methanol-to-oil molar ratio of 6:1, with a heating time of 60 minutes and a catalyst concentration of 0.4% by weight. Anwar et al. (2020) examined four biodiesel types (*beauty leaf, papaya seed, stone fruit, and tomato* seed) and diesel fuel at varying engine loads and speeds. The study proposed that blends of papaya seed biodiesel can provide ideal engine testing conditions for emissions, including NO_x, CO_2, HC, PM, CO, and EGT. The manuscript highlights the increasing need for alternative energy sources in response to declining petroleum reserves and rising global energy demand. A comprehensive literature review revealed that limited research has been conducted on biodiesel production from non-edible feedstocks, particularly *Argemone mexicana*. Despite its potential as a renewable energy source, attributable to its non-edible and waste plant characteristics, studies on *Argemone mexicana* biodiesel remain scarce. Moreover, while previous investigations have primarily focused on reducing NO_x and CO emissions, there is a lack of systematic evaluation concerning CO_2 and HC emissions under varying engine load conditions. The novelty of this research lies in its investigation of *Argemone mexicana*, a non-edible and waste plant, as a potential source for biodiesel production. This study systematically analyzes the performance and emission characteristics of *Argemone mexicana* biodiesel blends (AM5, AM10, AM15, AM20, and AM25) in a four-stroke diesel engine, offering new insights into their feasibility as alternative fuels. In addition to the transesterification process for its yield, the research evaluates key performance parameters, including brake thermal efficiency (BTE), brake-specific fuel consumption (BSFC), and exhaust gas temperature (EGT), alongside emissions of CO_2, HC, CO, and NO_x. The primary objective is to assess the thermal performance and emission behaviour of a single-cylinder compression-ignition engine operating on non-edible *Argemone mexicana* biodiesel blends under varying load conditions. The findings aim to establish the suitability of these blends as sustainable alternatives to conventional diesel fuel.

2. MATERIALS AND METHODS

The sample AM (*Argemone mexicana*) seed was planted in south Bihar, India (25.122265 Latitude and 85.456177 Longitude) from November to March in a 10m x 10m area in the alluvial soil. After minor irrigation, seeds germinated within 15 days, with two leaves approximately 10 mm in size. After two months of weekly irrigation, the plant had grown to approximately one meter in height. The bulk of the AM seeds was purchased from Rajasthan. The crude oil was collected

from a conventional oil expeller near the market, and its yield was found to be 31% by weight, with a yellowish appearance, as shown in Figure 1.

The argemone seed oil contains 30-40% oil, which is primarily composed of linoleic acid (50-60%), oleic acid (15-28%), palmitic acid (10-12%), and stearic acid (3-8%). These results agree with those of Martínez-Delgado et al. (2022). Many researchers have reported higher long-chain carbon FFA contents in argemone oil (Tesfay et al., 2019). The higher the FFA content in the oil, the more significantly it may impact the biodiesel yield, complicate purification and separation, and reduce reaction efficiency (Suresh et al., 2021). These FFA will react with alcohol and a catalyst during transesterification, forming a soap solution and thereby minimizing the biodiesel yield (Elgharbawy et al., 2021). Hence, a two-step method, involving esterification and transesterification, is used to increase its yield. First, esterification was done to remove free fatty acids (Naseef & Tulaimat, 2025). For esterification, 110 mL of *Argemone* crude oil was mixed with 28 mL of ethanol, and 1% (by weight) sulfuric acid (H_2SO_4) was added. The mixture was then heated on a hot plate magnetic stirrer at 60°C for up to one hour. Phase separation occurs after the oil is kept in a separating funnel for 5 hours. The lower layer consisted of a fatty acid, and the upper layer was an ester; the yield quantity measured was 100 mL. For the transesterification, the same amount of esterified oil was taken on a hot magnetic stirrer, and 26 mL of ethanol was added. A 1% (by weight) solution of KOH was then added as a catalyst, and the mixture was continuously stirred for up to 1 hour at 60 °C for biodiesel separation. At the end of the reaction, the mixture was allowed to settle. The lower layer was glycerol, which had been drawn off by separating the funnel, and the upper layer was transesterified *Argemone* ester (TAE). Finally, the TAE was washed 3-4 times to remove impurities and excess water, thereby obtaining pure biodiesel. The flow diagram and extraction process from crude oil to biodiesel are shown in Figures 2, 3, and 4. The properties of *Argemone*-blend biodiesel are shown in Table 1. Each experiment was performed at a fixed temperature of 22°C.

