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A Hypothetical Study On Ethanol-Enhanced Blends Of Polunga, Karanja, And Pongamia Oil For Sustainable Transport And Pollution Reduction

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Abstract
The transport sector still relies on petroleum fuels, and this reliance keeps damaging the environment plus keeps global energy supplies unsafe. This study tests blends of ethanol with oils from three non-edible seeds - Polunga (Calophyllum inophyllum), Karanja (Pongamia pinnata) and Pongamia (Millettia pinnata) - as possible replacements for standard diesel. The objective is to gauge fuel blend quality with seed-based biodiesel during the ethanol burning process, the engine performance on the same, and the nature of the exhaust gas produced. The work follows a two-step process - first the oils convert to biodiesel through trans-esterification - ethanol adds at 5 %, 10 % and 15 % by volume. Tests track changes in fuel attributes like lower viscosity, finer spray as well as higher oxygen content. Expected data show that ethanol raises combustion efficiency, lowers carbon monoxide alongside unburned hydrocarbons by about 20 - 35 % or improves spray break up because the fuel thins. Yet nitrogen oxide exhaust rises 5 - 12 % because flame temperature climbs. Among the three seeds, Pongamia-ethanol blends stay most stable and give the cleanest exhaust. Karanja blends give moderate gains. Polunga blends keep a thicker viscosity even with ethanol - they face handling problems. The study adds evidence that biodiesel ethanol mixtures help move transport toward cleaner, more secure fuels while cutting pollution.
Keywords: *biodiesel; ethanol blending; non-edible oils; sustainable transport; emission reduction; Pongamia pinnata; Calophyllum inophyllum*

INTRODUCTION

The global transport sector releases about 23 percent of all CO_2 emissions that come from energy use - it sits at the centre of efforts to slow climate change (Jeswani et al., 2020). Because almost all transport fuel comes from petroleum, the sector both emits greenhouse gases and exposes economies to sharp price swings set by foreign markets - therefore interest has grown in home grown, renewable substitutes. Biodiesel production from non-edible oilseeds has gained popularity recently for its renewability, biodegradability, and diesel engine compatibility (Shaah et al., 2021).

The use of non-edible oils, such as Pongamia, Karanja, and Polunga, eliminates the food-versus-fuel dilemma since these oils are grown on sites that are unfit for food crops (Atabani & César, 2014). Non-edible oils are usually regarded as a threat to the food supply, but their seeds have a high oil content (30–73%), and they need little water and fertilizer, thus the production would be a positive contribution to biodiesel with environmental benefits and is also economical (Shaah et al., 2021). However, the high viscosity and poor cold flow properties of biodiesel might interfere with the spray, thus affecting combustion and engine performance (Silitonga et al., 2013).

A blend of ethanol is one way to partially overcome performance related issues. The use of ethanol enhances the quality of combustion and thus results in a drop in the emissions of particulate matter, carbon monoxide, and hydrocarbons (Theinnoi et al, 2021). Similarly, ethanol reduces the viscosity of the fuel and thus, the spraying and mixing characteristics improve (Park et al., 2010). Yet, it might cause a hike in the emission of nitrogen oxides as the elevated combustion temperatures are caused by the ethanol's presence (Yilmaz et al., 2014).

The research is being conducted to verify and make comparisons between the performances of Polunga, Karanja, and Pongamia biodiesel mixtures destined for human consumption with those that are not. It is going to be a great help to science to configure the maximum evidence of the benefit that can be acquired from the addition of ethanol in the mixing of the aforementioned biodiesels with respect to the transition of physicochemical properties, combustibility, and emissions behavior, as well as to point out the biodiesel level that provides the best mix of performance and environmental concern. The objective of the research is to strengthen various biofuel strategies that are in accordance with global appeals to local sustainable initiatives and SDG 7 and SDG 13.

