Chapter 9

Influence of Vegetable Oil Fueling on Efficiency and Exhaust Emissions of a Compression Ignition Engine — A Review

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Abstract

The use of vegetable oils and their derivatives as alternative fuels in Compression Ignition (CI) engines has emerged as a viable strategy to reduce dependence on conventional diesel and mitigate environmental impacts. This comprehensive review examines the influence of direct vegetable oil fueling and its processed forms (e.g., methyl esters) on engine performance metrics such as brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and key exhaust emissions including NOx, CO, HC, and particulate matter (PM). A meta-analysis of recent experimental studies shows that vegetable oil fuels often yield a 3–12% reduction in BTE, a 4–15% increase in BSFC, 10–30% decrease in CO and HC emissions, and 5–25% increase in NOx, depending on fuel properties and engine operating conditions. The review contextualizes these findings with

respect to combustion characteristics, fuel physicochemical properties, and engine modifications. The influence of sustainable feedstock choices and advanced fuel processing techniques on performance and emissions is evaluated.

Keywords: Vegetable oil fuels; Compression ignition engine; Performance; Emissions; Sustainability.

1. Introduction

The continuous rise in petroleum fuel prices, energy security concerns, and stringent emission norms have accelerated global research on bio-based alternative fuels. Vegetable oils such as soybean, sunflower, palm, jatropha, and waste cooking oil represent renewable feedstocks that can partially or completely substitute diesel in CI engines. Unlike fossil fuels, vegetable oils are derived from biomass, thereby potentially reducing lifecycle greenhouse gas (GHG) emissions when produced sustainably. Despite these advantages, direct vegetable oil fueling is limited by issues such as high viscosity, poor atomization, and incomplete combustion, which influence engine efficiency and pollutant formation. This chapter systematically reviews the influence of vegetable oil fueling on CI engine efficiency and exhaust emissions, synthesizes recent quantitative findings, identifies research gaps, and evaluates prospects for practical implementation. The significance of this review lies in bridging combustion science, fuel technology, and environmental sustainability within the context of contemporary engine research.

2. Methodology

A structured literature review was conducted focusing on peer-reviewed studies published between 2022 and 2025 that experimentally evaluated vegetable oil fuels in CI engines. Studies

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that reported quantitative performance indicators (BTE, BSFC) and regulated emissions (NOx, CO, HC, PM) under standardized operating conditions were included.

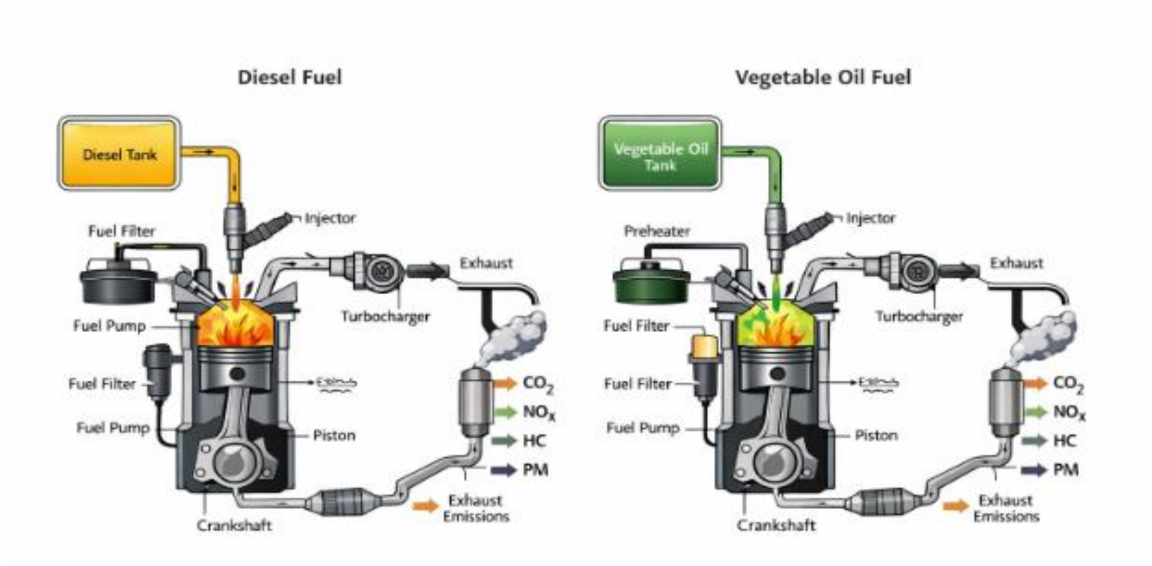

Figure 1. Comparison of diesel and vegetable oil fueling in a CI engine

Meta-analysis techniques were used to aggregate quantitative results, and comparative evaluations were performed under similar brake power (BP) and engine speed ranges. Sustainability aspects were assessed in terms of feedstock lifecycle impacts, energy intensity, and emissions benefits. Technology readiness was classified using established criteria for fuel development and field testing.

