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Performance and Emission Analysis of a VCR Diesel Engine Fuelled with Karanja Biodiesel–Diesel–Ethanol Blends

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Abstract: The depletion of petroleum reserves and tightening emission norms have increased interest in renewable, oxygenated fuels for compression ignition (CI) engines. This work evaluates ternary blends of Karanja (Pongamia pinnata) biodiesel, diesel and ethanol, designated K20 (15% biodiesel, 80% diesel, 5% ethanol), K25 (20/75/5) and K30 (20/70/10) by volume, in a single-cylinder, four-stroke, variable compression ratio (VCR) diesel engine running at 1500 rpm. Injection angle (19°–23° CA bTDC), compression ratio (16–18), blend and load were taken as input parameters in a Taguchi L9 orthogonal array. One-way ANOVA showed that load, compression ratio and injection angle, in that order, are the significant parameters, and grey relational analysis (GRA) gave an optimum at 19° CA bTDC injection and a compression ratio of 18, with K20 and K30 showing almost equal grey grades. Against baseline diesel at full load, K30 gave a brake thermal efficiency of 30.4% (32.21% for diesel) with about 3% higher BSFC, about 8% lower NOx, and lower CO and HC, while peak cylinder pressure, rate of pressure rise and net heat release rate stayed within about 1% of diesel. An artificial neural network (ANN) trained on the experimental data predicted the engine responses with errors below 10%.

Keywords: Karanja biodiesel, ethanol, VCR diesel engine, Taguchi method, grey relational analysis, ANN, performance, emissions

I. INTRODUCTION

The growing demand for transport energy, the depletion of petroleum reserves and the harmful exhaust emissions of diesel engines have intensified the search for renewable alternatives. Biodiesel is attractive because it is renewable, biodegradable, free of sulfur and carries oxygen in its molecular structure, which promotes more complete combustion [1], [2]. Its commercial uptake is limited by economic and supply barriers [3]. Non-edible oils such as Karanja (Pongamia pinnata) avoid the food-versus-fuel conflict that limits edible feedstocks, and the choice among candidate oils can be made with systematic selection methods [4]–[6].

Biodiesel, however, has a higher viscosity and density, a lower calorific value and usually higher NOx emission than diesel, and long-term use can lead to injector deposits and corrosion of metal parts [7], [8]. Blending with diesel is the usual remedy. Jatropha [9] and soybean [10], [11] biodiesel blends and ternary biodiesel blends [12] have all been tested in diesel engines.

Ethanol is a low-viscosity, highly oxygenated fuel that can be blended with diesel and biodiesel to cut CO and HC; ternary blends containing ethanol have been examined with multi-objective optimisation [13]. Ethanol also lowers the calorific value, cetane number and lubricity of the blend, so its share must be limited. Nano-additives are another route to better combustion in biodiesel-fuelled engines [14]–[17], including green-synthesised and bio-derived nanoparticles [18], [19], and nanocatalysts have been applied in biodiesel production [20]. Their feasibility is reviewed in [21]; because the dispersion stability and exhaust toxicity of nanoparticles remain open questions, this study uses oxygenated blends only. Ignition delay and combustion phasing depend on fuel composition and injection conditions [22], and the suitable compression ratio and injection timing depend on fuel density and cetane number, so a VCR engine is a convenient tool for finding the highest useful compression ratio for a blend. This paper studies Karanja biodiesel–diesel–ethanol blends with up to 30% oxygenates in a VCR engine. The Taguchi method [23] with ANOVA and grey relational analysis is used to find the best combination of injection angle, compression ratio, blend and load, the optimum is compared with baseline diesel, and an ANN model is built to predict the engine responses.

