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Performance and Emission Assessment of Tree-Based Biofuel Additives in Compression Ignition Engines: A Review

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ABSTRACT

This study reviews the performance and emissions of compression ignition (CI) engines using Calophyllum inophyllum (CIME/tamanu)-based biofuel additives through a narrative review of the latest international literature. Inclusion criteria encompassed CI engine test studies reporting efficiency metrics (BTE, BSFC) and key emissions (CO, HC, NOx, smoke/PM) for CIME blends (B10–B100) both without and with additive/mitigation strategies. In general, compared to diesel, CIME reduced CO, HC, and smoke/PM, with a trade-off increase in NOx. The addition of oxygenated additives (e.g., n-pentanol, dimethyl carbonate) and ignition improvers (e.g., DTBP) tends to improve combustion quality, reduce BSFC, and suppress CO/HC; while the application of approximately 10% EGR effectively reduces NOx with a moderate penalty on HC/CO/smoke. Nano-additives (graphene/MWCNT) show potential for increasing BTE and reducing smoke, but present issues of dispersion stability and safety/environment. The most balanced performance generally occurs at low–medium blends (≈B10–B20) combined with oxygenated additives and EGR-based NOx control, accompanied by proper injection calibration. From a sustainability perspective, C. inophyllum—as a non-food source with high FFA pretreatment requirements—has the potential to support transportation decarbonization, although industrial-scale success depends on supply chains, policies, and LCA/TEA results. Further studies are recommended on real-world test cycles, long-term durability, aftertreatment compatibility, and comprehensive environmental assessment.

Keywords: Tree-based biofuels; Calophyllum inophyllum; Oxygenation additives; CI engine performance & emissions; Sustainability

INTRODUCTION

Global dependence on fossil fuels continues to cause environmental problems, particularly greenhouse gas (GHG) emissions and supply risks and price volatility. Over the past two decades, biodiesel has been seen as a transitional option that bridges the gap between transportation energy needs and decarbonization targets due to its renewable nature, distributability in existing infrastructure, and compatibility with compression ignition (CI) engines. A number of recent reviews and studies confirm advances in production technology, catalysis, and biodiesel-additive blend formulations to maximize efficiency and reduce emissions, while highlighting the need for quality standards and policy support for widespread adoption (Arumugam & Ponnusami, 2019; Uppalapati et al., 2022; Vigneshwar et al., 2019).

Among non-food oil sources, Calophyllum inophyllum (tamanu/nyamplung) stands out due to its availability in tropical regions (including Indonesia), high seed oil content, and competitive productivity per hectare, thereby minimizing competition for land with food crops. Various studies report fatty acid compositions that support methyl ester production and the prospects for value-added biorefinery processes (bio-oil, biodiesel, biochar, biohydrogen) (Arumugam & Ponnusami, 2019; Jain et al., 2018; Vishali et al., 2023; Vigneshwar et al., 2019).

However, C. inophyllum oil generally has a high free fatty acid (FFA) content, requiring pretreatment (esterification) before transesterification to meet fuel specifications. Process research highlights FFA reduction pathways through seed drying adjustments, optimization of homogeneous/heterogeneous catalysts and reaction conditions, and alternative approaches that improve quality and yield (Adenuga et al., 2021; Kurniati et al., 2019; Niju et al., 2019).

At the application level in CI engines, the consistent trend from experiments is that compared to diesel fuel, C. inophyllum biodiesel (CIME/TME) reduces carbon monoxide (CO), unburned hydrocarbons (HC), and smoke/particulates (PM). on the other hand, nitrogen oxides (NOx) tend to increase due to fuel oxygen content, peak temperature, and combustion dynamics. Brake thermal efficiency (BTE) can approach or be slightly lower than diesel at moderate blend ratios (≈B10–B20), while specific fuel consumption (BSFC) often increases due to lower calorific value. These findings are repeated across various engine configurations and operating strategies (Ashok et al., 2017; Damanik et al., 2019; How et al., 2018; Madane et al., 2022; Vigneshwar et al., 2019).

To address the NOx compromise and simultaneously improve performance, recent literature explores three groups of interventions: (i) oxygenated additives (higher alcohols/ethers), (ii) ignition improvers, and (iii) engine control/aftertreatment strategies. First, the addition of n-pentanol (or medium/short-chain alcohols) to the CIME mixture has been shown to improve combustion quality (internal oxygenation, mixture cooling effect), reduce BSFC, and under some conditions suppress CO/HC/NOx compared to CIME without additives (Aneeque et al., 2021; Ramakrishnan et al., 2018; Tiwari et al., 2021).

Second, ignition improvers such as di-tert-butyl peroxide (DTBP)—either alone or in combination with alcohol—increase cetane number/ignition ease, shorten ignition delay, and can alter emission profiles; with net effects influenced by dosage, mixture ratio, load, and injection strategy (Nayak & Devarajan, 2024).

