Green Chemical Conversion of Argemonemexicana Oil into Sustainable Biodiesel: Engine Performance Assessment

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Abstract: This study evaluates the production, blending, and engine performance of biodiesel derived from Argemonemexicana seed oil as a sustainable alternative to conventional diesel. Crude oil was extracted from seeds collected across different regions of India and converted into biodiesel via a two-step transesterification process, comprising acid-catalyzed esterification followed by base-catalyzed transesterification to reduce free fatty acids and optimize fatty acid methyl ester yield. The synthesized biodiesel was blended with commercial diesel at varying concentrations and characterized for fuel properties. Engine performance and emission tests were conducted on a single-cylinder, four-stroke diesel engine, assessing parameters including brake thermal efficiency, specific fuel consumption, and exhaust emissions (NO, HC, CO, CO_2, and O_2). Among the tested blends, B10 (10% biodiesel) exhibited the most favorable performance, achieving stable engine operation, lower fuel consumption, and an improved emission profile compared to neat diesel and higher biodiesel blends. Higher biodiesel content, such as B15 (15% biodiesel), resulted in slightly reduced engine stability and increased fuel consumption due to its lower calorific value and higher viscosity. These results demonstrate that A. mexicana biodiesel, particularly at 10% blending, offers an optimal balance between engine efficiency, fuel economy, and emission reduction, confirming its potential as a renewable diesel substitute.

Keywords: Argemonemexicana; Biodiesel; Transesterification; Oil extraction; Fuel properties; Renewable energy; Diesel substitution

1. Introduction

Biodiesel has emerged as a promising renewable energy source, offering biodegradability, non-toxicity, and an environmentally friendly alternative to petroleum diesel. Its high flash point, excellent lubrication properties, and ability to reduce greenhouse gas emissions, particulate matter, and hydrocarbons make it a viable substitute for diesel engines without major modifications [1–8]. A major challenge in biodiesel production is the cost and limited availability of feedstocks, as the use of edible oils such as soybean, palm, and rapeseed is increasingly discouraged due to their competition with food resources and associated price volatility [9–11]. Consequently, non-edible oils, waste cooking oils, animal fats, and microalgae lipids have gained attention as cost-effective and sustainable alternatives [12–15]. Among non-edible sources, Argemonemexicana, a drought-tolerant weed widely distributed in arid and semi-arid regions, has shown high seed oil content (22–38%), making it a promising candidate for biodiesel production [16–18]. However, the high free fatty acid (FFA) content of A. mexicana oil (8–20%) poses challenges for conventional base-catalyzed transesterification, as it can lead to soap formation, reduced ester yield, and difficulty in separating products [19–21]. To overcome this limitation, a two-step conversion process is commonly employed, with an initial acid-catalyzed esterification to reduce FFA levels below 1–2%, followed by base-catalyzed transesterification for efficient conversion of triglycerides into fatty acid methyl esters (FAME). Catalyst selection is critical for process efficiency, as homogeneous catalysts such as NaOH, KOH, and H_2SO_4 are effective but suffer from drawbacks including corrosivity, saponification, and complex separation. Heterogeneous catalysts, including metal oxides, carbonates, and supported bases, offer advantages such as reusability, lower environmental impact, and simplified separation. Specifically, manganese carbonate ($MnCO_3$) has demonstrated high catalytic efficiency for both esterification and transesterification, particularly for high-FFA oils like A. mexicana, enhancing conversion and sustainability [22, 23]. The global push towards renewable and carbon-neutral fuels is driven by fossil fuel depletion, rising energy costs, environmental regulations, and climate change mitigation efforts [1,5,10,11]. Biodiesel production from non-edible sources like A. mexicana aligns with these objectives, providing a cost-effective, eco-friendly, and sustainable alternative while mitigating the food-versus-fuel conflict [12,14,15]. This study investigates biodiesel production from Argemonemexicana seed oil via a two-step esterification–transesterification process using $MnCO_3$ as a heterogeneous catalyst, focusing on the optimization of reaction parameters, catalyst efficiency, and fuel quality, thereby demonstrating the potential of A. mexicana as a sustainable feedstock for industrial biodiesel production [16–23].