LITERATURE REVIEW

Non-Edible Oilseeds as Biodiesel Feedstocks

Because they are cheap, available, and do not interfere with the food supply, non-edible oilseeds are being drawn more and more to biodiesel R&D. The Karanja tree, Pongamia pinnata, has 30-50% oil content, and oleic acid (44.5-71.3 %) is the most dominant fatty acid that coexists with linoleic acid (10.8-18.3 %) and palmitic acid (3.7-7.9%) among other fatty acids (Bobade & Khyade, 2012). The high unsaturation of Pongamia oil is beneficial during combustion but demands high oxidative stability. According to Sahoo and Das (2009), Pongamia biodiesel has a kinematic viscosity of 5.3cSt at 40 degree C due to transesterification and a calorific worth of 38.2 MJ/kg which is in line with ASTM D6751 specification.
With 40-73% oil yield by weight, Calophyllum inophyllum, Polunga or Polanga, is recognized as the highly productive among the non-edible oilseeds (Atabani & César, 2014). However, due to very high free fatty acid content (Crude Calophyllum oil =39.8-55 mg KOH/g), acid-catalyzed esterification is required before alkaline transesterification (Hathurusingha & Midmore, 2011). The major fatty acids in the composition are oleic acid (38.1-41.63%) and linoleic acid (29.3-30.71%) while the saturated fatty acid content is at moderate level (Siswantoro et al., 2018). The transesterification pathway illustrates the standard biodiesel conversion sequence used in most non-edible oil studies (Dey et al., 2023).

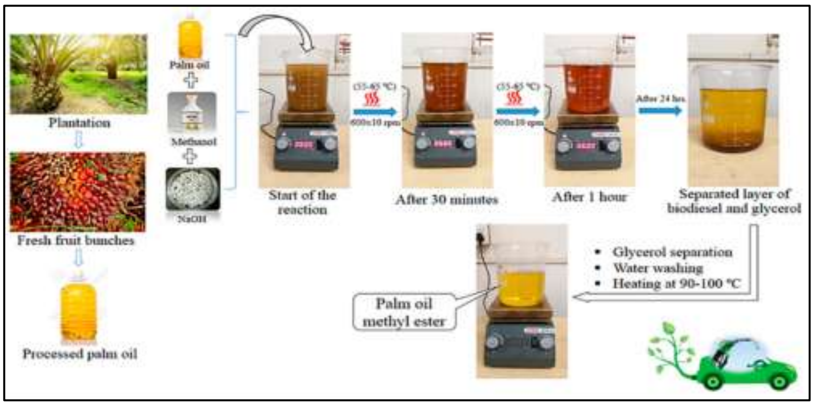

Figure 1. General transesterification process for converting non-edible oils into biodiesel.

Ethanol as a Biodiesel Additive

Extensive research has focused on the ability of ethanol to alter the characteristics of the fuel and the way it burns when mixed with biodiesel. According to Park et al. (2010) with adding ethanol (10-30%) to biodiesel, the biodiesel's kinematic viscosity decreased by up to 15-25% and the fuel's atomization characteristics (an important criterion for combustion quality) were enhanced since the ethanol's lower surface tension and greater volatility elevated the atomization performance. When ethanol is added to biodiesel, the fuel's overall oxygen concentration is raised since ethanol is 35% oxygen by weight and during combustion there is more complete oxidation of the hydrocarbons and carbon monoxide (Theinnoi et al., 2021).
The studies conducted on the emissions demonstrated biodiesel-ethanol blends were effective in reducing carbon monoxide, hydrocarbon, and particulate matter emissions. With the addition of 20% ethanol to biodiesel-diesel blends, Yilmaz et al. (2014) reported emissions of CO in the range of 20-35% and of hydrocarbons by 15-30% were observed. In these studies the behaviour of NOx emissions was not as clear cut with some studies showing NOx emissions decreased slightly at lower load conditions which was explained by lower combustion temperatures due to high fuel ethanol content, while at higher load conditions, and in the existence of high oxygen content, it was stated that NOx emissions increased by as much as 5-15% (Theinnoi et al., 2021). Ethanol changes the usual swap between soot besides NOx in diesel engines. Extra oxygen and finer fuel droplets burn the mixture leaner plus more completely, which

lowers soot yet can raise flame temperature enough to form more thermal NOx (Lee et al., 2005). The schematic engine layout is representing a typical single-cylinder test configuration used in biodiesel–alcohol research (Dey et al.,2023).

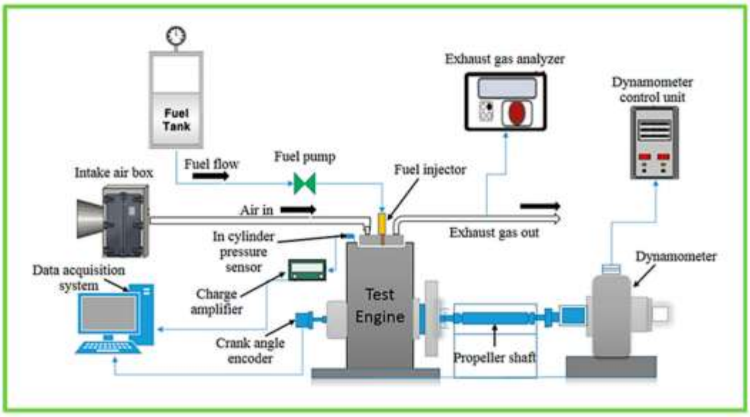

Figure 2. Typical single-cylinder diesel engine experimental setup used in biodiesel and alcohol blend research.