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II. MATERIALS AND METHODS

A. Fuels and Blend Preparation

Commercial diesel was procured in Sangli, Maharashtra. Karanja biodiesel (KBD) was supplied by GKVK, Bengaluru, and Apex Innovation Pvt. Ltd., Sangli, and anhydrous ethanol (99.9%) was purchased from Jalgaon, Maharashtra. Biodiesel quality is specified by ASTM D6751 [24] and IS 15607 [25]. Three blends were prepared on a volume basis: K20 (15% KBD, 80% diesel, 5% ethanol), K25 (20/75/5) and K30 (20/70/10); the number is the combined biodiesel-plus-ethanol share. Samples of 2000 mL were stirred with a hand blender and kept for more than 12 h before testing. All blends stayed clear, with no phase separation, at the ambient temperature above 37 °C prevailing in June. Properties of diesel, biodiesel and ethanol were taken as standard values; blend properties were measured and are listed in Table I.

TABLE I
PHYSICOCHEMICAL PROPERTIES OF THE TEST FUELS

Property	K20	K25	K30	Ethanol	KBD	Diesel
Density at 40 °C (kg/m^3)	844	845	842	786.85	860	850.786
Viscosity at 40 °C (mm^2/s)	2.53	2.64	2.48	1.068	–	1.3–4.1
Flash point (°C)	16	17	16	13	–	60–80
Cetane number	46	45.7	43.8	8	42.7	47–51
Calorific value (MJ/kg)	41.4	41.22	40.5	26.8	37	42–46

Diesel limits as per ASTM D975.

B. Test Engine and Instrumentation

Tests used a Kirloskar single-cylinder, four-stroke, water-cooled, multi-fuel VCR research engine (Table II) coupled to an eddy-current dynamometer, installed at Apex Innovation Pvt. Ltd., Sangli. Fig. 1 shows the layout. In-cylinder pressure was sensed by a piezoelectric transducer with a 1° crank-angle encoder. Air and fuel flow, speed, load and temperatures (K-type thermocouples) were logged by an NI USB-6210 data acquisition unit through EngineSoft (LabVIEW) software. CO, CO2, HC, NOx and O2 were measured with an AVL DiGas 444 analyser (CO 0–10%, CO2 0–20% and O2 0–22% by volume; HC 0–20000 ppm; NOx 0–5000 ppm). The stated uncertainties are ±5 ppm for NOx, ±1 ppm for HC, ±5% of reading for CO, CO2 and O2, ±1 °C for temperature, 0.5% for brake power, 1.5% for BSFC and 1% for BTE.

TABLE II
ENGINE SPECIFICATIONS

Parameter	Specification
Engine type	Single cylinder, 4-stroke, multi-fuel, VCR, water cooled
Displacement	661 cc (bore 87.5 mm, stroke 110 mm)
Rated output	3.5 kW at 1500 rpm
Compression ratio	12–18 (standard 17.5)
Injection timing	0–25° bTDC (standard 23° bTDC)
Injection opening pressure	210 bar (standard)
Dynamometer	Eddy current, water cooled
Pressure sensor	Piezoelectric, 350 bar range
Crank angle sensor	1° resolution, with TDC pulse
Data acquisition	NI USB-6210, 16-bit, 250 kS/s
Gas analyser	AVL DiGas 444