2. Literature review

Biodiesel has gained significant attention as a sustainable and environmentally benign alternative to petroleum-derived diesel fuel due to its renewable origin, biodegradability, low sulfur content, and reduced greenhouse gas emissions. Growing concerns over fossil fuel depletion, climate change, and stringent emission regulations have accelerated global research efforts toward the development of efficient biodiesel production technologies [1–3]. In recent decades, emphasis has shifted from edible oil feedstocks toward non-edible and waste oils to overcome the food–fuel conflict and reduce production costs [4–7]. Consequently, several non-edible oils such as jatropha, mahua, neem, karanja, pongamia, and Argemonemexicana have been extensively explored for biodiesel synthesis because of their high oil content, low cultivation input requirements, and ability to grow on marginal or wastelands [8–10].

Argemonemexicana is a drought-tolerant, non-edible weed species commonly found in arid and semi-arid regions of India and other developing countries. The plant produces seeds containing approximately 22–38% oil, making it a promising feedstock for biodiesel production [11–13]. Its ability to thrive on degraded and unused lands ensures that its cultivation does not compete with agricultural food crops, thereby supporting sustainable bioenergy development. Several studies have reported favorable physicochemical properties of A. mexicana oil for biodiesel synthesis, while also highlighting challenges associated with its high free fatty acid (FFA) content [14–16].

The presence of high FFAs in non-edible oils such as A. mexicana significantly affects biodiesel production through conventional base-catalyzed transesterification. Elevated FFA levels lead to soap formation, catalyst deactivation, reduced ester yield, and difficulties in phase separation [17–19]. To overcome these limitations, a two-step transesterification approach is widely employed. This method involves an initial acid-catalyzed esterification process to reduce FFA content, followed by base-catalyzed transesterification to convert triglycerides into fatty acid methyl esters (FAME) [20–22]. Numerous studies have confirmed that this two-step route enhances conversion efficiency and improves fuel quality for high-FFA feedstocks.

Catalyst selection and development remain critical aspects of biodiesel research. Homogeneous catalysts such as NaOH, KOH, and H_2SO_4 are commonly used due to their high catalytic activity and low cost; however, they suffer from several drawbacks including corrosiveness, soap formation, wastewater generation, and difficulties in catalyst recovery and reuse [23–25]. To address these challenges, heterogeneous catalysts have been increasingly investigated owing to their environmental friendliness, reusability, ease of separation, and reduced downstream processing requirements [26–28]. Metal oxides such as CaO, MgO, ZnO, and supported catalysts have shown

promising results in biodiesel synthesis. In particular, manganese carbonate ($MnCO_3$) has demonstrated effective catalytic performance for both esterification and transesterification reactions, especially for high-FFA oils, offering high conversion efficiency with minimal corrosion and operational complexity [29–31].

Optimization of process parameters—including alcohol-to-oil molar ratio, catalyst loading, reaction temperature, and reaction time—is essential for achieving maximum biodiesel yield and desirable fuel properties [32]. Previous investigations on A. mexicana and similar non-edible oils have reported biodiesel yields exceeding 90% under optimized two-step transesterification conditions, producing fuel that meets international standards in terms of viscosity, density, cetane number, and oxidative stability [14,31,32].

The performance and emission characteristics of biodiesel derived from non-edible oils have also been extensively studied. Engine tests indicate that biodiesel–diesel blends up to B20 generally exhibit comparable brake thermal efficiency to conventional diesel fuel, along with significant reductions in carbon monoxide, hydrocarbons, and particulate matter emissions [6,12]. However, a marginal increase in nitrogen oxide emissions is often observed due to the higher oxygen content and combustion temperature associated with biodiesel fuels.

Overall, the literature underscores the importance of sustainable feedstock selection, efficient catalyst development, and optimized reaction conditions for economically viable biodiesel production. Argemonemexicana, with its high oil yield, adaptability to marginal lands, and compatibility with two-step transesterification using heterogeneous catalysts, emerges as a promising and sustainable feedstock for large-scale biodiesel synthesis.