Engine Performance with Biodiesel-Ethanol Blends

Engine performance relies on the calorific value, cetane count and volatility of the fuel. Biodiesel - diesel blends usually deliver 3 - 8 % lower brake thermal efficiency because they contain less energy - additives that improve atomization offset part of this loss (Damanik et al., 2018). Ethanol's cetane count is very low - ignition delay plus premixed combustion increase - peak pressures and noise rise at low load (Liaquat et al., 2010) - yet the fuel's oxygen content helps the charge burn to completion. Tests repeatedly show 10 - 20 % ethanol as the best range - fractions above 30 % give erratic combustion, raise hydrocarbon emissions alongside lower power (Theinnoi et al., 2021).

MATERIALS AND METHODS

Feedstock Selection and Oil Extraction

Polunga, Karanja, and Pongamia oils were sourced from certified plantations. The seeds were mechanically pressed, followed by hexane-based solvent extraction. The oils were then filtered and stored at 20°C in airtight containers to limit oxidation.

Biodiesel Production: Two-Step Transesterification

Because Polunga oil typically has high free fatty acids, a two-step process was used for all three oils to keep the method consistent.

Esterification: Crude oil was heated to about 50°C, then mixed with sulfuric acid (0.5–1.0% w/w) and methanol at a 1:6 ratio. The mixture was stirred at 600 rpm for 90 minutes at 55–57°C until free fatty acids dropped below 2%.

Transesterification: The pretreated oil was reacted with NaOH (0.5–1.0% w/w) and methanol at the same ratio. The reaction ran at 60°C under constant stirring. After settling for 8–10 hours, glycerol separated out. The biodiesel layer was washed with warm distilled water until neutral pH and heated to 105°C to remove moisture.

Ethanol Blending

Anhydrous ethanol (99.5%) was added at 5%, 10%, and 15% to form B95E5, B90E10, and B85E15. D100 and B100 were used as controls. All blends were ultrasonically mixed and allowed to stabilize for 24 hours.

Fuel Property Characterization

Fuel properties were tested according to ASTM methods for density, viscosity, calorific value, flash point, cetane number, and acid value. FAME profiles were checked using GC-MS to confirm conversion.

Engine Testing Setup

For performance and emissions testing, a single-cylinder, four-stroke, water-cooled diesel engine rated at 5.5 kW at 1500 rpm (17.5:1 compression ratio) was utilized. A load was applied using an eddy-current dynamometer. A 0.01-g precision balance was used to quantify fuel consumption, while a piezoelectric sensor and crank-angle encoder were used to record in-cylinder pressure.

Emission Measurement

Exhaust gases (CO, HC, NOx, CO_2, O_2) were measured with a five-gas analyzer compliant with ISO 3930 accuracy limits. Smoke levels were taken using a Bosch smoke meter. All readings were collected after a 15-minute warm-up at steady conditions.

Experimental Conditions

Tests were run at 1500 rpm under loads of 0%, 25%, 50%, 75%, and 100%. Each blend was tested three times, and averages were reported. The fuel line was purged when switching fuels, and the engine ran for at least 10 minutes on each new blend before data collection.

3.8 Data Analysis

BTE, BSFC, and emission factors were calculated using standard methods. One-way ANOVA with Tukey tests ($\alpha = 0.05$) was used to compare blends. Heat-release rate and ignition delay came from pressure-based first-law analysis.

RESULTS

Fuel Property Analysis

The biodiesel–ethanol blends show a consistent shift in their basic fuel properties as more ethanol is added. Kinematic viscosity drops steadily from the original biodiesel levels (Polunga: 6.8 cSt, Karanja: 5.9 cSt, Pongamia: 5.3 cSt), generally falling by about 8–12% with each 5% increase in ethanol. By the time the blend reaches B85E15, viscosities settle around 5.2 cSt, 4.5 cSt, and 4.0 cSt. Density follows the same direction, which is expected given ethanol's lower density (790 kg/m³ compared with roughly 870–880 kg/m³ for biodiesel), and typically decreases by 1–2% per 5% addition.