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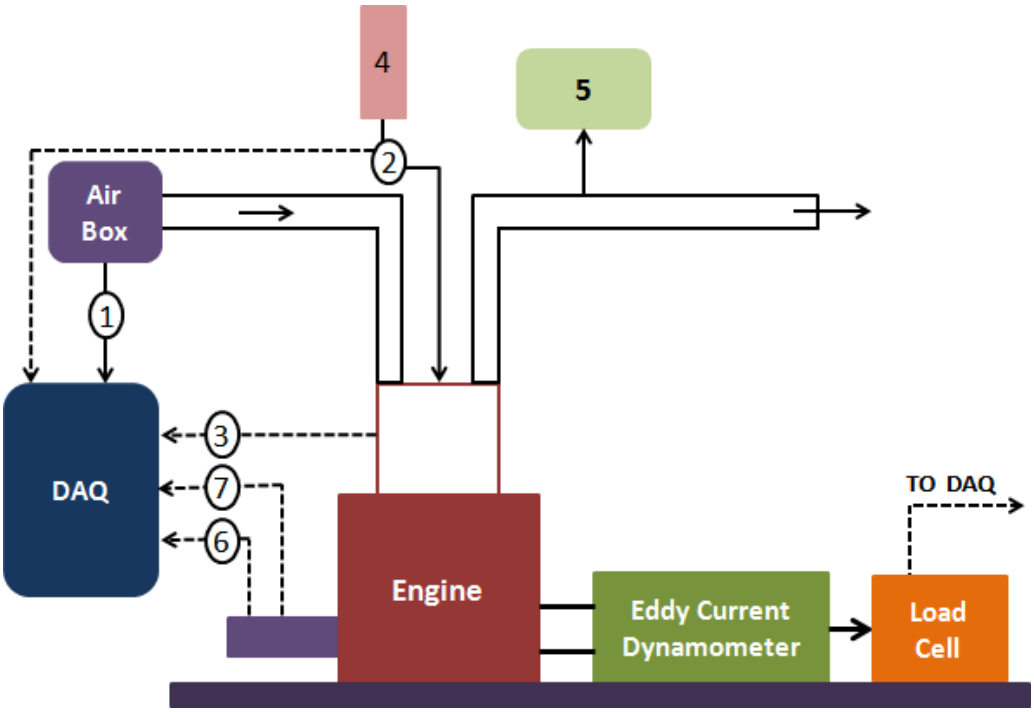


Fig. 1. Experimental setup: 1 air-flow sensor, 2 fuel-flow sensor, 3 pressure sensor, 4 fuel tank, 5 gas analyser, 6 speed sensor, 7 crank-angle sensor.

C. Experimental Design and Data Analysis

The engine ran at a constant 1500 rpm. Four input parameters at three levels each (Table III) were assigned to a Taguchi L9 orthogonal array, so nine runs replaced the 81 of a full factorial. The average of two consecutive trials was used for each run. Full-load runs over injection angles of 19°–25° bTDC and compression ratios of 16–18 for the three blends were also made to study parametric trends. The responses were BTE, BSFC, EGT, CO2, CO, NOx and HC. BTE and BSFC were computed from

$$\eta_{bth} = BP / (\dot{m}_f \times CV) \times 100 \quad (1)$$

$$BSFC = \dot{m}_f / BP \quad (2)$$

where BP is the brake power, ṁf the fuel mass flow rate and CV the calorific value of the blend.

TABLE III
INPUT PARAMETERS AND LEVELS

Parameter	Level 1	Level 2	Level 3
Injection angle (° CA bTDC)	19	21	23
Compression ratio	16	17	18
Blend	K20	K25	K30
Load (kg)	6 (50%)	9 (75%)	12 (100%)

The contribution of each parameter to the responses was found by one-way ANOVA in Minitab 2019. GRA combined the seven responses into one grade to select a single optimum, and confirmation runs checked the Taguchi predictions. An ANN with four inputs (injection angle, compression ratio, blend, load) and one output node per response was built in MATLAB R2013b.

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III. RESULTS AND DISCUSSION

A. Effect of Injection Angle, Compression Ratio and Blend at Full Load

Baseline diesel gave a maximum BTE of 32.21% at full load (12 kg). K20 reached 31.69% at 21° bTDC and CR 17, and K30 reached 30.75% at 21° and CR 18, which is 1.46 percentage points below diesel and 0.94 below K20; K30 at 19° and CR 18 was 1.81 points below diesel (Fig. 2a). The BSFC of diesel was 0.27 kg/kWh, against 0.28 kg/kWh (about 3.5% higher) for K30 at 19° and 21° with CR 18, and 0.27 kg/kWh for K20 at 21° and CR 17. EGT was lowest at 19° and CR 18, where it was 2.6% (K20) and 3.28% (K30) above diesel. CO2 of K30 at 19° and CR 18 was 18% higher than diesel, indicating more complete oxidation of carbon, and exhaust O2 was highest at 21° for all blends.