3. Experimental setupfor biodiesel production

A magnetic stirrer equipped with an integrated hot plate (Model: MH 2 LT), as shown in Figure-1(a), was used to provide controlled heating and uniform agitation of the reaction mixture during biodiesel synthesis. The apparatus heated Argemonemexicana oil to approximately 60 °C while maintaining continuous stirring throughout the transesterification process, thereby ensuring homogeneous mixing of reactants and favorable reaction kinetics. After completion of the reaction, phase separation was performed using a separating funnel, illustrated in Figure-1(b), which separates immiscible liquids based on density differences. The lighter biodiesel phase formed the upper layer, whereas the denser glycerol settled at the bottom, enabling efficient separation and subsequent purification of the biodiesel. Temperature during the experimental procedure was monitored using a laboratory thermometer designed for

non-biological measurements, with a working range of –10 °C to 110 °C, ensuring accurate temperature control under laboratory conditions.

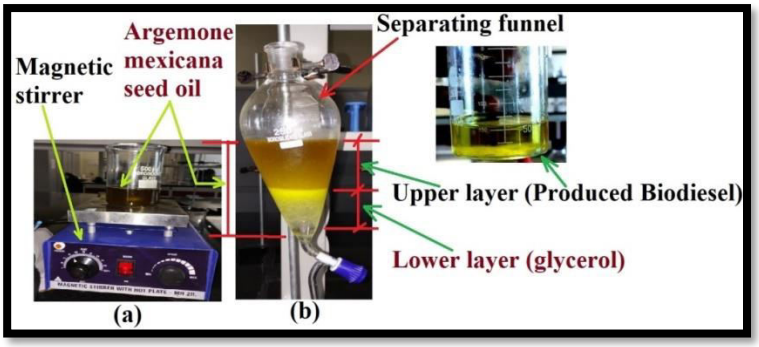

Figure-1: Experimental setup for biodiesel production from argemonemexicanaseed oil

4. Experimentation

(i) Production of Pure Biodiesel

Crude oil extracted from Argemonemexicana seeds was used as the feedstock for biodiesel production. The seeds were collected from various regions of India, including central Madhya Pradesh and areas near Patna, Bihar, to account for feedstock variability. Analytical-grade methanol, sulfuric acid (H_2SO_4), and sodium metal were employed as alcohol and catalysts, and all chemicals were used without further purification.

Biodiesel synthesis was carried out using a two-step process consisting of acid-catalyzed esterification followed by base-catalyzed transesterification. The initial free fatty acid (FFA) content of the crude oil was approximately 6%, which necessitated pretreatment, as oils with FFA levels above 2.5% are unsuitable for direct base-catalyzed conversion. Therefore, the two-step method recommended by Fadhil and Ahmed (2018) was adopted, with reaction temperature, alcohol-to-oil ratio, catalyst concentration, stirring, and reaction time maintained as controlled parameters.

During the esterification step, the oil was reacted with methanol in the presence of concentrated H_2SO_4 and stirred continuously at 60 °C for 1 h 15 min using a magnetic stirrer with a hot plate. The reaction mixture was then transferred to a separating funnel and allowed to settle for approximately 4 h to remove excess methanol and glycerol, reducing the FFA content to 1.79%.

The esterified oil was subsequently subjected to base-catalyzed transesterification using a predetermined oil-to-methanol ratio (x:y) and 0.5% (w/w) sodium catalyst. The reaction was carried out at 60 °C with continuous stirring for 1 h, followed by phase

separation for 3–4 h. The upper biodiesel layer was collected, washed with warm water, heated to 110 °C to remove residual moisture, and filtered to obtain purified biodiesel for further analysis and engine testing.

