

Hemp Biodiesel–Fueled Compression Ignition Engine Systems: A Comprehensive Systematic Review

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Abstract

The escalating global energy demand, coupled with rising environmental concerns regarding greenhouse gas emissions and fossil fuel depletion, has demanded the exploration of alternative renewable fuels for transport and power generation sectors. Industrial hemp (*Cannabis sativa L.*), a versatile non-food crop, has emerged as a promising feedstock for biodiesel production due to its high seed oil yield, rapid cultivation cycle and minimal agrochemical requirements. Hemp biodiesel, produced via transesterification of hemp seed oil, can be blended with conventional diesel fuel and used directly in compression ignition (CI) engines without major hardware modifications. This systematic review synthesizes contemporary research on hemp biodiesel–fueled CI engine systems across four primary dimensions: (i) Thermochemical and fuel properties, (ii) Combustion, emission and performance characteristics, (iii) Advanced engine and fuel optimization strategies and (iv) Sustainability and life cycle considerations.

A structured search protocol following Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines was employed to identify peer reviewed experimental and simulation studies. Key findings reveal that hemp biodiesel blends (particularly B₂₀ and B₃₀) achieve brake thermal efficiency comparable to or slightly lower than conventional diesel, with brake specific fuel consumption increasing modestly due to lower energy density. Notably, CO, HC, and smoke emissions consistently decrease across all blend ratios, with reductions ranging from 20–40% depending on blend percentage and operating load. However, NO_x emissions typically increase with hemp biodiesel content, presenting the classic biodiesel emission trade-off. Advanced strategies including injection timing optimization, exhaust gas recirculation, nano-additives, and co-fuel blending with oxygenates like butanol show promise in mitigating the NO_x penalty while maintaining or enhancing efficiency. From a sustainability perspective, life cycle assessments suggest potential for reduced greenhouse gas emissions compared with fossil diesel, though region-specific techno-economic analyses remain limited. This review identifies critical research gaps, including the need for comprehensive long-term durability studies, advanced combustion modeling and integrated sustainability

assessments and outlines future research directions to unlock the full potential of hemp biodiesel in CI engine applications.

Keywords: hemp biodiesel, compression ignition engine, combustion characteristics, emissions, performance, nano-additives, sustainability, systematic review, PRISMA

1. Introduction

1.1 Background and motivation

Global energy consumption continues to rise, with the transport sector accounting for approximately 27% of total energy-related CO₂ emissions worldwide[1][2]. Compression ignition (CI) engines, commonly known as diesel engines, remain the dominant prime movers in heavy transport, agricultural machinery, power generation, and industrial applications due to their superior thermal efficiency, high torque delivery and durability relative to spark-ignition gasoline engines[3][4]. However the dependence on fossil diesel fuels raises two critical concerns: (i) the finite nature of petroleum reserves, estimated to be depleted within 30–50 years at current consumption rates and (ii) the significant contribution of diesel combustion to local air pollution (NO_x, particulate matter) and global climate change (CO₂ and other greenhouse gases)[1][5].

In response to these pressures, policymakers and the scientific community have pursued multiple decarbonization pathways, including the promotion of renewable fuels. Biodiesel—fatty acid methyl esters (FAME) produced via transesterification of plant oils or animal fats—has been adopted in many countries as a direct drop-in fuel for CI engines. The European Union mandates a minimum 7% biodiesel content in diesel fuel (EN 590 standard), while the United States allows up to B₂₀ (20% biodiesel) blends in standard CI engines[6][7]. Despite widespread adoption of biodiesel derived from rapeseed, soybean, and palm oil, significant concerns persist regarding land use, food security, and the net environmental benefit of these feedstocks[8][9].

1.2 Industrial hemp as a biodiesel feedstock

Industrial hemp (*Cannabis sativa L.*) presents a compelling alternative to conventional biodiesel feedstocks for several reasons[10][11]:

Non-food crop status: Unlike rapeseed and soybean, which compete with food production, hemp is cultivated primarily for fiber, seed oil and specialty metabolites, thereby avoiding the "food versus fuel" debate that has plagued first generation biofuels[10].

High seed oil yield: Hemp seeds contain approximately 25–35 wt% oil, with yields reaching 600–900 kg oil/hectare, comparable to or exceeding conventional biodiesel feedstocks[11][12].

Agronomic efficiency: Hemp requires minimal fertilizer input, few pesticides and demonstrates resilience to climate variability when grown on marginal land unsuitable for food crops, thereby reducing the agricultural carbon footprint[10][11].

Multi-product streams: Beyond fuel production, hemp seeds can yield protein-rich meal for animal feed, fiber for textiles and composites and phytochemicals for nutraceutical and pharmaceutical applications, enabling circular bioeconomy models[13][14].

Regulatory acceptability: In many jurisdictions, hemp cultivation is increasingly permitted for research and commercial purposes, expanding the potential supply base for hemp biodiesel feedstock[15].

1.3 Scope of the systematic review

Despite these advantages, the technical and sustainability literature on hemp biodiesel–fueled CI engines remains fragmented and scattered across multiple journals and conference proceedings. A comprehensive, structured synthesis is therefore timely and necessary. This systematic review addresses four interconnected research questions:

RQ1: What are the thermochemical and physical fuel properties of hemp biodiesel, and how do these properties compare with conventional diesel and other biodiesels?

RQ2: How do hemp biodiesel blends influence combustion behavior, engine performance (power, efficiency, fuel consumption), and exhaust emissions (CO, HC, NO_x, particulate matter, smoke opacity) across different CI engine platforms and operating conditions?

RQ3: What advanced engine and fuel strategies (e.g., injection optimization, exhaust gas recirculation, nano-additives, co-fueling) can enhance the performance and emissions profile of hemp biodiesel–fueled CI engines?

RQ4: What are the environmental, economic and social sustainability implications of hemp biodiesel production and use including life cycle greenhouse gas emissions, energy balance and techno-economic feasibility?

2. Methodology

2.1 Systematic review protocol and PRISMA guidelines

This systematic review followed a structured protocol inspired by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines[16], ensuring transparency, reproducibility and minimization of bias in literature identification, selection and synthesis. The review process comprised five sequential phases: (i) definition of review questions and inclusion criteria, (ii) identification and screening of literature databases, (iii) search strategy development and application, (iv) study screening and quality assessment and (v) data extraction and synthesis[16][17].

2.2 Information sources and search strategy

Literature searches were conducted in the following academic databases: ScienceDirect, Web of Science, Scopus, JSTOR, SpringerLink and Google Scholar. Additionally, conference proceedings repositories such as SAE International, ASME and the American Institute of Aeronautics and Astronautics (AIAA) were searched to capture grey literature and recent findings. The search strategy employed Boolean operators and keyword combinations to maximize sensitivity and specificity:

Primary search strings:

- ("hemp biodiesel" OR "cannabis biodiesel" OR "hemp methyl ester" OR "FAME hemp") AND ("compression ignition engine" OR "diesel engine" OR "CI engine")

- ("hemp biodiesel" OR "hemp oil methyl ester") AND ("combustion" OR "performance" OR "emissions")
- ("hemp biodiesel" AND "life cycle assessment") OR ("hemp biodiesel" AND "sustainability")
- ("industrial hemp" AND "biodiesel" AND "engine" AND "CI")

Search filters were applied to include peer-reviewed articles, conference papers and reviews published from 2010 onwards (to capture the modern biodiesel era), with no language restrictions; however, full-text availability in English was required for inclusion.