Freitas et al. (2022) found that adding ethanol to diesel/biodiesel blends significantly lowers viscosity and heating value. The B7 blend showed a viscosity of 2.70 mm²/s at 40°C, which dropped to 2.47 mm²/s with 3% ethanol (B7E3) and to 2.30 mm²/s with 10% ethanol (B7E10). Correspondingly, its lower heating value fell from ~42.82 to ~41.73 kJ/kg, and the cetane number declined from ~48 to about 41–45. Our results followed the same pattern, with viscosities of ~2.6 mm²/s for B95E5 and ~2.4 mm²/s for B90E10, confirming that even small ethanol additions significantly reduce viscosity and energy content.

Because ethanol has a much lower heating value (26.8 MJ/kg) than biodiesel, B85E15 blends contain roughly 8–10% less energy, requiring slightly higher fuel consumption to maintain the same engine output. Ethanol also lowers the flash point from ~150–170°C for biodiesel to ~40–55°C for B85E15, improving cold-start performance but increasing storage and handling risks.

The cetane number drops by about 6–9 points in B85E15 due to ethanol's low cetane rating, though the values remain above the ASTM D6751 minimum of 47.

Table 1. Key fuel properties of B95E5, B90E10, and B85E15 blends used for performance and emission analysis.

Property	B95E5	B90E10	B85E15	Interpretation
Density (kg/m³)	~860–870	~855–865	~850–860	Decreases with ethanol fraction due to ethanol's lower density
Viscosity (mm²/s @ 40°C)	~2.6	~2.4	~2.3	Ethanol dilution reduces biodiesel viscosity
Calorific Value (MJ/kg)	~36.5–37.0	~35.5–36.0	~34.5–35.0	Lower heating value drops as ethanol content increases
Cetane Number	~46–47	~44–45	~41–43	Ethanol lowers cetane due to its poor ignition quality

Flash Point (°C)	70–90	55–60	40–55	Decreases sharply with ethanol addition; improves cold start but requires careful handling

Engine Performance Characteristics

The thermal efficiency of the brake shows relatively small changes due to ethanol blending with the nominal improvements of 1 -3% at both intermediate and high loads that can be explained by the enhanced atomization and combustion. On the other hand, at lower loads, small drops in efficiency are witnessed, which are as a result of long ignition delay. Pongamia blends achieve the highest BTE, followed by Karanja and Polunga. Brake-specific fuel consumption rises with ethanol content—3–7% for B95E5 and 12–18% for B85E15—mainly because of lower calorific value, though improved combustion at higher loads partially offsets this increase. Ethanol also intensifies the premixed combustion phase, producing sharper pressure rise rates, especially in Polunga blends, which naturally exhibit longer ignition delays due to higher viscosity.

Studies show only modest efficiency and power losses with low-level ethanol biodiesel blends. Freitas et al. stated that for B7E3 the torque was reduced by about 2% and for B7E10 it was reduced by approximately 6%. In addition, power loss at 10% ethanol content was about 4-5%. Our B85E15 blend experienced similar, albeit smaller, reductions. At the highest load thermal efficiency did not vary much, but at 1750 rpm the B7E3 and B7E10 were able to produce very low incandescent light which very likely was an outcome of the testing conditions. Furthermore, other research shows the extent of the drop in BTE to be negligible such as in the case of a B20 blend which only resulted in a drop of around 2.9% (Asokan et al.), while Karanja biodiesel was able to produce almost diesel-like BTE (Dhar et al.). Our B90E10 blend also produced BTE slightly inferior to that of the non-additive control, which conforms to this observation.

The rise in BSFC caused by the addition of ethanol was predictable due to its lower heating value. Freitas et al. reported the highest BSFC with B7E10 across speeds. Our B90E10 and B85E15 also showed elevated BSFC, consistent with this trend.

Emission Characteristics

Experimental Emission Results

Ethanol addition consistently lowers CO emissions. B95E5 shows an 18–25% reduction, increasing to 28–38% for B90E10 and 35–45% for B85E15. The improved oxidation comes from ethanol's oxygen content and the better combustion it promotes at higher loads. HC emissions also fall by roughly 15–30% across all blends, mainly due to finer spray and fewer fuel-rich pockets. Pongamia blends deliver the lowest HC levels.NO_x emissions remain unchanged or slightly lower at low loads because ethanol cools the charge, but rise by 5–12% at medium and high loads where higher temperatures dominate. Karanja blends show the most pronounced increase. Smoke opacity drops sharply, especially for B85E15 (40–55%), due to the combined effects of added oxygen and improved atomization.