NOx was lowest (810 ppm) for K30 at 23° and CR 16, and K20 and K30 at 23° with CR 16 and 17 gave about 35% lower NOx than diesel; K30 at 19° and 23° with CR 18 gave about 12% lower (Fig. 2b). CO of K30 at 21° and CR 18 was 0.071% by volume, 38% below diesel (Fig. 2c), and HC of K30 at 19° and CR 18 was 75% below diesel, or 68% at 21° and CR 18 (Fig. 2d). The oxygen carried by biodiesel and ethanol promotes complete combustion and so lowers CO and HC, while the high latent heat of vaporisation of ethanol is generally credited with cooling the charge and limiting thermal NOx. Injection at 19°–21° bTDC with CR 18 gave the best balance, at a BTE penalty of only 1.4–1.8 points.

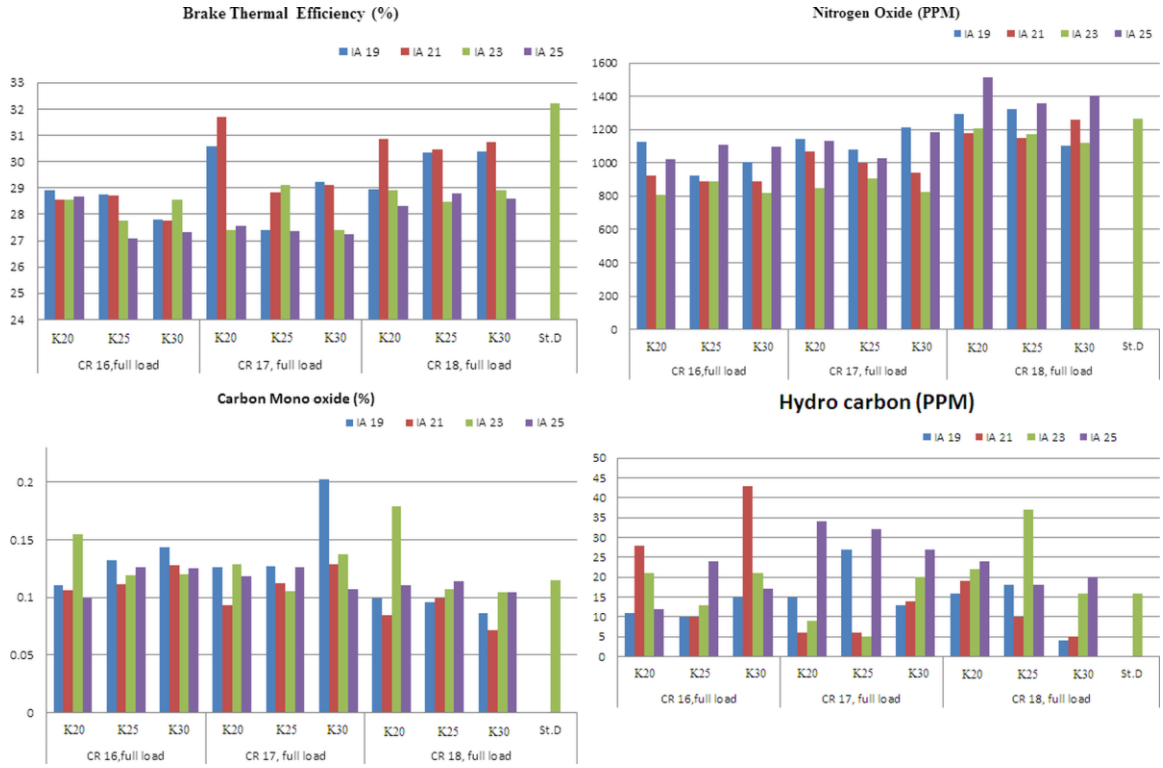


Fig. 2. Effect of injection angle (IA), compression ratio and blend at full load: (a) BTE, (b) NOx, (c) CO, (d) HC. St.D is baseline diesel.