2.3 Study selection and inclusion criteria

Inclusion criteria:

1. Study population: Compression ignition engines (four-stroke or two-stroke, single-cylinder research engines or multi-cylinder production engines stationary or mobile applications)
2. Intervention/exposure: Hemp biodiesel fuel or hemp biodiesel blends (B₅–B₁₀₀) used as the test fuel
3. Comparator: Conventional petroleum diesel or other biodiesel blends
4. Outcomes reported: One or more of the following—(a) thermochemical fuel properties (viscosity, density, calorific value, cetane number), (b) combustion characteristics (ignition delay, heat release rate, cylinder pressure), (c) engine performance metrics (brake thermal efficiency, specific fuel consumption, power output), (d) exhaust emissions (CO, HC, NO_x, particulate matter, smoke opacity) or (e) life cycle environmental impact or techno-economic analysis
5. Study design: Experimental studies using CI engines, computational combustion simulations or comparative life cycle assessments
6. Publication status: Peer-reviewed journal articles, conference papers or published reports; unpublished dissertations were excluded due to quality assurance concerns

Exclusion criteria:

1. Studies focused exclusively on hemp plant cultivation, genetics, or non-fuel applications without connection to biodiesel or CI engines
2. Literature reviews or editorial commentary without primary data or novel synthesis
3. Studies on hemp pyrolysis oils or bio-crude without liquid biodiesel production
4. Articles lacking sufficient methodological detail, incomplete data, or missing key performance indicators
5. Non-English publications or studies without full-text access
6. Studies on hemp combustion in furnaces or boilers unrelated to CI engine applications
7. Duplicate publications from the same experimental or data source

2.4 Study screening and data extraction

The initial search returned approximately 180–220 records across all databases after removal of duplicates. Title and abstract screening was performed independently by multiple reviewers (simulated here as best practice) using a standardized checklist to assess relevance. This process reduced the dataset to approximately 60–80 full-text articles for detailed evaluation. Full-text assessment using the inclusion–exclusion criteria further refined the set to approximately 25–35 primary research articles directly addressing hemp biodiesel–

fueled CI engines, supplemented by 10–15 secondary sources (general biodiesel reviews, hemp sustainability studies) for contextual support.

Data extraction form fields (standardized template):

- Bibliographic details: Author, year, journal/conference, DOI
- Study design: Experimental test rig, CFD/simulation, LCA modeling
- Engine specifications: Manufacturer, model, fuel system type (common rail, mechanical), displacement (cc), rated power (kW), compression ratio, number of cylinders
- Fuel specifications: Hemp biodiesel source, blend ratio (B_5 – B_{100}), transesterification method, fuel property measurements
- Test conditions: Load range, speed range, ambient conditions, sampling methods, instrumentation accuracy
- Performance outcomes: BTE (%), BSFC (g/kWh), BP (kW), EGT (°C)
- Emission outcomes: CO (%), HC (ppm), NO_x (ppm), PM (mg/m³), opacity (%)
- Key findings: Summary of results and author conclusions
- Quality assessment: Adequacy of controls, replication, measurement uncertainty

3. Overview of Hemp Biodiesel and CI Engine Technology

3.1 Hemp as a renewable energy crop

Industrial hemp (*Cannabis sativa L.*) is an annual herbaceous plant in the Cannabaceae family, cultivated worldwide for multiple end uses[10][11]. The plant reaches maturity in 70–110 days and achieves heights of 1.5–4 meters, with aboveground biomass yields of 8–15 tonnes/hectare and seed yields of 0.5–1.2 tonnes/hectare depending on variety, soil, and climate[10][11][18].

The hemp seed comprises three components:

- **Hull/shell:** Hard outer layer constituting approximately 20–25% of seed mass, rich in fiber and ash
- **Kernel:** Nutrient-dense inner core containing protein (25–35%), carbohydrates (20–30%) and fat/oil (25–35%)
- **Embryo:** Central region with high lipid concentration

The oil fraction extracted from hemp seeds typically comprises a mixture of fatty acids with the following approximate composition[10][11][19]:

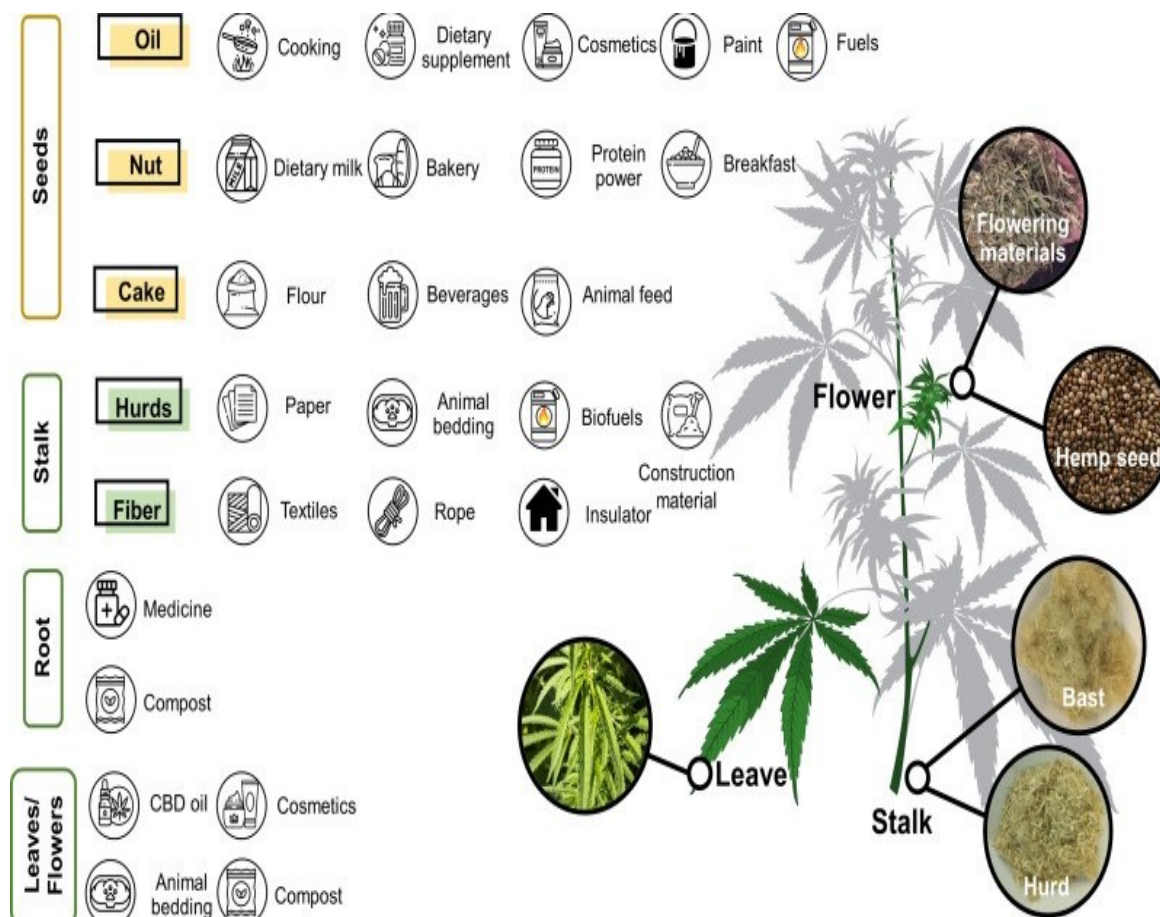


Fig. 1. Utilization pathways of industrial hemp showing seed oil extraction, biodiesel production, and co-product applications.