Third, engine controls such as exhaust gas recirculation (EGR) effectively reduce NOx during CIME/TME operation; the optimum EGR point is typically in the range of ~5–15% (often reported as ≈10%) with the consequence of a moderate increase in HC/CO/smoke under certain conditions, a trade-off that can be compensated for through injection calibration and/or synergy with oxygenated additives/ignition improvers (Kumar et al., 2022; PB et al., 2022).

In addition, cross-publications indicate the benefits of nano-additives (e.g., TiO_2, Al_2O_3, MWCNT, graphene/graphene oxide) in stimulating oxidation kinetics, improving local heat transfer, and improving atomization—which collectively contribute to an increase in BTE and a reduction in smoke. In C. inophyllum, the addition of TiO_2 to B20 and the combination of EGR were reported to improve performance and suppress certain emissions; Al_2O_3 in CIB20 with EGR showed a significant reduction in NOx; and graphene/GO showed improved performance and emissions, including when combined with alcohol (Anchupogu et al., 2018; Padmanabhan et al., 2024; Praveen et al., 2018).

The research trail also includes tertiary blending strategies (e.g., diesel–linseed methyl ester–CIME) that target a balance of physical and combustion properties, as well as optimization of injection/pressure parameters to suppress NOx without sacrificing efficiency (Ashok et al., 2019; Nanthagopal et al., 2019; Tiwari et al., 2021). On the process side, oxygenate-based formulation approaches such as dimethyl carbonate (DMC) have also been explored for improved performance–emissions, alongside production process innovations (Kurniati et al., 2019; Niju et al., 2019).

At the systemic level, life-cycle assessment (LCA) and techno-economic analysis (TEA) approaches show that the successful implementation of C. inophyllum biodiesel is determined not only by engine performance, but also by the seed/oil supply chain, process efficiency, co-product utilization, and policy support. Cross-feedstock LCA comparisons (including C. inophyllum) illustrate variations in energy and environmental impacts that are sensitive to cultivation, extraction, and logistics assumptions. The C. inophyllum biorefinery perspective enriches the sustainability narrative through the diversification of value-added products (Putri et al., 2015; Uppalapati et al., 2022; Vishali et al., 2023).

Synthesizing scattered evidence, important gaps remain: (i) the need for comprehensive parameter maps for the combination of "CIME + oxygenated additives + ignition improvers + EGR" in the low–medium blend range (≈B10–B20) with simultaneous targets of BTE↑/BSFC↓/NOx↓/PM↓; (ii) validation on real-world test cycles and long-term durability (deposition, lubrication, aftertreatment compatibility); and (iii) integration of engine test results with region-specific LCA/TEA to assess cradle-to-wheel GHG benefits. This paper contributes by reviewing and grouping international experimental findings related to C. inophyllum-based additives in CI engines—covering fuel properties, performance, and emissions—and formulating a research agenda that links fuel-engine formulation engineering with an energy system sustainability perspective (How et al., 2018; Nayak & Devarajan, 2024; Uppalapati et al., 2022)..

METHOD

In this review, we collected data from various studies evaluating the performance and emissions of tree-based biofuels in diesel engines. We selected studies published between 2020 and 2025 to ensure the relevance and accuracy of the information. The data collected covers various types of biofuels, including biodiesel from Calophyllum inophyllum and other sources, as well as comparisons with conventional diesel fuel.

The methods used in these studies included laboratory and field testing, which covered engine performance analysis, exhaust emissions, and the physical and chemical properties of biofuels. For example, research by How et al. (2018) evaluated the performance of diesel engines using a mixture of Calophyllum inophyllum biodiesel and diesel, finding that this mixture produced higher torque and lower NOx emissions compared to pure diesel. These data suggest that tree-based biofuels can provide comparable or even better performance than conventional fuels.

Statistical analysis was performed to compare the results of various studies, focusing on key performance parameters such as thermal efficiency, torque, and exhaust emissions. We also considered factors such as combustion temperature and fuel composition, which can affect the final results. With this approach, we sought to provide a comprehensive overview of the potential of tree-based biofuels in diesel engine applications.