B. Statistical Analysis and Optimisation

In the confirmation test the deviation between predicted and measured BTE, BSFC, EGT, CO2, CO and NOx was within 10%, while HC deviated by 50%, probably because of its very low absolute level (4–16 ppm, Fig. 4d). One-way ANOVA showed that load, compression ratio and injection angle are the significant parameters, in decreasing order of contribution. GRA gave the optimum combination of 19° bTDC, CR 18, K20 and 50% load, but K20 and K30 had almost the same grey grade. Both were therefore compared with baseline diesel at 19° and CR 18 for all loads in the following sections.

C. Performance at the Optimum Setting

BTE rose with load for all fuels (Fig. 3a). At full load diesel gave 32.21% and K30 gave 30.4%, about 2 percentage points lower, and K20 was equal to or slightly below K30. The lower calorific value of the blends (Table I) explains the small loss, which their oxygen content partly offsets. BSFC fell with load (Fig. 3b); K20, K30 and diesel were equal at 75% load, and K30 was about 3% above diesel at full load. EGT increased with load (Fig. 3c) and was up to 3% higher for the blends at full load.

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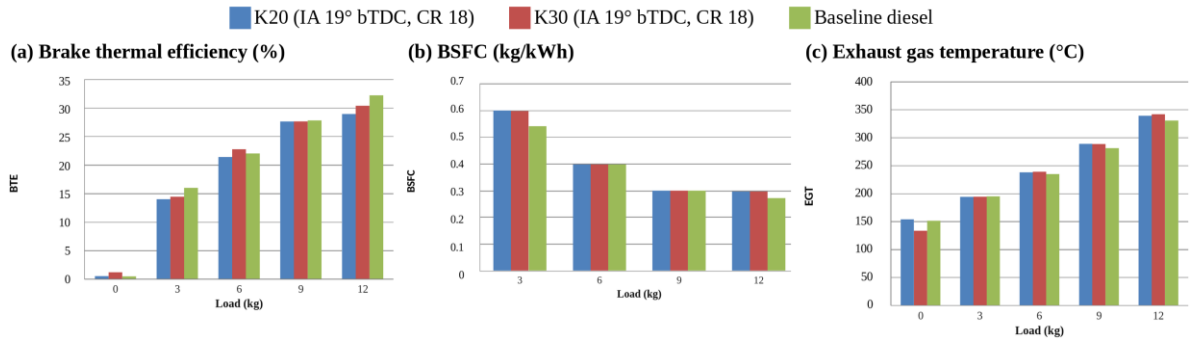


Fig. 3. Performance at the optimum setting (IA 19° bTDC, CR 18) versus load: (a) BTE, (b) BSFC, (c) EGT.

D. Emission Characteristics

CO2 rose with load; at full load K20 and K30 were 0.34 and 0.86 percentage points above diesel, and K30 exceeded K20 at all loads except zero load (Fig. 4a). NOx of K30 was about 8% lower than diesel at full load and lower at every load except 75% (9 kg); NOx increased up to 75% load and then fell at full load (Fig. 4b). CO rose steeply between 75% and 100% load, and at full load it was 0.029% by volume lower for K30 than for diesel (Fig. 4c). HC at full load was 12 ppm lower for K30 than for diesel; HC increased with load for K20 and diesel but decreased for K30 (Fig. 4d, where the lines are linear trend lines).