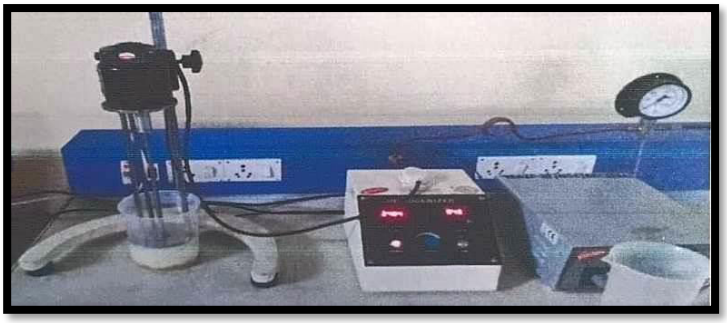

Figure-2: Blending setup

(ii) Blending of Biodiesel

The biodiesel produced was blended with commercially available diesel fuel in varying proportions to obtain different test fuels. Blending was carried out using a laboratory homogenizer, shown in Figure-2, operated at a rotational speed of 2000 rpm to ensure uniform mixing of the components. After blending, each fuel sample was kept undisturbed for a period of 24 h to confirm homogeneity and assess phase stability. The detailed composition of the prepared biodiesel–diesel blends is summarized in Table-1. Subsequently, the performance characteristics of the prepared blends were investigated using a single-cylinder, four-stroke diesel engine, as illustrated in Figure-3.

Figure-3: Single-cylinder, four-stroke diesel engine setup

Table-1: Preparation of biodiesel–diesel blends at various concentrations

Sl. No.	Blend Code	Biodiesel Concentration (%)	Diesel Concentration (%)	Blending Technique	Homogenizer Speed (rpm)	Settling Time (hours)
1	B0	0	100	No blending required	-	-
2	B5	5	95	Homogenized Mixing	2000	24
3	B10	10	90	Homogenized Mixing	2000	24
4	B15	15	85	Homogenized Mixing	2000	24

5. Engine testing and results

Engine tests were carried out using fuel blends B0, B5, B10, and B15 on a single-cylinder, four-stroke diesel engine to evaluate their performance and emission behavior. For each operating condition, the time taken to consume a fixed fuel volume of 10 mL (t) and the corresponding manometric pressure difference (d) were measured to determine fuel consumption rate and energy input. The flow rate of cooling water through the engine jacket (S) was maintained at a steady value, and the associated inlet (T_1) and outlet (T_2) temperatures were recorded to assess heat rejection from the engine. In addition, the inlet (T_3) and outlet (T_4) temperatures of the water circulating through the calorimeter were continuously monitored to account for heat losses and to ensure accurate estimation of brake thermal efficiency.

The collected measurements formed the basis for evaluating the influence of biodiesel proportion on key performance indicators, including brake thermal efficiency and specific fuel consumption, as well as on exhaust emissions such as nitric oxide (NO), hydrocarbons (HC), oxygen (O_2), carbon dioxide (CO_2), and carbon monoxide (CO). This systematic approach enabled a direct comparison between biodiesel–diesel blends and neat diesel fuel, thereby highlighting the performance trends and emission variations associated with increasing biodiesel content.

A concise description of the experimental variables is provided in Table 2. The engine performance results for blends B0, B5, B10, and B15 are presented in Tables 3, 5, 7, and 9, respectively, while the corresponding emission data are reported in Tables 4, 6, 8, and 10. A comparative summary of all tested fuels is presented in Table 11.

Table-2: Experimental variables and parameter description

Symbol	Parameter Description	Unit
t	Time required to consume 10 mL of fuel	s / min
d	Manometric pressure difference	kPa
S	Cooling-water flow rate through engine jacket	L/min
T_1	Cooling-water inlet temperature at engine jacket	°C
T_2	Cooling-water outlet temperature at engine jacket	°C
T_3	Water temperature entering the calorimeter	°C
T_4	Water temperature exiting the calorimeter	°C

Table-3: Engine performance parameters for Bo at different load conditions

Load (kW)	Weight (kg)	RPM	Fuel Time (t)	d	S	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)
0	4.0	1528	1:16:10	13.1	18.47	26.8	32.8	42.8	44.8
250	5.0	1504	1:17:13	13.1	18.47	26.8	32.6	59.9	62.4
500	6.0	1491	1:04:10	13.1	18.47	26.8	32.5	63.6	66.6
750	7.5	1484	1:00:86	13.1	18.47	26.8	33.2	65.5	66.5

Table 4: Exhaust emission characteristics for Bo fuel

Load (kW)	Weight (kg)	NO (ppm)	HC (ppm)	O_2 (%)	CO_2 (%)	CO (ppm)
0	4.0	0005	1534	0.1	17.9	1489
250	5.0	0005	1222	0.1	17.9	1096
500	6.0	0008	1314	0.1	17.9	0984
750	7.5	0019	1430	0.1	17.9	1119