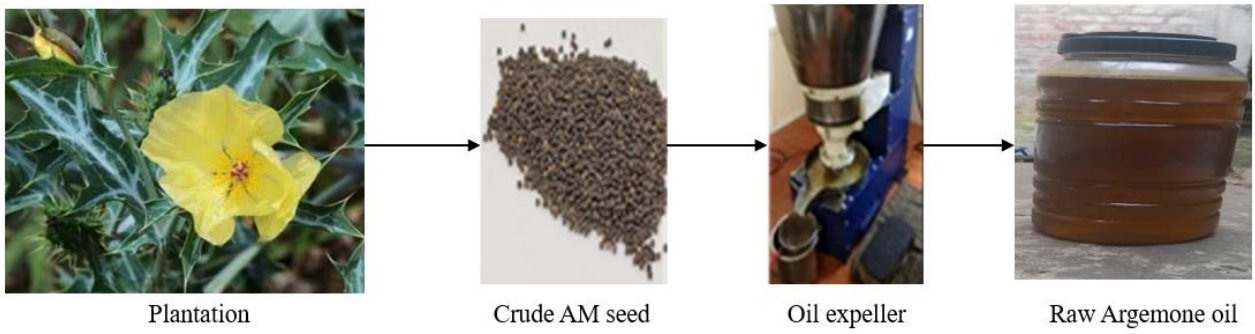


Figure 1. Extraction of crude oil from sample plants

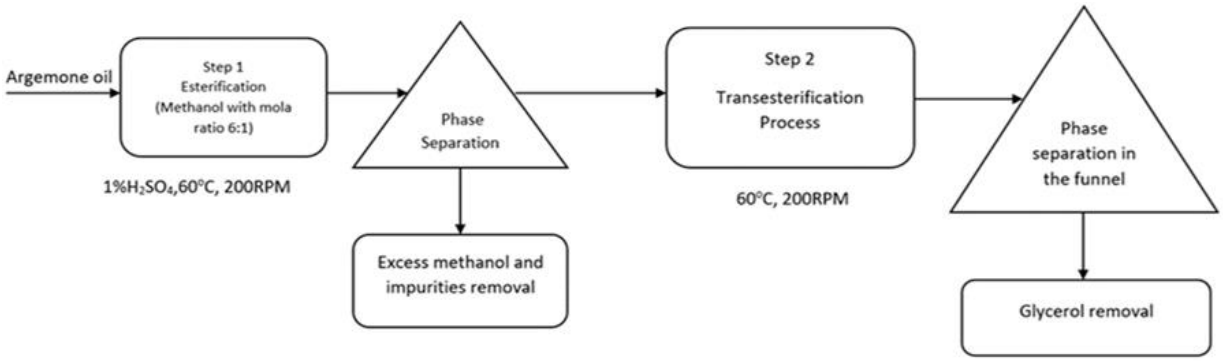


Figure 2. Flow diagram for esterification and transesterification process

Table 1. Properties of *Argemone mexicana* blend-type biodiesel

Property	Diesel	AM5	AM10	AM15	AM20	AM25	Method	ASTM	Units
Density at 22°C	825	828.7	830.4	834.3	838.6	839.2	Pycnometer	D854	Kg/m^3
Kinematic Viscosity at 22°C	2.75	3.43	3.55	3.98	3.93	3.92	Rheometer	D7042	cSt
Calorific value	44.5	43.5	42.5	41.6	41.3	41.6	Bomb calorimeter	D 4809-95	MJ/kg

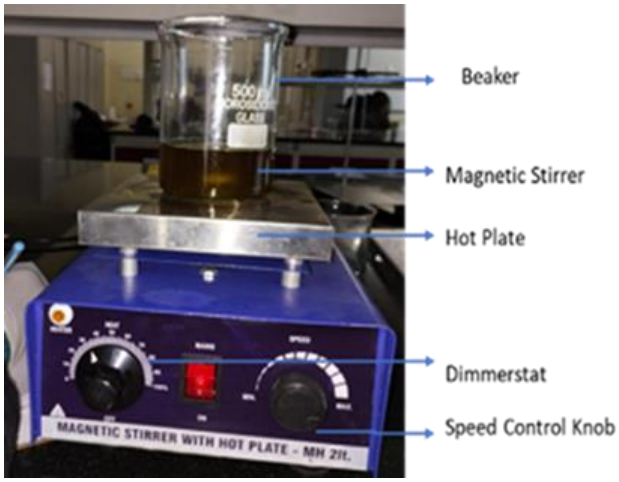


Figure 3. Magnetic stirrer with a hot plate during the esterification and transesterification



Figure 4. Separating funnel for the removal of glycerol

3. EXPERIMENTAL SETUP AND METHODOLOGY

After successfully preparing the biodiesel, the different blending ratios were prepared with the help of a homogeniser. The 5% TAE and 95% pure diesel by volume were mixed and homogenized at 1000 RPM for 1 hour in a mixing chamber named AM5. Similar steps were taken to prepare AM10, AM15, AM20, and AM25. The experimental work was conducted on a single-cylinder, four-stroke, direct-injection, water-cooled compression ignition engine (Kirloskar Oil Engine Ltd; Model: DM-10), and the emission characteristics of the biodiesel blends were characterized using an exhaust gas analyzer (ATS 206A). The specification of the experimental test rig is shown in Table 2.