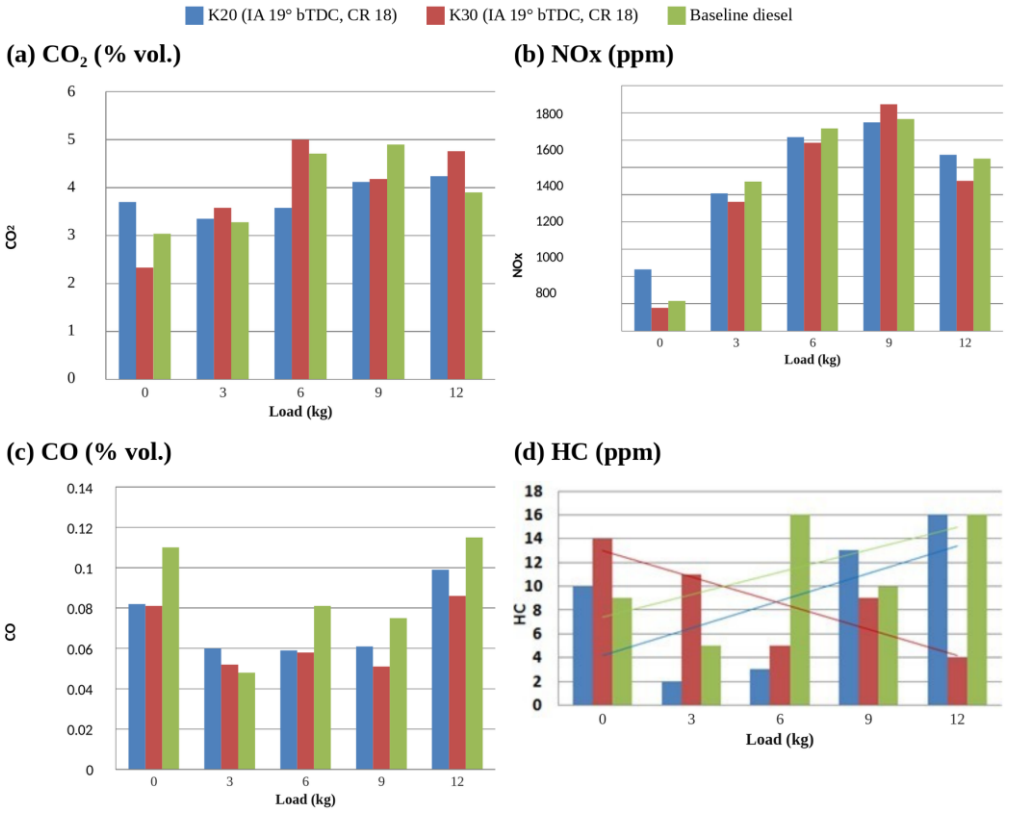


Fig. 4. Emissions at the optimum setting (IA 19° bTDC, CR 18) versus load: (a) CO_2, (b) NOx, (c) CO, (d) HC.

E. Combustion Characteristics

Table IV compares the combustion parameters at full load. Peak pressure was practically the same for K30, K20 and diesel, at 366° crank angle, and combustion started at −15° for all fuels. Because the blends were injected at 19° bTDC and diesel at its standard 23° bTDC, the ignition delay was 4° CA for the blends and 8° CA for diesel, and combustion ended 1–2° earlier for the blends. The maximum rate of pressure rise and net heat release rate were almost identical and both peaked at 352° CA, so the blends did not make combustion harsher.

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TABLE IV
COMBUSTION PARAMETERS AT FULL LOAD

Parameter	K20	K30	Diesel
Peak pressure (bar)	68.94	68.54	68.79
Crank angle at peak pressure (°)	366	366	366
Start of combustion (°)	−15	−15	−15
End of combustion (°)	31	30	32
Combustion duration (°)	46	45	47
Injection angle (° bTDC)	19	19	23
Ignition delay (° CA)	4	4	8
Max. rate of pressure rise (bar/°)	6.28	6.35	6.35
Max. net heat release rate (J/°)	55.95	56.79	56.53

Blends at IA 19° bTDC and CR 18; both rate peaks occur at 352° CA.

F. ANN Prediction of Engine Responses

The ANN used a multilayer feed-forward network with back-propagation training and log-sigmoid activation, with four input nodes and one output node. Its predictions agreed with the experimental data to within 10%, so the model can estimate BTE, BSFC, EGT and emissions at input combinations that were not tested.