Table-5: Engine performance parameters for B5 at different load conditions

Load (kW)	Weight (kg)	RPM	Fuel Time (t)	d	S	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)
00	3.5	1491	1:12:24	13.1	18:27	28.5	42.0	29.9	42.0
250	4.5	1486	1:06:70	13.1	18:27	28.9	35.9	31.1	35.9
500	5.5	1488	1:02:21	13.1	18:27	28.7	35.6	35.7	35.7
750	7.0	1612	58:37	13.1	18:27	28.5	34.8	34.8	36.0

Table-6: Exhaust emission characteristics for B5 fuel

Load (kW)	Weigh t (kg)	NO (ppm)	HC (ppm)	O_2 (%)	CO_2 (%)	CO (ppm)
00	3.5	0002	1623	00.1	17.9	1107
250	4.5	0001	1429	00.1	17.9	1107
500	5.5	0011	1606	00.1	17.9	1269
750	7.0	0016	1612	00.1	17.9	1198

Table-7: Engine performance parameters for B10 at different load conditions

Load (kW)	Weight (kg)	RPM	Fuel Time (t)	d	S	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)
00	3.5	1511	1:14:13	13.1	18:27	27.1	32.7	27.5	50.1
250	5.0	1492	1:10:31	13.1	18:27	27.1	32.7	27.5	49.9
500	5.5	1483	1:06:77	13.1	18:27	27.1	32.1	27.6	50.2
750	7.5	1479	1:02:28	13.1	18:27	27.1	33.4	27.5	50.9

Table-8: Emission DataExhaust emission characteristics for B10 fuel

Load (kW)	Weigh t (kg)	NO (ppm)	HC (ppm)	O_2 (%)	CO_2 (%)	CO (ppm)
00	3.5	0000	0378	00.1	17.9	0146
250	5.0	0002	1288	00.1	17.9	1055
500	5.5	0006	1368	00.1	17.9	1111
750	7.5	0007	1126	00.1	17.9	0894

Table-9: Engine performance parameters for B15 at different load conditions

Load (kW)	Weight (kg)	RPM	Fuel Time (t)	d	S	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)
00	3.5	1507	13.1	13.1	18:27	28.1	33.6	30.8	50.5
250	4.5	1491	1:04:81	13.1	18:27	28.1	33.7	32.5	53.7
500	5.0	1484	1:00:82	13.1	18:27	28.2	33.8	31.8	55.6
750	6.5	1480	56:43	13.1	18:27	28.3	34.1	58.9	58.9

Table-10: Exhaust emission characteristics for B15 fuel

Load (kW)	Weight (kg)	NO (ppm)	HC (ppm)	O_2 (%)	CO_2 (%)	CO (ppm)
00	3.5	0005	2056	00.1	17.9	2215
250	4.5	0008	2152	00.1	17.9	2018
500	5.0	0013	2017	00.1	17.9	1863
750	6.5	0011	1688	00.1	17.9	1228

Table-11: Comparative analysis of diesel B0, B5, B10, and B15 blends

Blend	Engine Performance (RPM Stability)	Brake Thermal Efficiency	Fuel Consumption	NO Emission	HC Emission	CO Emission	Overall Result
B00 (Diesel)	High	High	Moderate	Moderate	Moderate	Highest	Baseline reference
B05	Good	Improved	Slightly lower	Low	Reduced	Reduced	Acceptable
B10	**Best**	**Highest**	**Lowest**	**Lowest**	**Lowest**	**Lowest**	**Best overall blend**
B15	Slightly lower than B10	Moderate	Higher than B10	Higher	High	High	Acceptable but not optimal

6. Results discussion

(i) Engine Performance

Among the tested fuels (B0, B5, B10, and B15), the B10 blend exhibited the most stable engine operation, as indicated by consistent engine speed across the full range of applied loads. This behavior can be attributed to the favorable balance between oxygen content and viscosity in the B10 blend, which promoted improved fuel atomization and more uniform combustion, ultimately enhancing thermal efficiency. The B5 blend also demonstrated satisfactory performance, although its stability and efficiency were marginally lower than those observed for B10. In contrast, the B15 blend showed noticeable fluctuations in engine speed at higher loads, likely resulting from its higher viscosity and reduced calorific value, which adversely affected fuel–air mixing and

combustion quality.