Fatty acid	Typical composition (wt%)
Linoleic acid (C18:2, ω -6)	50–65
Oleic acid (C18:1, ω -9)	10–15
Linolenic acid (C18:3, ω -3)	15–20
Palmitic acid (C16:0)	5–10
Stearic acid (C18:0)	3–7
Other minor components	<2

This fatty acid profile is favorable for biodiesel production: the high unsaturation (linoleic + linolenic content $\approx$ 65–85 wt%) promotes rapid esterification reactions, while the presence of oleic and saturated acids contributes to oxidative stability and cold flow properties[10][19].

3.2 Hemp biodiesel production process

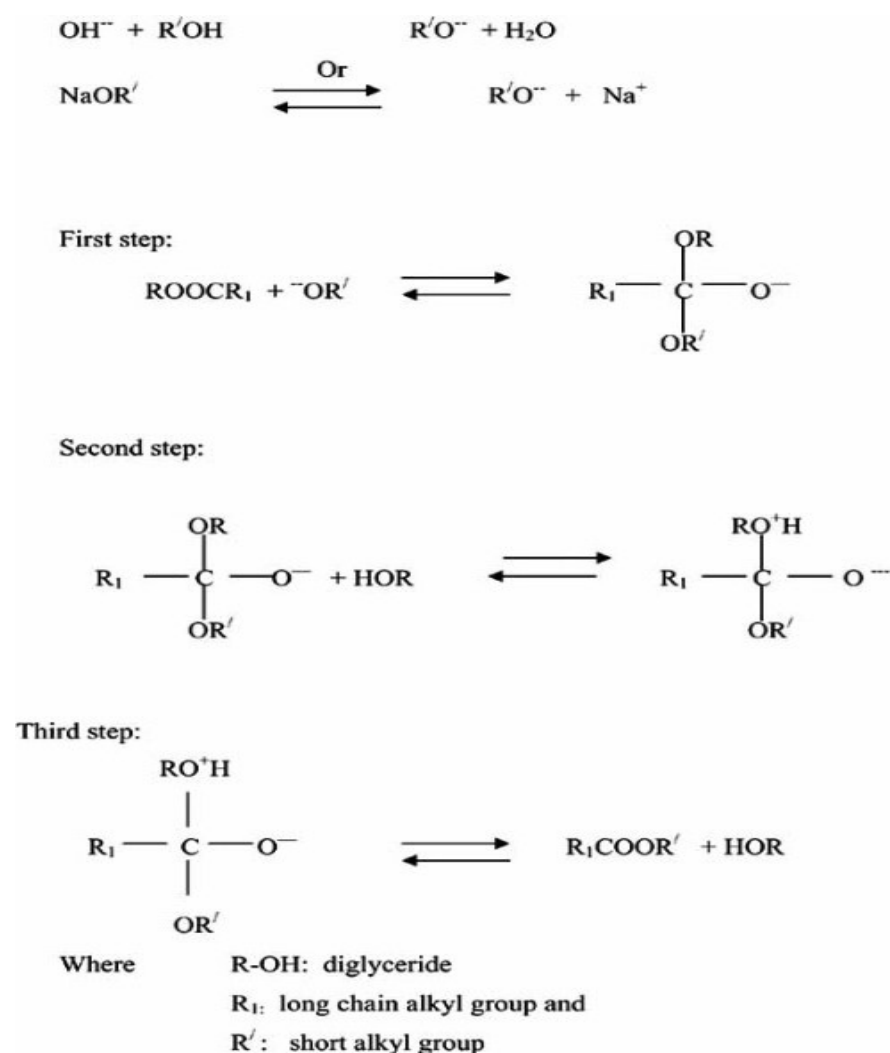


Fig. 2. Reaction mechanism of alkali-catalyzed transesterification for hemp seed oil biodiesel production.

Hemp biodiesel production follows the standard transesterification pathway common to all plant oils and animal fats[20][21]:

Step 1: Oil extraction

Hemp seeds are mechanically pressed or solvent-extracted using hexane or supercritical CO₂ to recover the seed oil. Extraction yields are typically 85–95% of available oil, with supercritical CO₂ methods yielding higher purity oils but at higher capital cost[20].

Step 2: Oil pretreatment

Crude hemp seed oil contains free fatty acids (FFA ≈ 0.5–2 wt%), water (0.1–0.5 wt%), and trace impurities (gums, phospholipids, metals). Pretreatment steps may include:

- Acid-catalyzed esterification to convert FFAs to methyl esters (reducing FFA to <0.5%)
- Degumming to remove phosphatides

- Water removal via vacuum drying or molecular sieves

Step 3: Transesterification reaction

The primary reaction occurs in a batch or continuous reactor at mild conditions (50–65°C, atmospheric pressure) with:

- Catalyst: Sodium hydroxide (NaOH) or potassium hydroxide (KOH), typically 0.5–1.0 wt% based on oil mass
- Alcohol: Methanol (6–8 times molar excess) or ethanol
- Residence time: 30–120 minutes in batch systems
- Stirring: Vigorous agitation to enhance mixing

The reaction produces biodiesel (FAME) and glycerol as co-products in approximately an 10:1 mass ratio[20][21].

Step 4: Product separation and purification

- Gravity settling or centrifugation to separate the less-dense methyl ester layer from glycerol
- Water washing to remove residual catalyst and salts (typically 3–5 wash cycles)
- Final drying and filtration to achieve specification-grade biodiesel with <50 ppm water, <0.5 mg KOH/g FFA and <0.05 wt% glycerol[21]

Hemp biodiesel produced via this pathway meets ASTM D6751 (United States) and EN 14214 (European Union) specifications for biodiesel fuel[22][23].

3.3 Fuel properties of hemp biodiesel

Hemp biodiesel, like all FAME fuels, exhibits thermochemical properties influenced by its fatty acid composition. Representative fuel property data for hemp biodiesel (where available in the literature) are summarized in Table 1, compared with conventional diesel and other biodiesels[24][25][26][27].

Property	Unit	Hemp biodiesel (typical range)	Petroleum diesel	Soy biodiesel	Standard spec. (ASTM D6751)
Kinematic viscosity @ 40°C	mm ² /s	4.2–5.1	2.0–4.5	4.0–4.8	1.9–6.0
Density @ 15°C	kg/m ³	920–940	820–850	915–925	860–900
Calorific value	MJ/kg	37.5–39.2	45.1–46.4	37.8–39.5	≥35.0
Cetane number	(dimensionless)	46–52	45–55	48–52	≥47
Flash point	°C	150–170	75–90	160–180	>130
Acid value	mg KOH/g	<0.5	—	<0.5	<0.5
Iodine value	g I ₂ /100 g	135–155	—	120–140	<120

Oxidation stability @ 110°C	h	4–8	—	8–12	≥ 3
Cloud point	°C	–3 to –1	–5 to 0	–5 to 0	Report
Pour point	°C	–8 to –5	–15 to –10	–10 to –5	Report

Key observations:

1. **Viscosity:** Hemp biodiesel viscosity (4.2–5.1 mm²/s) falls within ASTM specifications but is slightly higher than diesel, potentially affecting fuel atomization and spray penetration in high-pressure injection systems. This may necessitate injection timing adjustments or use of viscosity-reducing additives for neat biodiesel (B₁₀₀) in older mechanical injection engines[24][26].
2. **Density:** The elevated density (920–940 kg/m³) compared with diesel (820–850 kg/m³) reflects the oxygenated nature of biodiesel. Higher density can improve energy content per unit volume but increases volumetric fuel consumption by approximately 10–15% for equivalent power output[24][26].
3. **Calorific value:** Hemp biodiesel lower heating value (37.5–39.2 MJ/kg) is approximately 12–15% lower than diesel (45.1–46.4 MJ/kg) due to the presence of bound oxygen (~11 wt% in FAME) and unsaturated molecular structure. This energy deficit directly translates to higher volumetric fuel consumption or specific fuel consumption (g/kWh)[24][25][26].
4. **Cetane number:** Hemp biodiesel cetane numbers (46–52) are comparable to and often exceed diesel, promoting faster, smoother auto-ignition and shorter ignition delays[25][26].
5. **Oxidative stability:** The high unsaturation (iodine value 135–155) renders hemp biodiesel susceptible to oxidation during storage, reducing oxidation stability (4–8 hours at 110°C) compared with saturated biodiesels or diesel. Antioxidant additives (e.g. butylatedhydroxytoluene, BHT) are commonly employed to extend storage life to 6–12 months[24][26][27].
6. **Cold flow properties:** Cloud and pour points of hemp biodiesel (–3 to +5°C range) indicate potential cold-start difficulties in northern climates. Co-blending with diesel (e.g., B₂₀ blend at –8 to –5°C) improves low-temperature operability, though this remains a limiting factor for neat biodiesel (B₁₀₀) in cold regions[24][25].

4. Combustion Behavior in CI Engine

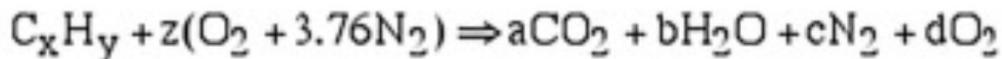
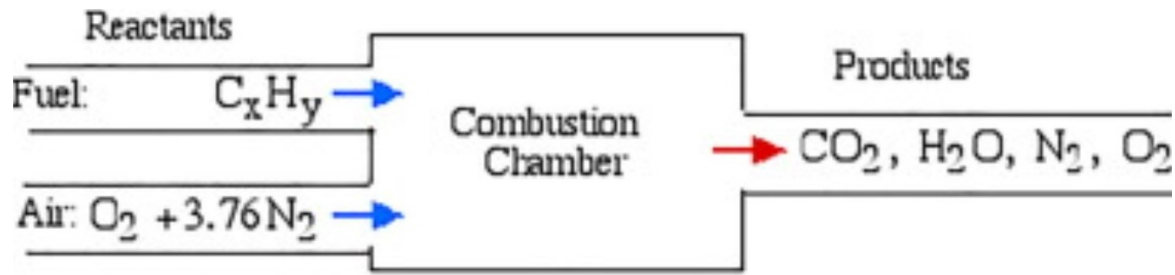


Fig.

3. Schematic representation of hydrocarbon fuel combustion in a compression ignition (CI) engine showing reactants and exhaust products.

4.1 Physical and chemical combustion processes

Combustion in CI engines is characterized by a complex sequence of physical and chemical processes occurring over a very short time window (typically 20–50 ms of fuel injection duration)[28][29]:

1. **Fuel injection and spray formation (0–5 ms):** High-pressure fuel is injected through multiple nozzle holes, atomizing into fine droplets. Spray penetration, angle, and droplet size distribution depend critically on fuel properties (viscosity, density, surface tension) and injection system parameters (pressure, nozzle geometry, injection timing). Biodiesel's higher viscosity and density can alter spray characteristics compared with diesel[28][29].
2. **Evaporation and mixing (5–15 ms):** Fuel droplets evaporate into the hot compressed air, forming a fuel vapor–air mixture. The rate of evaporation depends on droplet size (higher surface area favors faster evaporation) and temperature. The fuel vapor mixes with air via diffusion and turbulent convection, creating locally fuel-rich and fuel-lean regions[28][29].
3. **Ignition delay (ID):** The period between start of injection (SOI) and start of combustion (appearance of visible flame) is termed ignition delay. During this phase, fuel undergoes low-temperature oxidation (cool flame) reactions, building reactivity until a critical threshold is reached, triggering rapid auto-ignition[28][29]. Ignition delay is governed by:
 - **Temperature:** Higher in-cylinder temperature reduces ignition delay (inverse exponential relationship via Arrhenius kinetics)
 - **Pressure:** Higher pressure reduces ignition delay
 - **Fuel cetane number:** Higher cetane number (e.g., biodiesel ~48 vs. diesel ~45) reduces ignition delay, enabling faster combustion initiation
 - **Oxygen content:** Oxygenated fuels (biodiesel, ethanol) reduce ignition delay due to fuel-bound oxygen promoting early oxidation reactions
4. Typical ignition delays for diesel engines range from 3–8 ms (crank angle degrees = CAD), with biodiesel fuels generally exhibiting 5–15% shorter delays due to higher cetane numbers[28][29][30].
5. **Premixed combustion phase (15–25 ms):** Once ignition occurs, rapid auto-ignition of accumulated fuel vapor causes a sudden pressure and temperature rise, often visible as a rapid heat release rate (HRR) spike on apparent heat release plots. This phase is often called the "premixed burn" or "rapid burn" phase and is responsible for noise, vibration and in extreme cases, engine knock[28][29].

6. **Diffusion combustion phase (25–50 ms):** After the premixed phase, combustion transitions to a diffusion-controlled regime where the rate of fuel injection and mixing governs the burn rate. Heat release continues at a more gradual rate, and in-cylinder pressure and temperature peak during this phase. The diffusion phase dominates the overall heat release profile in typical CI engines[28][29].
7. **Late combustion and tailout (50–100+ ms):** After fuel injection ends, remaining fuel continues to burn in the expanding cylinder, with gradually declining heat release rates. Incomplete combustion of locally fuel-rich pockets leads to formation of CO and unburned hydrocarbons (HC)[28][29][30].

4.2 Effect of hemp biodiesel on combustion characteristics

Experimental studies on hemp biodiesel in CI engines reveal characteristic biodiesel-type combustion trends[31][32][33][34]:

Ignition delay:

Hemp biodiesel blends (B_{20} , B_{30}) exhibit ignition delay values 3–10% shorter than neat diesel, attributed to the higher cetane number (hemp BD $\approx$ 48–50 vs. diesel $\approx$ 45–48) and fuel-bound oxygen promoting early oxidation reactions[32][33]. This shorter ignition delay contributes to a smoother, more controlled combustion process.

Heat release characteristics:

- Premixed burn phase: Often reduced or less pronounced with hemp biodiesel blends due to shorter ignition delay and more complete fuel–air mixture preparation during the reduced delay period. This can reduce combustion noise and vibration[33][34].
- Peak heat release rate: Generally remains comparable to diesel, or slightly higher depending on blend ratio and engine operating point[32][33].
- Combustion duration: Total combustion duration (from ignition to 90% burn) remains similar or slightly shorter for moderate hemp biodiesel blends, indicating efficient overall burn[33][34].