The detailed experimental setup and schematic diagram are shown in Figure 5 and 6, respectively. Relative engine performance parameters and emission characteristics were collected under varying load conditions, from part to full load.

Table 2. Specification of experimental test rig

Type of engine	**Kirloskar single-cylinder, four-stroke, vertical diesel engine test rig**
Cooling system	Water cooled
Loading Arrangement	Electrical Brake Dynamometer
Electric Supply	Single Phase, 220 volts, 5 amp
Continuous water supply	10 LPM Approx
Floor area	3m x 4m
Ignition	Compression-Ignition
CR	12 to 20
Stroke length	80mm
Bore Diameter	85mm
Torque length	0.138m
Dynamometer type	Eddy current

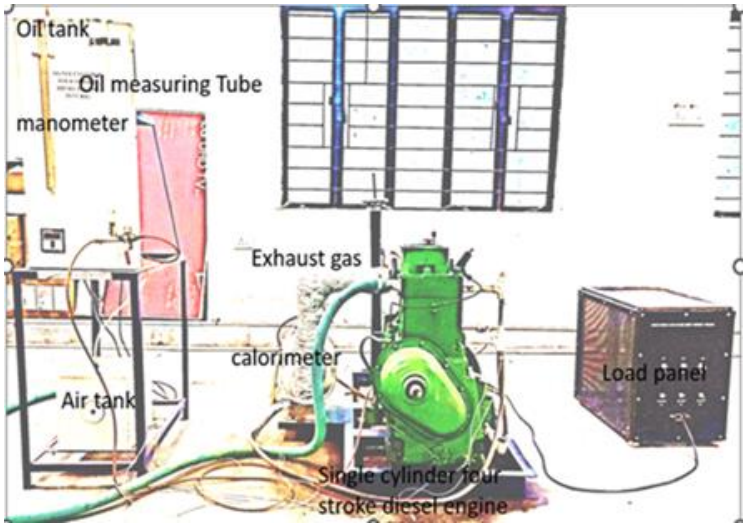
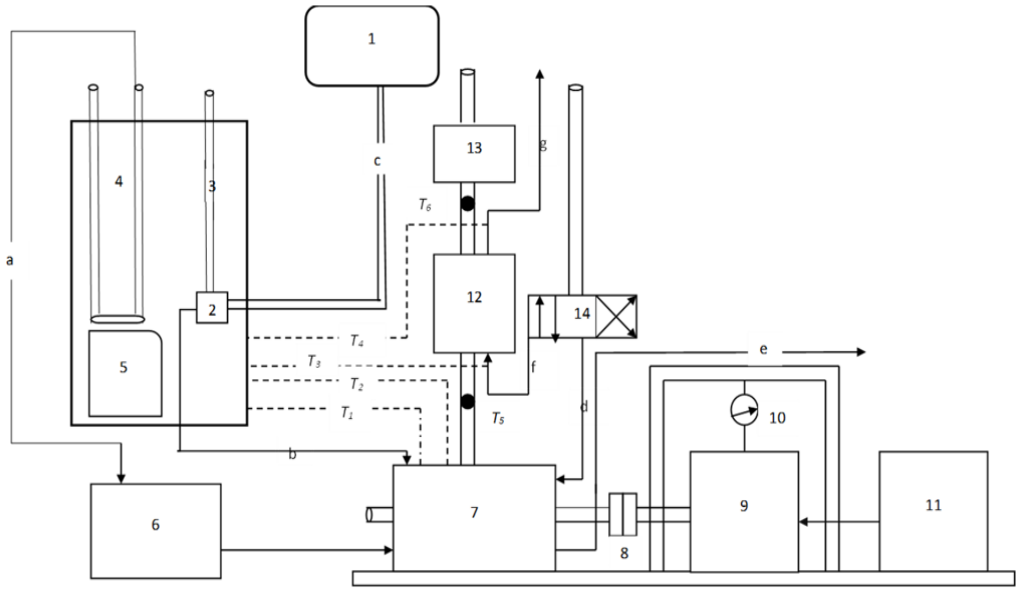


Figure. 5. Experimental setup (Kirloskar Oil Engine Ltd; Model: DM-10)



1. Diesel Tank 2. Controlling Valve 3. Burette 4. Manometer 5. Temperature Indicator 6. Air Box 7. Diesel Engine 8. Coupling 9. Eddy Current Dynamometer 10. Load gauge 11. Load Cell 12. Calorimeter 13. Exhaust Gas analyzer 14. Water flow control valve

T_1 and T_2 represent the cooling water temperature for the engine jacket.