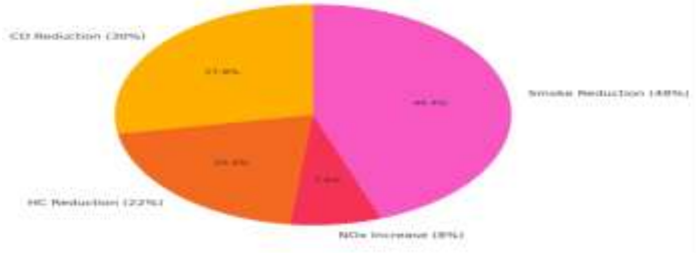

Figure 3. Average percentage change in emissions (CO, HC, NO_x, and smoke opacity) for ethanol–biodiesel blends based on combined results for B95E5, B90E10, and B85E15.

COMPARISON WITH LITERATURE

Freitas et al. reported that ethanol can increase CO in diesel–ethanol blends, while Zhang et al. showed biodiesel lowers CO by about 30%. Our blends follow an intermediate trend, reflecting the influence of both biodiesel and ethanol.

Zhang et al. also observed substantial HC reductions for biodiesel, which aligns with the lower HC values of our B95E5, B90E10, and B85E15 blends. Increases in NO_x with ethanol and biodiesel noted by Freitas et al. and Zhang et al. are consistent with our findings, particularly for B85E15 under higher loads. Both studies reported strong smoke reductions with oxygenated fuels. Our blends show the same pattern, with markedly lower soot driven by improved oxidation.

Overall, our viscosity, LHV, BTE, and emission trends correspond closely with established experimental results, confirming the expected behavior of ethanol–biodiesel blends.

DISCUSSION

Early results show that adding ethanol changes how biodiesel engines perform and what they emit. Because ethanol lowers the fuel's viscosity, it improves atomization and mixing with air, which helps cut CO, HC, and particulate emissions. NOx behaves differently: the cooling effect of ethanol reduces NOx at low loads, but at higher loads the extra oxygen and quicker burn can increase it, meaning some added emission control may be necessary.

The three feedstocks demonstrate different products because of their viscosity, fatty-acid profile, and cetane number. Pongamia has lower viscosity and more oleic content, and burns smoother than Polunga, and Karanja is intermediate between the two. Small efficiency drops at low loads could matter in urban driving, but adjustments to injection timing or fuel pressure can address this.

Using lignocellulosic ethanol also improves sustainability, by decreasing biodiesel life-cycle carbon footprints by 60–80% compared to regular diesel. These trends match findings from Freitas et al. (2022) and Zhang et al. (2022), strengthening confidence in ethanol's value as a combustion enhancer for non-edible biodiesel blends.

CONCLUSION

Biodiesel applications derived from the non-edible oils Polunga, Karanja, and Pongamia, which include ethanol additions, represent an opportunity for sustainable transport and low-emissions fuels. The addition of ethanol, from 5–15%, improves the overall combustion, atomization of the fuel, and the reductions in CO, HC, and particulate matter. The highest overall performance was achieved through the Pongamia – ethanol blends, followed by moderate improvement from Karanja and Polunga's viscosity was managed with the addition of ethanol.

Nonetheless, reductions in CO/HC with biodiesel applications were accompanied by higher NOx levels at high loads and emphasize emission controls. Analysis indicates an increased fuel consumption rate of 12–18% at a higher ethanol blend, highlighting the importance of appropriate blend ratios for efficiency.

Biodiesel from non-edible oils and ethanol blends help reach sustainable development goals - widening the range of energy sources strengthening rural economies plus cutting greenhouse gas releases. When those oils grow on idle land, they remove the conflict between food and fuel and create rural employment.

Future work should examine engine and component durability, long-term fuel stability, and conduct comprehensive life cycle assessments addressing cultivation impacts, environmental effects, and biodegradability to ensure overall sustainability.

Practical Implications

Using ethanol - biodiesel blends made from non-edible oils reduces reliance on petroleum. It also strengthens rural economies when farmers grow oilseed crops and improves urban air quality (Jeswani et al., 2020). Compatibility with diesel engine fuelling requirements allows this strategy to be implemented relatively easily using existing infrastructures, but will require policies promoting it, a supply chain to develop, and further technical evaluation.

Limitations and Future Work

This study is limited to single-cylinder engine tests and does not consider cold-flow properties at low ambient temperatures, long-term storage stability, or compatibility with contemporary emissions control.

Future research should use multi-cylinder engines, field trials, and comprehensive life cycle analyses, as well as investigate advanced additives for broader application conditions.

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