(ii) Fuel Consumption

Specific fuel consumption was found to be lowest for the B10 blend, indicating more effective energy utilization and a higher degree of combustion completeness. Neat diesel (B0) showed moderate fuel consumption characteristics, while B15 required a comparatively higher fuel input to sustain identical load conditions. This increase in fuel consumption for higher biodiesel blends can be primarily associated with their lower energy density.

(iii) Emission Characteristics

The emission behavior of the tested blends revealed clear trends with increasing biodiesel concentration. Nitric oxide (NO) emissions followed the order B15 < B10 < B5 < B0, suggesting that higher biodiesel content contributed to reduced NO formation, possibly due to lower peak combustion temperatures. Hydrocarbon (HC) emissions decreased progressively with increasing biodiesel proportion, with B10 recording the minimum HC levels, indicating cleaner and more complete combustion. Carbon monoxide (CO) emissions were significantly lower for B5 and B10 compared to diesel, reflecting improved oxidation during combustion. However, slightly higher CO levels were observed for B15 under certain load conditions, which may be attributed to incomplete combustion caused by poorer atomization.

Overall, the B10 blend consistently demonstrated the most favorable balance between engine performance, fuel economy, and emission reduction, supporting its selection as an optimal biodiesel–diesel blend for diesel engine applications.

7. **Conclusion**

Based on the experimental investigation of B0, B5, B10, and B15 blends in a single-cylinder, 4-stroke diesel engine, the following conclusions were drawn:

- B10 biodiesel blend demonstrated the best overall performance, including stable RPM, improved thermal efficiency, and reduced fuel consumption.
- Emission analysis showed that B10 significantly reduces HC, CO, and moderate NO emissions, indicating cleaner combustion compared to diesel.
- Higher blends such as B15 exhibited increased fuel consumption and less favourable combustion characteristics.
- B10 offered the optimal balance among performance, fuel economy, and emission reduction, making it the most suitable blend for diesel engine operation.
- Therefore, B10 biodiesel blend can be recommended as a sustainable alternative to conventional diesel for single-cylinder diesel engines.

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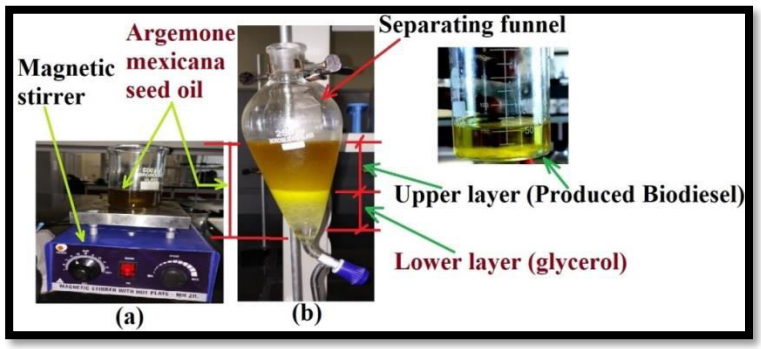

Figure-1: Experimental setup for biodiesel production from argemonemexicanaseed oil

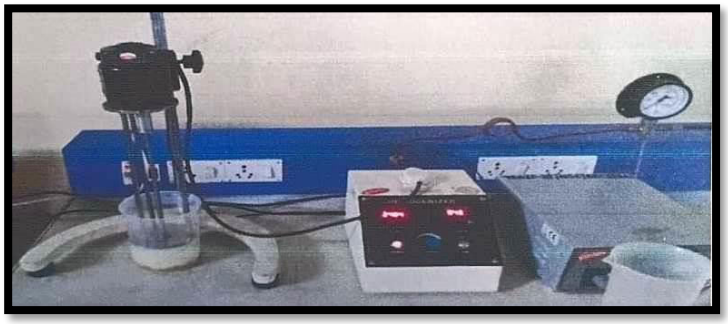

Figure-2: Blending setup

Figure-3: Single-cylinder, four-stroke diesel engine setup