T_3 and T_4 represent water passing through the calorimeter.

T_5 and T_6 represent exhaust gas temperature before and after the calorimeter.

Figure 6. Schematic diagram of the detailed experiment

3.1 Uncertainty Analysis

Experimental work is subject to numerous sources of uncertainty, including instrumentation, data analysis, and data acquisition. Therefore, an uncertainty analysis was done to prove the accuracy, consistency, and reliability of the experimental data by Moffat (1988) and Saravanan et al. (2020). The value of the uncertainty of the typical parameter during the experiment is shown in Table 3. However, according to the principle of the propagation of error, the overall percentage uncertainty during the experimental work can be computed as shown in Equation (1).

Table 3 Technical Specification of the various quantities during the experiment

1	Sensor	Range	Resolution	Accuracy	Uncertainty
CO	Electrochemical	0-10000 PPM	1PPM	±10 ppm	±0.1
CO_2	TCD/NDIR	0-25%,100% V/V	0.1%	±0.04%	±0.4
NO_x	Electrochemical	0-5000 PPM	1PPM	±15ppm	±0.05
HC	Solid State/NDIR	0-10000 PPM	1PPM	±10ppm	±0.05
Engine Speed	Tachometer	500-5500RPM		±10RPM	±1.8
U-tube manometer		0-300mm	1mm	±1 mm	±1
Dynamometer load cell	Rope-Brake	0-25kg	100g	±50g	±0.8
Temperature Indicator	Thermocouple	0-1000ºC	1ºC	±1ºC	±0.15
Stop-watch	Digital			±0.2 sec	±0.2 sec
BSFC	-	-	-	-	±3.2
BP	-	-	-	-	±0.2
BTE	-	-	-	-	±3.3

Overall uncertainty (U) =

$$\sqrt{(u_{BTE})^2 + (u_{BP})^2 + (u_{BSFC})^2 + (u_{time})^2 + \left(u_{Temp}\right)^2 + \left(u_{speed}\right)^2 + (u_{Utube})^2 + (u_{HC})^2 + (u_{\mathrm{NOx}})^2 + (u_{\mathrm{CO2}})^2 + (u_{\mathrm{CO}})^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Overall uncertainty (U) =

$$\sqrt{(3.2)^2 + (0.2)^2 + (3.3)^2 + (0.2)^2 + (0.15)^2 + (1.8)^2 + (1)^2 + (0.05)^2 + (0.05)^2 + (0.4)^2 + (0.1)^2} = \pm 5.06\%.$$

The overall uncertainty during the experiments, caused by different instrumentation, is equal to ± 5.06 %.

4. RESULTS AND DISCUSSION

An investigation was carried out to examine various performance parameters and emission characteristics. The characteristics of *Argemone mexicana* (AM) with the diesel blend (AM5, AM10, AM15, AM20, and AM25) under different loading conditions at 0%, 17%, 33%, 50%, 67%, 83%, and 100% (full load) were investigated.

4.1 Exhaust gas temperature (EGT)

Figure 7 illustrates that the AM25 biofuel blend consistently produces the highest EGT compared to conventional diesel across all load conditions. Specifically, the EGT for AM25 ranges from 92°C (at no load) to 155°C (at full load), whereas diesel ranges from 82°C to 140°C under the same conditions. This indicates that the AM25 blend yields an EGT 10–15% higher than diesel, particularly at higher loads. Several reasons can explain the increased exhaust gas temperature (EGT) noted with AM25. One significant factor is the higher oxygen levels in biodiesel (Zheng & Cho, 2024), which facilitate more thorough and effective combustion (Zhang et al., 2022). Additionally, the longer ignition delay allows for a greater build-up of the fuel-air mixture before combustion. While biodiesel typically has a marginally lower heating value than conventional diesel, the enhanced combustion efficiency and oxygen content result in a greater heat release. During the combustion process, especially at the end of the compression stroke. As a result, the exhaust gases exit the engine at higher temperatures. These findings are consistent with existing literature (Ong et al., 2014; Yesilyurt et al., 2020), which reports that biodiesel blends tend to produce higher EGTs than pure diesel, particularly under increased engine loads.