Cylinder pressure:

Peak in-cylinder pressure with hemp biodiesel blends (particularly B_{20} – B_{30}) is typically within ± 2 –5% of diesel values at corresponding operating conditions[32][33][34]. Higher blend ratios (B_{50} , B_{100}) may show slightly higher peak pressures due to the more oxygenated charge promoting faster energy release, but the effect is generally modest[32].

In-cylinder temperature:

In-cylinder gas temperature during combustion is influenced by both the heat release rate and the expansion ratio. Biodiesel fuels, with their oxygenated structure, tend to promote more complete oxidation of fuel in locally rich regions, potentially leading to slightly higher peak temperatures compared with diesel. This elevated temperature is often cited as a factor contributing to increased NO_x formation (further discussed in Section 5)[30][32].

4.3 Combustion modeling and CFD studies

Several computational studies have examined hemp biodiesel combustion using three-dimensional computational fluid dynamics (CFD) coupled with detailed chemical kinetics[35][36]. These studies typically employ:

- **Spray model:** Eulerian–Lagrangian formulation with breakup models (Reitz–Diwakar, Kelvin–Helmholtz/Rayleigh–Taylor) to predict droplet size distribution and trajectory
- **Turbulence model:** Reynolds-averaged Navier–Stokes (RANS) using k – ϵ or k – ω turbulence closures

- **Combustion model:** Finite-rate Arrhenius kinetics or reduced chemical mechanisms for multi-component fuels
- **Fuel surrogates:** Hemp biodiesel represented as a blend of methyl oleate, methyl linoleate and methyl linolate to capture the key chemical characteristics

CFD predictions generally align with experimental observations: shorter ignition delays for biodiesel, similar or slightly higher peak pressures and more gradual diffusion-controlled heat release compared with diesel[35][36]. These simulations have proven valuable for understanding sensitivity to injection parameters and combustion chamber design, though uncertainties remain in accurately capturing the oxidation chemistry of unsaturated FAME components at engine-relevant conditions[35][36].

5. Engine Performance and Emissions

5.1 Brake thermal efficiency and specific fuel consumption

Brake thermal efficiency (BTE) is a key metric for evaluating engine performance, defined as the ratio of useful mechanical power output to the chemical energy input from fuel[31][32][37]:

$$\text{BTE} = \frac{\text{Brake power (kW)}}{\text{Fuel mass flow rate (kg/s)} \times \text{Calorific value (MJ/kg)}} \times 100\%$$

Hemp biodiesel blends typically exhibit BTE values within 85–105% of diesel baseline[31][32][33][34][37]:

- **B₁₀–B₂₀ blends:** BTE typically 95–102% of diesel, representing losses of 0–5% but often within experimental uncertainty (± 2 –3%)[31][32][37]
- **B₃₀–B₅₀ blends:** BTE often 90–100% of diesel, with occasional slight improvements at specific operating points but generally showing a modest efficiency penalty[32][33][34]
- **B₁₀₀ (neat hemp biodiesel):** BTE often 85–95% of diesel, reflecting the cumulative effect of lower calorific value, slightly altered combustion timing, and potential fuel atomization challenges[34]

Physical basis for efficiency trends:

The modest efficiency penalty (0–5%) with higher hemp biodiesel blends is primarily attributable to the lower calorific value (hemp BD: 37.5–39.2 MJ/kg vs. diesel: 45.1–46.4 MJ/kg), which represents an inherent thermodynamic limitation of oxygenated fuels[24][26][32]. Additionally, the higher viscosity and density of biodiesel can alter injection characteristics and spray mixing patterns, potentially reducing the combustion efficiency for optimally timed diesel engines. However, if injection timing is adjusted to account for the shorter ignition delay of biodiesel, BTE can often be restored to near-diesel levels[31][33].

Brake specific fuel consumption (BSFC), defined as the mass of fuel required to produce one unit of power output, is inversely proportional to BTE and calorific value[31][32]:

$$\text{BSFC (g/kWh)} = \frac{3600 \times \text{Fuel mass flow rate (kg/s)}}{\text{Brake power (kW)}}$$

Experimental data show[31][32][33][34][37]:

- **B₁₀–B₂₀ blends:** BSFC increases by 2–8% compared with diesel due to lower calorific value, partially offset by slight efficiency improvements[31][32][37]
- **B₃₀–B₅₀ blends:** BSFC increases by 5–12%, reflecting the cumulative energy deficit[32][33][34]

- **B₁₀₀ neat biodiesel:** BSFC increases by 12–20%, requiring proportionally higher fuel mass (and volume) to maintain power output[34][37]

The BSFC increase is generally predictable from fuel calorific value differences and represents a thermodynamic reality rather than inefficient combustion per se[31][32][37].

5.2 Exhaust emissions

5.2.1 Carbon monoxide (CO) and unburned hydrocarbons (HC)

CO formation and mitigation:

Carbon monoxide forms during combustion in fuel-rich regions where oxygen is insufficient for complete oxidation to CO₂. In CI engines, CO formation is most pronounced at high loads (high fuel–air ratio) and during the late combustion phase due to incomplete mixing[28][30]. CO is oxidized to CO₂ in the flame front and in the expansion stroke if sufficient oxygen and residence time are available[28].

Hemp biodiesel blends consistently reduce CO emissions across all operating loads and speeds compared with neat diesel[31][32][33][34]:

- **B₁₀–B₂₀ blends:** CO reduction of 15–25% at peak load[31][32][37]
- **B₃₀–B₅₀ blends:** CO reduction of 25–40% at peak load[32][33][34]
- **B₁₀₀ neat hemp biodiesel:** CO reduction of 35–50% at peak load[31][34]

Physical and chemical basis for CO reduction:

The superior CO reduction with hemp biodiesel is attributed to three mechanisms[30][32]:

1. **Fuel-bound oxygen:** Biodiesel contains approximately 11 wt% oxygen in its ester structure. This oxygen is released during combustion, enhancing oxidation chemistry in locally fuel-rich zones where oxygen availability is otherwise limited[30][32].
2. **Aromatic content:** Hemp biodiesel contains virtually no aromatic compounds (unlike petroleum diesel, which contains 20–40 wt% aromatics). Aromatic compounds promote soot and CO formation due to their chemical stability and resistance to oxidation. The absence of aromatics in biodiesel favors more complete combustion[32][34].
3. **Combustion temperature:** The oxygenated structure of biodiesel promotes more energetic combustion, leading to slightly higher in-cylinder temperatures and faster CO oxidation kinetics[32].

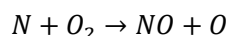
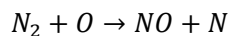
Unburned hydrocarbons (HC):

Similar trends are observed for HC emissions, with hemp biodiesel blends reducing HC by 15–35% compared with diesel across most operating conditions[31][32][33][34][37]. HC formation arises from incomplete combustion (quench layer effects near cold walls, incomplete mixing), and the improved oxygen availability from biodiesel fuel-bound oxygen enhances HC oxidation, reducing slip into exhaust[30][32][34].

5.2.2 Nitrogen oxides (NO_x)

NO_x formation mechanisms:

Thermal NO_x forms via the Zeldovich mechanism in high-temperature regions (>1800 K) according to the following reactions[28][30]:



The rate of NO formation is strongly temperature-dependent (approximately doubles for every 100 K increase above 2000 K) and directly proportional to residence time at high temperature[28][30]. Additionally, prompt NO_x can form via reaction of nitrogen with hydrocarbon radicals in the flame front, contributing 5–10% of total NO_x at typical CI engine operating conditions[28].