IV. CONCLUSION

Karanja biodiesel–diesel–ethanol blends K20, K25 and K30 were clear and stable with no phase separation; Karanja is a non-edible, locally available feedstock suited to blending at about 20%. A Taguchi L9 design with ANOVA showed that load, compression ratio and injection angle are the significant parameters, in decreasing order. GRA gave an optimum of 19° bTDC, CR 18, K20 and 50% load, with K20 and K30 almost equal in grey grade. At 19° bTDC and CR 18, K30 gave a full-load BTE of 30.4% against 32.21% for diesel, about 3% higher BSFC and up to 3% higher EGT. At full load K30 reduced NOx by about 8%, CO by 0.029% by volume and HC by 12 ppm relative to diesel; parametric runs showed reductions of up to 35% in NOx, 38% in CO and 75% in HC at suitable settings. CO2 was 0.86 percentage points higher, indicating more complete combustion. Peak pressure, rate of pressure rise and net heat release rate were within about 1% of diesel, with a shorter combustion duration. The ANN predicted the responses within 10% of the measured values, and the test results support the direct use of K30 in the engine. Long-duration durability tests and smoke or particulate measurements are suggested as future work.

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REFERENCES

[1] A. B. Avagyan and B. Singh, “Biodiesel: Feedstocks, technologies, economics and barriers,” in *Assessment of Environmental Impact in Producing and Using Chains*, 2019.
[2] A. Ashfaque *et al.*, “Impact of biodiesel on engine performance and emission,” *Mater. Today Proc.*, 2023.
[3] B. Amigun, R. Sigamoney, and H. von Blottnitz, “Commercialisation of biofuel industry in Africa: A review,” *Renew. Sustain. Energy Rev.*, vol. 12, no. 3, pp. 690–711, 2008.
[4] A. E. Atabani, A. S. Silitonga, H. C. Ong, T. M. I. Mahlia, H. H. Masjuki, I. A. Badruddin, and H. Fayaz, “Non-edible vegetable oils: A critical evaluation of oil extraction, fatty acid compositions, biodiesel production, characteristics, engine performance and emissions production,” *Renew. Sustain. Energy Rev.*, vol. 18, pp. 211–245, 2013.
[5] M. Anwar, M. G. Rasul, and N. Ashwath, “The efficacy of multiple-criteria design matrix for biodiesel feedstock selection,” *Energy Convers. Manag.*, vol. 198, Art. no. 111790, 2019.

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DOI: 10.17148/IARJSET.2026.131069

[6] A. Abdulvahitoglu and M. Kilic, "A new approach for selecting the most suitable oilseed for biodiesel production; the integrated AHP-TOPSIS method," *Ain Shams Eng. J.*, vol. 13, no. 3, Art. no. 101604, 2022.

[7] A. T. Hoang and A. T. Le, "A review on deposit formation in the injector of diesel engines running on biodiesel," *Energy Sources A, Recovery Util. Environ. Eff.*, vol. 41, no. 5, pp. 584–599, 2019.

[8] A. T. Hoang, M. Tabatabaei, and M. Aghbashlo, "A review of the effect of biodiesel on the corrosion behavior of metals/alloys in diesel engines," *Energy Sources A, Recovery Util. Environ. Eff.*, pp. 1–21, 2019.

[9] B. S. Chauhan, N. Kumar, and H. M. Cho, "A study on the performance and emission of a diesel engine fueled with Jatropha biodiesel oil and its blends," *Energy*, vol. 37, no. 1, pp. 616–622, 2012.

[10] R. A. Candeia *et al.*, "Influence of soybean biodiesel content on basic properties of biodiesel-diesel blends," *Fuel*, vol. 88, no. 4, pp. 738–743, 2009.

[11] Ö. Can, E. Öztürk, H. Solmaz, F. Aksoy, C. Çinar, and H. S. Yücesu, "Combined effects of soybean biodiesel fuel addition and EGR application on the combustion and exhaust emissions in a diesel engine," *Appl. Therm. Eng.*, vol. 95, pp. 115–124, 2016.