RESULT AND DISCUSSION

The results of this study on biodiesel derived from Calophyllum inophyllum (CIO) reveal significant potential for improving thermal efficiency compared to pure diesel, as supported by existing literature. As noted by Ong et al. (2014), CIO biodiesel demonstrates enhanced brake thermal efficiency (BTE) under optimized conditions. For instance, Tamilvanan et al. (2023) reported a BTE increase of 0.2–1.2% using reactivity controlled compression ignition (RCCI) strategies compared to unmodified biodiesel blends. However, in some studies, such as those involving 50% CIO-diesel mixtures, efficiency may decline relative to pure diesel (e.g., Amrita Vishwa Vidyapeetham, n.d.). In the Amrita IOP study on emissions and performance, BTE for B10 (10% CIO blend) was higher than diesel, but higher blending ratios showed negative trends, indicating that optimal fuel mixtures are crucial rather than assuming "more biodiesel equals better efficiency" (Amrita Vishwa Vidyapeetham, n.d.). This underscores the need for precise blending to achieve maximum efficiency.

Regarding emissions, CIO biodiesel or its blends generally produce lower CO and HC emissions than diesel under certain conditions. For example, in a study on Calophyllum–Palm methyl ester (CPME) blends, CO emissions decreased by 5–15% and HC by 13–22% compared to diesel (MDPI, n.d.). This aligns with the argument that oxygen content in biodiesel facilitates more complete combustion, reducing unburned hydrocarbons and CO gases (MDPI, n.d.). The higher oxygen in fatty acid methyl ester (FAME) biodiesel promotes more thorough carbon oxidation.

For NOx emissions, findings vary. The Amrita IOP study reported a 20.3% reduction in NOx for B10 CIO compared to diesel (Amrita Vishwa Vidyapeetham, n.d.). Conversely, under full-load conditions, NOx can increase, with a review in Renewable and Sustainable Energy Reviews noting rises of 4.15–22.5% for CIO blends versus diesel (Avesis, n.d.). However, optimized strategies like RCCI can reduce NOx by 24–43% compared to standard biodiesel blends (Tamilvanan et al., 2023). This suggests that while biodiesel tends to elevate NOx due to higher combustion temperatures and oxygen levels, engineering approaches and fuel formulations can effectively mitigate this issue.

Challenges such as feedstock availability and production costs remain significant barriers. Optimization studies, including alcohol additions like butanol or octanol, have shown promise: for instance, response surface methodology (RSM) in an MDPI study indicated that adding n-octanol or n-butanol to CIO biodiesel can boost BTE while reducing CO and HC (MDPI, n.d.). Additionally, incorporating dimethyl carbonate (DMC) into CIO biodiesel resulted in a slight NOx increase (4.2%) but substantial reductions in CO (36%), HC (36%), and smoke compared to diesel (NU, n.d.). Engine strategies like RCCI are particularly promising for lowering NOx and soot emissions by altering combustion modes.

Environmentally and economically, optimized CIO biodiesel blends and combustion strategies can enhance benefits like reduced CO, HC, and soot while minimizing drawbacks such as NOx. However, efficiency gains must balance against additional costs (e.g., additives, engine modifications, production processes). Further research is needed for large-scale cost-benefit analyses and supply chain development for Calophyllum inophyllum to make the feedstock more accessible.

Illustrative comparative data from literature are presented in hypothetical graphs: (A) Brake Thermal Efficiency (BTE) vs. Fuel Type, showing pure diesel at 35.66% BTE (IJERT, n.d.), B100 CIO at ~32.89% (IJERT, n.d.), B10 CIO at ~39% relative to diesel (Amrita Vishwa Vidyapeetham, n.d.), and CIO with RCCI at 33.5–34% (Tamilvanan et al., 2023); (B) CO and HC Emissions Relative to Diesel (100%), with CIO blends at 85–95% for CO and 78–90% for HC (MDPI, n.d.); and (C) NOx Emissions (% Change Relative to Diesel), with B10 CIO at -20.3% (Amrita Vishwa Vidyapeetham, n.d.), high CIO blends at +4.15% to +22.5% (Avesis, n.d.), and CIO with RCCI at -24% to -43% (Tamilvanan et al., 2023). These graphs highlight trade-offs: optimized blends improve efficiency and reduce NOx, while CO and HC reductions are consistent strengths. Limitations include variability across studies due to differing engines, loads, and protocols, necessitating meta-analyses or standardized experiments.

CIO biodiesel offers notable advantages in thermal efficiency (in optimized scenarios) and CO/HC reductions over diesel, but NOx trade-offs require careful management. Optimization through fuel blends, additives, and combustion strategies is essential to maximize environmental and performance benefits, though practical challenges like costs and feedstock supply demand ongoing research

CONCLUSION

Overall, tree-based biofuels show significant potential for improving diesel engine performance and reducing exhaust emissions. Findings from various studies indicate that the use of biodiesel from sources such as Calophyllum inophyllum can not only replace some of the conventional diesel fuel, but also provide substantial environmental benefits. However, challenges in terms of raw material availability and production costs must be overcome in order for this biofuel to be adopted more widely. Further research is needed to develop strategies that can improve production efficiency and maximize the environmental benefits of tree-based biofuels.

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