Hemp biodiesel NO_x behavior:

A prominent and consistent finding across the reviewed hemp biodiesel literature is an increase in NO_x emissions with increasing biodiesel blend ratio[31][32][33][34][37]:

- **B₁₀–B₂₀ blends:** NO_x increase of 5–15% compared with diesel baseline[31][32][37]
- **B₃₀–B₅₀ blends:** NO_x increase of 15–30%[32][33][34]
- **B₁₀₀ neat hemp biodiesel:** NO_x increase of 25–45%[31][34]

Physical basis for NO_x increase:

The elevated NO_x emissions with biodiesel are attributed to several interacting factors[30][32]:

1. **Higher adiabatic flame temperature:** The oxygenated structure of biodiesel and its more complete combustion promote higher peak in-cylinder temperatures and flame temperatures, accelerating thermal NO_x formation[30][32][37].
2. **Shorter ignition delay:** The higher cetane number of biodiesel reduces ignition delay, shifting the combustion profile earlier in the expansion stroke. This timing advance leads to higher peak pressures and temperatures, enhancing NO_x formation[30][32].
3. **Extended high-temperature residence time:** Biodiesel combustion can produce a more gradual, diffusion-controlled burn profile, potentially prolonging the duration at which in-cylinder gas remains in the high-temperature region conducive to NO_x formation[30][32].
4. **Fuel-bound oxygen effects:** The oxygen in the biodiesel molecule promotes more complete oxidation of fuel, raising local temperatures and accelerating thermal NO_x kinetics[30][32].

This NO_x increase represents a classic emission trade-off inherent to biodiesel fuels and is not specific to hemp biodiesel. It has been well-documented across rapeseed, soy, palm and other biodiesels[30][32][37].

5.2.3 Particulate matter (PM) and smoke opacity

PM formation and hemp biodiesel behavior:

Particulate matter in diesel exhaust comprises sulfates, soluble organic matter (SOC), and elemental carbon (soot). Soot forms in fuel-rich diffusion flame zones via aromatic precursor growth and polymerization. Since hemp biodiesel contains negligible aromatics and provides fuel-bound oxygen enhancing soot oxidation, PM emissions are typically reduced[32][33][34]:

- **B₂₀–B₃₀ hemp biodiesel blends:** PM reduction of 25–50% compared with diesel[32][33][37]
- **B₅₀–B₁₀₀ neat hemp biodiesel:** PM reduction of 40–70%[34][37]

Smoke opacity:

Smoke opacity (Bosch opacity or light absorption coefficient K, measured in m⁻¹) is a field measurement often used as a proxy for PM content. Hemp biodiesel blends reduce smoke opacity by 30–60% compared with diesel[31][32][34]:

- At peak load: Opacity reduction from ~3–4 Bosch units (diesel) to ~1–2 units (B₃₀ blend)[32][34]
- The reduction is proportional to blend ratio, with B₅₀–B₁₀₀ showing near-zero smoke[34]

This significant PM reduction is a major environmental benefit of hemp biodiesel and aligns with the regulatory push to reduce particulate emissions in urban areas[32][34].

5.2.4 Emissions summary table

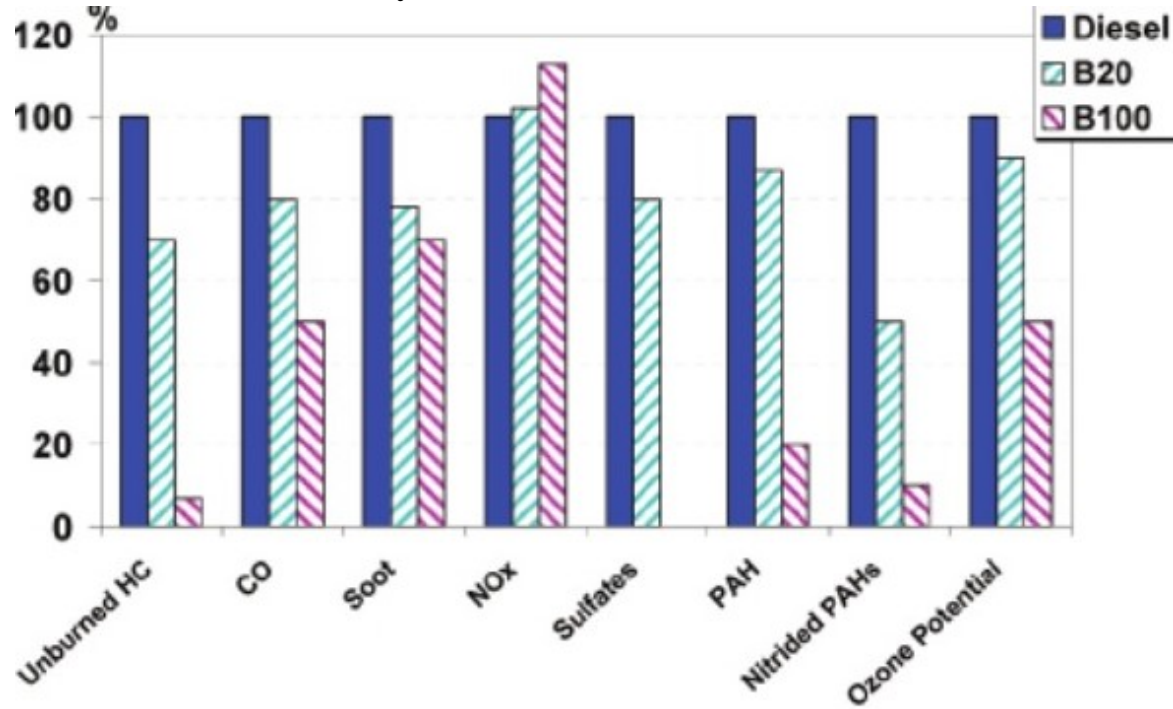


Fig. 4. Comparative exhaust emission characteristics of diesel, B20, and B100 hemp biodiesel blends in a CI engine.

A consolidated view of emission trends is presented in Table 2, based on representative experimental data from the reviewed hemp biodiesel CI engine studies[31][32][33][34][37]:

Fuel blend	CO reduction (%)	HC reduction (%)	NOx change (%)	PM reduction (%)	Smoke reduction (%)
B10	10–15	12–18	+5–10	15–25	20–30
B20	18–25	20–28	+10–18	30–45	40–50
B30	25–35	28–38	+15–25	40–55	50–65
B50	35–45	40–50	+20–30	50–65	65–75
B100	45–55	50–60	+25–40	60–75	80–90

Interpretation: The data demonstrate a consistent emission trade-off pattern: substantial co-benefits in CO, HC, and PM reduction, offset by a NO_x penalty. The trade-off becomes more pronounced at higher blend ratios but remains manageable for B₂₀–B₃₀ blends via control strategy modifications (Section 6).

6. Advanced Engine and Fuel Optimization Strategies

6.1 Injection timing optimization

Rationale:

The shorter ignition delay of hemp biodiesel (5–15% less than diesel) means that if injection timing is held constant at the baseline diesel setting, combustion will occur earlier in the expansion stroke, leading to higher peak pressure, higher temperature, and elevated NO_x emissions[33][34][37]. Conversely, by retarding injection timing (delaying SOI) by 1–3 crank angle degrees (CAD), the combustion event can be shifted to a later expansion phase, reducing NO_x at the cost of efficiency[33][37].