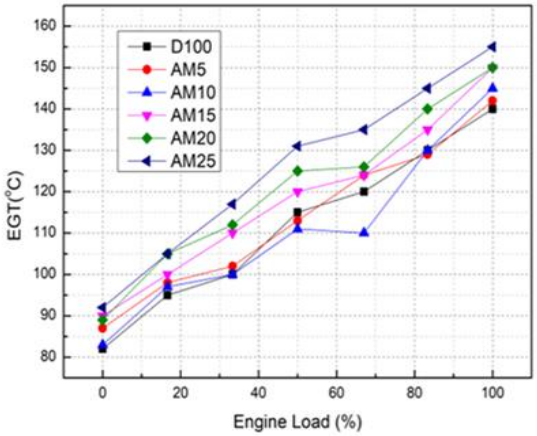


Figure 7. Exhaust gas temperature of different biodiesels blends at various loads

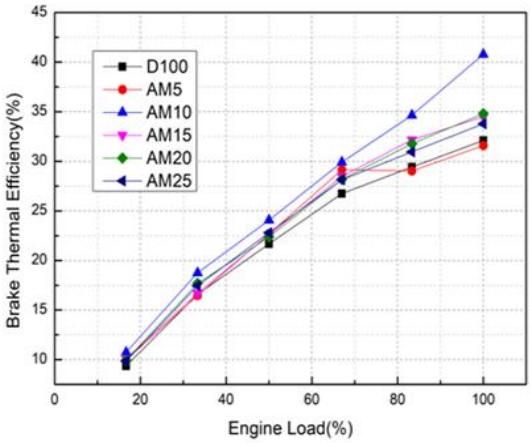


Figure 8. Brake thermal efficiency of different biodiesels and blends at various loads

4.2 Brake Thermal Efficiency (BTE)

Figure 8 illustrates the variation in brake thermal efficiency (BTE) for diesel and its biodiesel blends under different loading conditions. Across all fuels tested, BTE increases with engine load. At the same time, BSFC decreases, a trend attributed to the fact that higher engine power output results in a smaller proportion of energy being lost as heat (Singh & Sandhu, 2020). Among the blends, the AM10 biodiesel blend consistently demonstrates the highest BTE at every load condition, indicating superior combustion efficiency and fuel utilization compared to higher biodiesel blends and pure diesel (D100). In contrast, the AM20 and AM25 blends exhibit lower BTE and higher BSFC, suggesting diminished performance as the proportion of biodiesel increases. This decline in efficiency with higher biodiesel content can be attributed to the greater viscosity and lower calorific value of the biofuels (Ashfaque et al., 2023), which hinder proper atomization and combustion, resulting in increased fuel consumption and reduced energy conversion efficiency. These observations are consistent with previous research (Harsha et al. 2020). This suggests that while lower-percentage biodiesel blends can enhance engine performance, higher concentrations may result in a slight deterioration of efficiency and fuel economy due to the inherent physical and chemical properties of biodiesel.

4.3 Brake-specific fuel consumption

Figure 9 illustrates the impact of different fuels on brake-specific fuel consumption (BSFC) across different engine loads. The experimental results reveal that BSFC decreases for all fuel types as the engine load increases, which can be attributed to the fact that the increase in brake power with load is proportionally greater than the increase in fuel consumption (Ghazali et al., 2015). Among the tested blends, AM10 consistently shows the lowest BSFC at every load condition, indicating more efficient fuel utilization, while AM25 exhibits the highest BSFC, particularly at part-load conditions such as 17% (Knothe et al., 2006). The rise in brake-specific fuel consumption (BSFC) associated with higher biodiesel blends can be attributed mainly to their lower energy density and increased viscosity compared to traditional diesel. As a result, more fuel must be injected to produce an equivalent energy output, leading to increased fuel consumption. Additionally, the higher cetane number and altered injection timing associated with biodiesel can impact combustion characteristics, sometimes leading to less efficient energy conversion. The oxygen content in biodiesel also promotes a leaner combustion process, which, while beneficial for emissions, can result in poorer energy efficiency and further elevate BSFC. These findings are consistent with previous studies (Singh & Sandhu, 2020), which have observed that higher biodiesel blends tend to increase BSFC due to these combined factors.

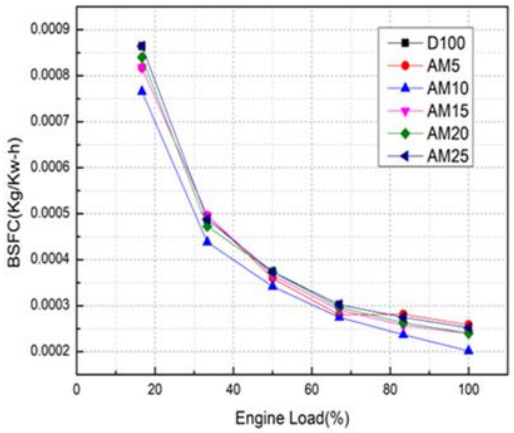


Figure 9. BSFC of different biodiesels and blends at different loads

4.4 Engine Exhaust Emission

4.4.1 CO emission characteristics

Carbon monoxide (CO) and hydrocarbons (HC) are primarily generated as a result of incomplete combustion within internal combustion engines. As illustrated in Figure 10, CO emissions exhibit an increasing trend with rising engine load. Under low-load conditions (up to 50%), the AM10 biodiesel blend demonstrates the lowest CO emissions, whereas at higher loads (above 50%), the AM20 blend produces the least CO emissions. This reduction in CO output can be attributed to the higher cetane number and favourable fatty acid composition of biodiesel, as reported in previous studies (Xue et al., 2011; Mohan et al., 2024). The CO emissions from the AM25 blend fall between those of AM10 and AM5. In the case of AM10 and AM15, the relatively higher viscosity and incomplete fuel combustion may contribute to elevated CO emissions. Moreover, at low load conditions (up to 50%), all biodiesel blends (AM5, AM20, and AM25) exhibit higher CO emissions compared to conventional diesel. This behaviour may be due to lower in-cylinder temperatures caused by reduced injection and boost pressures at partial loads (Hoekman