[12] A. K. Azad, P. Halder, Q. Wu, M. G. Rasul, N. M. S. Hassan, and V. Karthickeyan, "Experimental investigation of ternary biodiesel blends combustion in a diesel engine to reduce emissions," *Energy Convers. Manag. X*, vol. 20, Art. no. 100499, 2023.

[13] S. Bhowmik, A. Paul, R. Panua, and S. K. Ghosh, "Performance, combustion and emission characteristics of a diesel engine fueled with diesel-kerosene-ethanol: A multi-objective optimization study," *Energy*, vol. 211, Art. no. 118305, 2020.

[14] C. S. Aalam, C. G. Saravanan, and M. Kannan, "Experimental investigations on a CRDI system assisted diesel engine fuelled with aluminium oxide nanoparticles blended biodiesel," *Alexandria Eng. J.*, vol. 54, no. 3, pp. 351–358, 2015.

[15] H. H. Al-Kayiem, H. A. A. Wahhab, E. Magaril, and A. R. A. Aziz, "Performance and emissions investigation of a single cylinder diesel engine using enhanced blend biodiesel by nanoparticles," in *AIP Conf. Proc.*, vol. 2035, no. 1, Art. no. 020008, 2018.

[16] A. M. Ansari, L. A. Memon, M. T. Ghannam, and M. Y. Selim, "Impact of biodiesel blended fuel with nanoparticles on performance and noise emission in compression ignition engine," *Int. J. Thermofluids*, vol. 19, Art. no. 100390, 2023.

[17] R. Bharathiraja, K. S. Amirthagadeswaran, N. Praveenkumar, D. S. Periyasamy, and K. R. Babu, "Study on characteristics of CI engine using nano additive blended diesel fuel," *Int. J. Appl. Eng. Res.*, vol. 10, no. 67, pp. 328–334, 2015.

[18] K. Andiyappan and S. Ramalingam, "Intensification of bio-synthesis of zirconium oxide (ZrO_2) nanoparticles derived from novel Crescentia cujete fruits: Effects on diesel engine characteristics powered by waste engine oil methyl ester-diesel blend," *Chem. Eng. Process.: Process Intensif.*, vol. 195, Art. no. 109642, 2024.

[19] S. O. Bitire and T.-C. Jen, "The role of a novel green synthesized nanoparticles added parsley biodiesel blend on the performance-emission characteristics of a diesel engine," *S. Afr. J. Chem. Eng.*, vol. 41, no. 1, pp. 161–175, 2022.

[20] E. Bet-Moushoul, K. Farhadi, Y. Mansourpanah, A. M. Nikbakht, R. Molaei, and M. Forough, "Application of CaO-based/Au nanoparticles as heterogeneous nanocatalysts in biodiesel production," *Fuel*, vol. 164, pp. 119–127, 2016.

[21] M. M. Ahmed, H. S. Pali, and M. M. Khan, "Feasibility of nanoparticles fused in biodiesel for CI engines: An integrated and historic review," *J. Therm. Anal. Calorim.*, vol. 149, no. 11, pp. 5091–5123, 2024.

[22] A. F. Alhikami, C.-E. Yao, and W.-C. Wang, "A study of the spray ignition characteristics of hydro-processed renewable diesel, petroleum diesel, and biodiesel using a constant volume combustion chamber," *Combust. Flame*, vol. 223, pp. 55–64, 2021.

[23] C. Aseibichin *et al.*, "Modeling and optimization of transesterification of Jatropha oil to fatty acid methyl ester: Application of response surface methodology (CCD) and Taguchi orthogonal method," *RSC Adv.*, vol. 14, no. 17, pp. 11784–11796, 2024.

[24] ASTM International, *Standard Specification for Biodiesel Fuel Blend Stock (B100) for Middle Distillate Fuels*, ASTM D6751-20, West Conshohocken, PA, USA, 2020.

[25] Bureau of Indian Standards, *Biodiesel (B100) – Fatty Acid Methyl Esters (FAME) – Specification (Second Revision)*, IS 15607:2022, New Delhi, India, 2022.

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