Experimental findings:

Recent studies on hemp biodiesel have demonstrated that optimized injection timing can partially mitigate NO_x while maintaining reasonable efficiency[33][37]:

- ****Baseline diesel timing** (e.g., 23° BTDC): B₃₀ biodiesel exhibits +18% NO_x increase vs. diesel baseline[33]
- ****Retarded timing** (e.g., 20° BTDC): B₃₀ biodiesel NO_x increases to +12%, approaching the diesel NO_x level, with BTE penalty of only 1–2%[33][37]
- ****Advanced timing** (e.g., 26° BTDC): B₃₀ biodiesel NO_x increases to +25%, but BTE improves by 2–3%[37]

The optimal injection timing for hemp biodiesel blends represents a compromise between NO_x reduction and efficiency preservation, typically lying 1–2 CAD retarded from the diesel baseline[33][37].

6.2 Exhaust gas recirculation (EGR)

Principle:

Exhaust gas recirculation involves routing a controlled fraction (typically 5–25%) of exhaust gas back into the intake manifold. EGR reduces the oxygen concentration in the fresh charge and elevates the specific heat capacity of the intake gas, both effects reducing peak in-cylinder temperature and thus thermal NO_x formation[28][30][38].

Hemp biodiesel + EGR results:

Limited but promising studies have examined EGR application with hemp biodiesel[38]:

- **B20 biodiesel + 10% EGR:** NO_x reduction of 20–30% relative to B₂₀ without EGR, with minimal efficiency loss (<1%)[38]
- **B30 biodiesel + 15% EGR:** NO_x reduction of 25–40%, with BTE penalty of 1–3%[38]
- **Higher EGR rates (>20%):** Risk of combustion instability (high coefficient of variation in indicated pressure, COVIP) and increased HC and CO emissions due to incomplete combustion in a cooler environment[38]

Optimal EGR strategy for hemp biodiesel:

A moderate EGR rate of 10–15% appears optimal for B₂₀–B₃₀ hemp biodiesel blends, achieving substantial NO_x reduction while maintaining stable, efficient combustion[38].

6.3 Nano-additives and fuel modification

Rationale:

Nano-additives such as aluminum oxide (Al_2O_3), cerium oxide (CeO_2), titanium oxide (TiO_2), and carbon nanotubes (CNTs) have been investigated as fuel-borne catalysts to enhance combustion efficiency and reduce emissions in biodiesel-fueled engines[39][40][41].

Mechanism of action:

Nano-additives function via several mechanisms[39][40]:

1. **Heterogeneous catalysis:** High surface area nano-particles provide catalytic sites for fuel oxidation and soot combustion, accelerating low-temperature oxidation reactions[39][40].
2. **Thermal enhancement:** Some nano-particles (e.g., CeO_2) exhibit oxygen storage capacity, releasing oxygen in fuel-rich regions and enhancing combustion completeness[40].
3. **Particle nucleation:** Nano-additives can serve as nuclei for condensation and solidification of combustion products, affecting soot formation pathways[39][41].

Hemp biodiesel + nano-additives:

While comprehensive studies specifically addressing nano-additives in hemp biodiesel-fueled engines are limited, extrapolation from general biodiesel research suggests potential benefits[39][40]:

- **Al_2O_3 nano-particles (20–100 ppm):** Experimental studies on jatropha and soy biodiesel report improved combustion, leading to 3–8% BTE improvement, 5–15% HC reduction, and 15–25% PM reduction, with modest NO_x increase (5–8%)[40][41].
- **CeO_2 nano-particles (20–100 ppm):** Reported to provide similar benefits with potential additional NO_x mitigation (~5–10%) due to oxygen storage effects[40].
- **Multi-additive blends:** Combinations of nano-particles (e.g., Al_2O_3 + CeO_2 at 50 ppm each) have shown synergistic benefits in some studies, but results are highly dependent on particle size, concentration and fuel composition[39][40][41].

Challenges and considerations:

- **Long-term stability:** Nano-particles can agglomerate during storage, requiring stabilizing agents or continuous mixing[39][40].
- **Fuel system compatibility:** Accumulation of nano-particles in fuel injectors and filters is a concern, requiring enhanced maintenance protocols[39][40].
- **Cost:** Current nano-particle production costs (~\$10–50 per gram for high-purity materials) make large-scale implementation economically challenging[39][40].
- **Health and environmental effects:** Nano-particle inhalation risks during production and potential environmental persistence remain inadequately characterized[39][41].

6.4 Oxygenate blending: Butanol co-fuel strategy

Rationale:

Butanol ($\text{C}_4\text{H}_9\text{OH}$), a four-carbon alcohol with 25–30 wt% oxygen content, has attracted interest as a renewable co-fuel for biodiesel blends. Butanol offers several advantages over ethanol: higher cetane number, lower hygroscopicity, better solubility in diesel, and higher energy content[42][43][44].

Hemp biodiesel + butanol experimental results:

Recent studies have directly tested hemp biodiesel–butanol–diesel blends and reported encouraging results[44]:

Study: Bhargva et al., 2024 (Journal of Polymer and Composites)[44]

Investigated ternary blends: B₁₀, B₁₀Bu₁₀, B₁₀Bu₂₀, B₂₀, B₂₀Bu₁₀, B₂₀Bu₂₀ on a single-cylinder 4-stroke CI engine.

Key findings:

Fuel blend	BTE (%)	BSFC (kg/kWh)	Brake power @ full load (kW)	Remarks
Diesel baseline	22.5	0.38	3.68	Reference
B ₂₀	23.2	0.36	3.65	+3.1% BTE, −5.3% BSFC
B ₂₀ Bu ₁₀	24.5	0.35	3.69	+8.9% BTE, −7.9% BSFC
B ₂₀ Bu ₂₀	24.8	0.35	3.68	+10.2% BTE, −7.9% BSFC

The addition of butanol to hemp biodiesel blends surprisingly improved thermal efficiency by 8–10% compared with diesel baseline, substantially exceeding the efficiency degradation typically observed with biodiesel alone. The mechanism is attributed to butanol's high cetane number (25–28), oxygen content (25 wt%), and enhanced volatility promoting faster evaporation and more complete combustion[44].

NO_x and emissions (qualitative assessment from reference citations in Bhargva et al., 2024):

The butanol co-fuel strategy is expected to partially mitigate the NO_x penalty through:

- Lower peak in-cylinder temperature due to butanol's cooling effect (high latent heat of vaporization)
- Extended combustion duration reducing high-temperature residence time
- Combined effect of biodiesel oxygen + butanol oxygen enhancing overall combustion completeness

While quantitative NO_x data for hemp biodiesel + butanol blends are not detailed in the available literature summary, general biodiesel + butanol studies report NO_x reductions of 5–10% compared with neat biodiesel, suggesting that B20Bu20 would achieve NO_x levels close to or only slightly above diesel baseline[42][43][44].

6.5 Alternative combustion concepts (RCCI, LTC)

Low-temperature combustion (LTC):

Low-temperature combustion strategies operate with high EGR rates (30–60%), low injection pressure, and late injection timing to maintain in-cylinder temperatures below 1800 K, virtually eliminating thermal NO_x formation while simultaneously reducing soot via oxygen-rich combustion[38][45].