& Robbins, 2012), which hinder complete combustion by promoting a less homogeneous fuel–air mixture. Consequently, under low-load operation, the combined influence of lower calorific value, higher viscosity, and specific engine operating parameters results in increased CO emissions, as also observed in previous studies (Harsha et al., 2020).

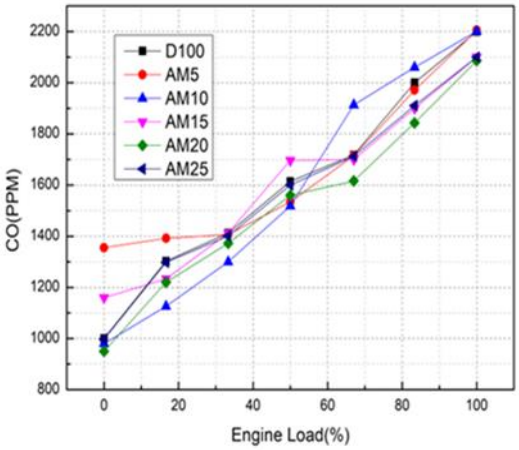


Figure 10. Emission characteristics of CO

4.4.2 NOx emission characteristics

Figure 11 shows that biodiesel blends generally produce higher NO_x emissions than conventional diesel across all load conditions, with the AM15 blend exhibiting the highest NO_x output among the tested fuels (Yongcheng et al., 2006). This behaviour is primarily attributed to the higher oxygen content of biodiesel (approximately 10–12% by mass), which enhances in-cylinder combustion efficiency and elevates local flame temperatures, thereby promoting thermal NO_x formation through the extended Zeldovich mechanism (Keller & Hongo, 1990). Under low-load conditions (~17%), the AM5, AM10, and AM15 blends exhibit NO_x emissions that are 2.9–6.7% higher than those of diesel, despite having lower average combustion temperatures.

This seemingly counterintuitive observation results from biodiesel's higher cetane number, which reduces ignition delay and shifts combustion toward the premixed phase, leading to locally higher peak temperatures even at partial loads. At higher loads, the disparity in NO_x emissions becomes more pronounced due to cumulative thermal effects. Specifically, the NO_x emissions from AM15 exceed those of diesel by approximately 12–18% under full-load conditions, as sustained in-cylinder temperatures (ranging between 500°C and 700°C) intensify oxidative interactions between nitrogen and oxygen. The relationship between NO_x formation and engine load is nonlinear, with emissions increasing disproportionately at elevated loads due to enhanced oxygen availability and extended residence times at peak temperatures. Although biodiesel's intrinsic oxygen content inherently promotes NO_x formation, engine calibration parameters such as fuel injection timing and exhaust gas recirculation (EGR) can effectively mitigate these effects by lowering combustion temperatures. These results are consistent with previous studies (Ying et al., 2006; Mohanty & Kotebavi, 2020; Merola et al., 2014; Duda et al., 2018; Abikusna et al., 2020), which have reported higher NO_x emissions from biodiesel derived from unsaturated feedstocks (e.g., soybean, rapeseed) compared to those from more saturated sources. However, feedstock-specific effects were not the focus of the present work.

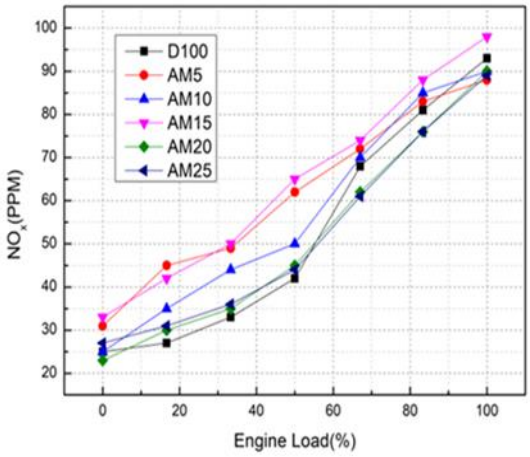


Figure 11. Emission characteristics of NO_x

4.4.3 HC Emission Characteristics

Figure 12 illustrates the relationship between hydrocarbon (HC) emissions and engine load. As a result of incomplete combustion, HC emissions exhibit a decreasing trend with an increasing load for all tested biodiesel blends, mirroring the behavior of CO emissions. The increased unburnt HC at low loads is attributed to the formation of localized fuel-rich zones due to the limited fuel injection (Abikusna et al., 2020). A key observation is that all biodiesel blends consistently produced low er HC emissions than diesel across the entire load range.