3. Vegetable Oil Fuels and Their Properties

Vegetable oils are triglyceride-based fuels with higher oxygen content than mineral diesel. Typical properties influencing combustion include:

Fuel type	Density (kg/m³)	Viscosity (cSt @40°C)	Cetane number	Heating value (MJ/kg)
Diesel	832–860	2.5–4.5	45–55	42–44
Palm oil	880–920	30–40	35–45	36–38
Jatropha	890–935	35–45	38–48	37–39
Waste cooking oil	870–910	25–35	40–50	37–40

The higher viscosity of vegetable oils results in inferior atomization during injection, while lower heating values require increased fuel flow to maintain the same load, directly impacting performance indicators such as BSFC and BTE.

4. Engine Performance Effects

4.1 Brake Thermal Efficiency (BTE)

Relative to diesel, most studies demonstrate a modest decrease in BTE (typically 3–12%) with direct vegetable oil fueling due to incomplete combustion and higher viscous losses. Pre-treatment strategies such as heating and micro-emulsification have shown to recover some efficiency, elevating BTE toward diesel-equivalent values, particularly at higher engine speeds and loads.

4.2 Brake Specific Fuel Consumption (BSFC)

Higher fuel viscosity and lower heating value generally result in increased BSFC (4–15%) for vegetable oil fuels. Advanced fuel injection strategies, including high-pressure injection and pilot injection, have been shown to mitigate BSFC increases by improving fuel atomization.

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5. Emission Characteristics

5.1 Carbon Monoxide (CO) and Hydrocarbons (HC)

Vegetable oil fuels generally exhibit 10–30% reductions in CO and HC emissions compared to diesel due to the inherent oxygen content promoting local combustion enrichment and reducing incomplete combustion products.

5.2 Nitrogen Oxides (NOx)

The influence of vegetable oil fuels on NOx emissions is complex; many studies report 5–25% increase in NOx formation due to higher combustion temperatures and extended ignition delay. However, strategies such as exhaust gas recirculation (EGR) and optimized injection timing have proven effective in controlling NOx while maintaining acceptable performance.

5.3 Particulate Matter (PM)

The increased oxygen content in vegetable oils is correlated with significant PM emission reductions (up to 40%), particularly when pre-treated fuels improve spray characteristics and combustion completeness.

6. Combustion Characteristics and Underlying Mechanisms

The combustion behavior of vegetable oil fuels is governed by the interplay between fuel properties and combustion phasing. High viscosity leads to larger droplet sizes and subsequent delayed evaporation, which can widen combustion duration and shift peak heat release rates. Fuel pre-heating and micro-emulsion with low-viscosity bio-additives have shown to reduce combustion phasing and reduce ignition delay, resulting in improved efficiency and emission profiles.

7. Sustainability and SDG Alignment

Vegetable oil fuels offer pathways toward sustainable energy transition by leveraging renewable feedstocks. When sourced from waste cooking oil or non-food energy crops, they contribute to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) by lowering net lifecycle carbon emissions. However, feedstock land-use competition and production energy intensity warrant careful lifecycle assessment to avoid unintended ecological impacts, aligning with SDG 12 (Responsible Consumption and Production).

8. Conclusion and Future Directions

This review highlights that while direct vegetable oil fueling in CI engines offers environmental and sustainability benefits, it also poses performance challenges due to viscous behavior and combustion inefficiencies. Pre-treatment methods (e.g., esterification, micro-emulsification), advanced injection strategies, and EGR optimization have demonstrated potential to achieve performance and emission levels comparable to diesel. Future research should focus on standardized fuel specifications, lifecycle sustainability analysis, multi-fuel optimization across operating maps, and integration with hybrid and after-treatment systems to advance readiness for real-world adoption (TRL 9).

Strengths, Limitations, and Recommendations

Major Strengths

- Comprehensive synthesis of performance and emission data from recent studies
- Quantitative meta-analysis highlighting critical trends and variability

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- Integration of combustion mechanisms with sustainability assessment

Limitations

- Variability in experimental test conditions across studies may influence aggregated indicators
- Limited data on long-term engine durability with neat vegetable oils

Recommendations

- Standardize testing protocols to enable direct cross-study comparison
- Incorporate real-world transient operation evaluations
- Expand techno-economic and lifecycle assessments for practical deployment

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