The superior combustion efficiency of AM5, AM10, and AM20, indicated by their lower HC emissions at both part and full load, is attributed to the higher in-cylinder temperatures (Ashfaque et al., 2023). The emission characteristics of AM5 and AM15 are lies in between D100 and AM10. At low load conditions (around 15% load), AM25 showed the least emission characteristics, and at high load, AM10 showed the least emission characteristics from all the fuels tested. At low load conditions (around 17% load), the decrement in HC emission is 1.2%, 3.6% and 9%, and around 83% load condition decrement in load condition is 6.8%, 13.33% and 1% for AM5, AM10, and AM15, respectively.

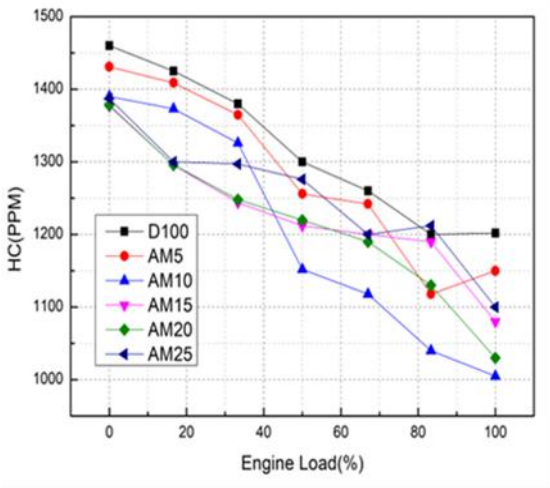


Figure 12. Emission characteristics of HC

4.4.4 CO2 emission

Figure 13 demonstrates that CO_2 emissions increase proportionally with engine load across all tested fuels, reflecting enhanced combustion efficiency at higher loads. Among the blends, AM5 exhibits the highest mean CO_2 emissions, followed by AM20, AM15, and AM10. Conventional diesel (D100) has the highest mean CO_2 emissions, followed by AM20, AM15, and AM10, with conventional diesel (D100) producing the lowest emissions. This hierarchy arises from competing factors influencing combustion dynamics: diesel's lower kinematic viscosity improves atomization, reduces fuel droplet size, and enhances brake thermal efficiency (BTE), promoting more complete combustion with relatively lower CO_2 output. Conversely, biodiesel blends, particularly AM5, generate higher CO_2 due to their oxygenated molecular structure, which originates from the alcohol content in the fuel. This inherent oxygen facilitates more thorough oxidation of carbon atoms during combustion, even under suboptimal conditions, leading to elevated CO_2 levels despite potential inefficiencies in fuel-air mixing. The trend aligns with studies indicating that oxygenated fuels, such as biodiesel, inherently produce 8–15% higher CO_2 emissions than diesel due to their chemically bound oxygen, which accelerates carbon oxidation (Yesilyurt et al., 2020). However, the results also suggest a nuanced interplay between fuel properties and combustion quality: while diesel's superior atomization and energy density reduce the fuel quantity needed for equivalent power output (thereby lowering CO_2), biodiesel's oxygen content dominates its emission profile, resulting in higher CO_2 even when combustion efficiency is marginally compromised. These findings underscore the complex trade-offs between fuel chemistry, combustion optimization, and emission outcomes in biodiesel-blended engines.

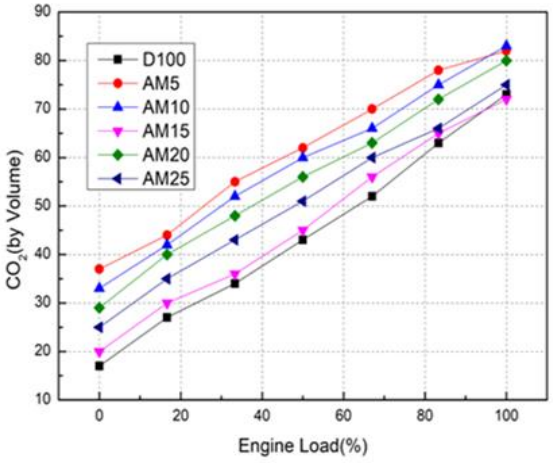


Figure 13. Emission Characteristics of CO_2

5. CONCLUSIONS

In this study, an experimental investigation was conducted on a four-stroke direct injection (DI) diesel engine using blends of *Argemone mexicana*-derived biodiesel (AM5, AM10, AM15, AM20, and AM25) with conventional diesel fuel. The significant findings are summarized as follows:

- For the maximum biodiesel yield, various molar ratios of '*Argemone mexicana*' oil and ethanol were reacted with H_2SO_4 on a hot plate magnetic stirrer at 60°C for 1 hour at 200 RPM. After removing free fatty acids, ethanol with 1% (by weight) of sodium hydroxide (KOH) was used as a catalyst for transesterification under the same stirring conditions.
- The EGT was observed to increase with engine load for all fuel types. Among the tested blends, AM25 exhibited the highest exhaust gas temperature, particularly at a 25% blending ratio.
- The BSFC decreased with increasing engine load for all biodiesel blends. AM10 consistently showed the lowest BSFC across all load conditions, while AM25 recorded the highest BSFC. AM10 demonstrated the best BSFC performance at full load, whereas at approximately 17% load, AM25 showed the maximum BSFC.
- The BTE increased with increasing load for all tested fuels, reflecting the inverse relationship between BSFC and BTE. AM10 exhibited the highest BTE at all load conditions among the biodiesel blends.
- *Regarding emission characteristics:*
- CO Emissions: An increasing trend with load was observed. At lower loads, AM10 showed the lowest CO emissions, while at higher loads, AM20 demonstrated the best performance. However, at lower load conditions (up to 50% load), AM5, AM20, and AM25 exhibited higher CO emissions compared to diesel.

- NO_x Emissions: AM5, AM10, and AM15 blends showed higher NO_x emissions than diesel across all load conditions. The emission trends for AM10 and AM20 were closer to those of diesel. At low load (~17%), NOx emissions increased by 6.7%, 2.9%, and 5.5% for AM5, AM10, and AM15, respectively.
- HC Emissions: Hydrocarbon (HC) emissions decreased with increasing load for all biodiesel blends. Compared to diesel, all biodiesel blends consistently exhibited lower HC emissions across all load conditions. At around 17% load, HC emission reductions were 1.2%, 3.6%, and 9% for AM5, AM10, and AM15, respectively; at approximately 83% load, reductions were 6.8%, 13.33%, and 1%, respectively.
- CO_2 Emissions: Among all fuels, AM5 showed the highest mean CO_2 emissions, while diesel recorded the lowest. The CO_2 emissions of AM10, AM15, and AM20 fell between those of diesel and AM5.
- Overall, AM10 emerged as the most promising blend in fuel efficiency and emission characteristics, suggesting its potential as an effective alternative to conventional diesel.

Data Availability Declaration

The datasets collected and examined in this study can be obtained from the corresponding author if requested appropriately.

Financial Interest

All authors declare that they have no connections or relationships with organizations or entities that could have a financial or non-financial stake in the topics or materials presented in this manuscript.

Funding Statement

The authors did not receive any funding support from any organization for the submitted work.

Author Contribution Statement

Pappu Kumar wrote the original draft, visualized the investigation of various researchers, and arranged them systemically. Om Prakash wrote the outline, edited the draft, supervised the work, and provided the resources.

Acknowledgement

The I.C. Engine Laboratory Research facility of the Mechanical Engineering department at NIT Patna, as well as the I.C. Engine lab at NCE, Nalanda, Bihar, is duly acknowledged.

NOMENCLATURE

D100	Diesel oil
AM5	5% Argemone biodiesel blended with 95% diesel
AM10	10% Argemone biodiesel blended with 90% diesel
AM15	15% Argemone biodiesel blended with 85% diesel
AM20	20% Argemone biodiesel blended with 80% diesel
AM25	25% Argemone biodiesel blended with 85% diesel
T_1	Temperature of the cooling water at the inlet of the cooling jacket
T_2	Temperature of the cooling water at the outlet of the cooling jacket
T_3	Temperature of the cooling water at the inlet of the calorimeter
T_4	Temperature of the cooling water at the outlet of the calorimeter
T_5	Temperature of the exhaust gas at the inlet of the exhaust gas calorimeter
T_6	Temperature of the exhaust gas at the outlet of the exhaust gas calorimeter

LIST OF ABBREVIATIONS

RPM	Revolution per minute
kWh	Kilowatt-hour
TWh	Terawatt-hour
NO_x	Nitrogen Oxide
CO_2	Carbon-dioxide
CO	Carbon-monoxide
GHG	Greenhouse gas
HC	Hydrocarbon
EGT	Exhaust gas temperature
CI	Compression-Ignition
H_2SO_4	Sulfur dioxide
TAE	Transesterified *Argemone* Ester
BSFC	Brake-Specific Fuel Consumption
BTE	Brake thermal Efficiency
CV	Calorific value
b_{th}	Brake Thermal Efficiency

Subscript

D	Diesel
AM	*Argemone mexicana*
T	Temperature
th	Thermal Efficiency

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