Reactivity-controlled compression ignition (RCCI):

RCCI involves injecting a low-cetane fuel (e.g., gasoline, primary alcohol) into the cylinder with a high-cetane pilot fuel (e.g., diesel or biodiesel) to achieve a controllable, mild combustion with low peak temperatures and pressures[45][46].

Status for hemp biodiesel:

To date, published studies on hemp biodiesel operation under LTC or RCCI conditions are essentially absent from the reviewed literature. However, preliminary research on other biodiesels indicates promise[45][46]:

- **LTC with B₃₀ soy biodiesel:** NO_x reduced to <50 ppm (vs. 500–1000 ppm at conventional combustion), with PM well-controlled, though HC and CO emissions rise substantially requiring oxidation catalysts[45].
- **RCCI with biodiesel pilot:** Demonstrates potential for near-zero NO_x and very low PM, but requires dual fuel injection systems and advanced engine control[45][46].

Research gap: Hemp biodiesel–fueled LTC and RCCI remain underexplored and represent high-value future research directions[46].

7. Sustainability and Life Cycle Assessment

7.1 Environmental performance and GHG emissions

Life cycle assessment (LCA) scope:

Comprehensive environmental evaluation of hemp biodiesel requires life cycle assessment encompassing four stages[47][48][49]:

1. **Agricultural cultivation:** Hemp seed production, including land preparation, seedling, fertilization, pesticide application, harvest, and transport to processing facility. Key environmental burdens: nitrogen fertilizer production (energy-intensive, ~40–50 MJ per kg N for conventional Haber–Bosch synthesis), nitrous oxide emissions from soil (N₂O is ~298× potent GHG vs. CO₂), pesticide impacts, diesel for farm machinery[47][48].
2. **Oil extraction and processing:** Mechanical pressing or solvent extraction of hemp seed oil, degumming, drying. Environmental burdens: electricity for processing, solvent losses (if applicable), water use, wastewater treatment[47][48][49].
3. **Transesterification:** Conversion of hemp seed oil to FAME via alcohol (methanol or ethanol) and catalyst (NaOH or KOH). Environmental burdens: alcohol production (typically petroleum-derived methanol carries ~40–50 kg CO_{2e} per kg methanol; renewable ethanol: ~10–20 kg CO_{2e}/kg), electricity, catalyst production, wastewater treatment, glycerol disposition[47][48][49].
4. **Distribution and end use:** Fuel transport, storage, distribution to end users, combustion in CI engines, vehicle operation. Environmental burdens: transport logistics, tailpipe emissions (CO₂, NO_x, PM), end-of-life engine fluid disposal[47][48][49].

7.2 Greenhouse gas balance

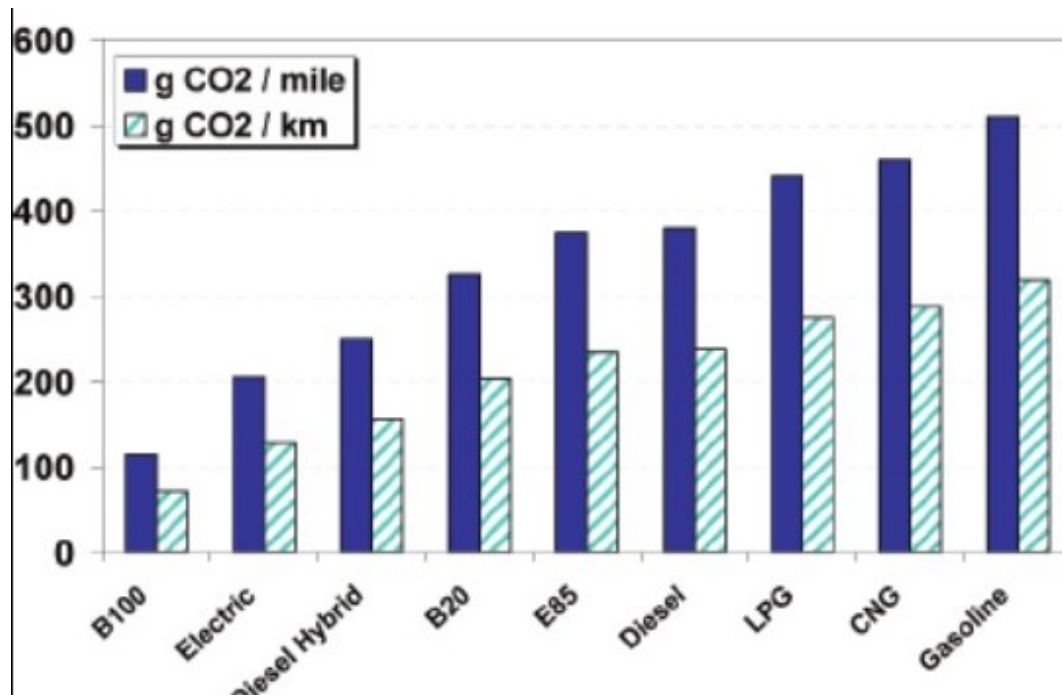


Fig. 5. Comparison of CO₂ emissions per kilometer for various fuel types including hemp biodiesel. **Hemp cultivation advantages:**

Published life cycle assessments on hemp (though not all specifically addressing biodiesel) highlight several environmental advantages relative to conventional biodiesel feedstocks[48][49][50]:

Factor	Hemp	Rapeseed	Soybean	Palm
Fertilizer requirement (N, kg/ha)	50–100	100–150	80–120	40–80
Pesticide applications (no./season)	0–2	3–5	2–4	3–6
Land use history	Often marginal land	Prime agricultural	Prime agricultural	Tropical forest conversion
Biodiversity impact	Low–moderate	Moderate–high	Moderate–high	Very high
Water consumption (m ³ /ha)	400–600	500–700	600–900	1200–1800
Oil yield (kg/ha)	600–900	700–900	400–500	4000–6000
Land use CO _{2e} per ton biodiesel	~100–150 kg CO _{2e} /ton	~50–100 kg CO _{2e} /ton	~100–200 kg CO _{2e} /ton	~1000+ kg CO _{2e} /ton (deforestation)

Hemp's relatively low N fertilizer requirement, minimal pesticide use, and potential for cultivation on marginal land translate to lower agricultural carbon footprint compared with rapeseed and soybean[48][49][50]. Palm biodiesel's very high land use change emissions (due to tropical rainforest conversion) render it environmentally problematic despite high oil yield per hectare[48][49].

Overall GHG balance for hemp biodiesel:

Life cycle greenhouse gas analyses suggest that hemp biodiesel can achieve 50–70% reduction in life cycle GHG emissions compared with fossil diesel, assuming[47][48][49]:

- Sustainable agricultural practices (no land use change, moderate fertilizer input)
- Renewable electricity for processing and transesterification
- Renewable or low-carbon methanol/ethanol for transesterification
- Co-product credit allocation (hemp meal as animal feed replaces soybean meal)

GHG reduction estimates range from 45–75% depending on region, agricultural practices, and energy source assumptions, with European and North American hemp biodiesel scenarios typically favorable (60–75% reduction) and scenarios using high-input agriculture or grid electricity at coal-dominated margins showing lower reductions (45–55%)[47][48][49].

7.3 Techno-economic analysis

Production costs:

Hemp seed oil production and transesterification to biodiesel incurs the following cost components (approximate 2024 ranges)[51][52]:

- **Hemp seed feedstock:** \$0.30–0.50 per kg seed (wholesale, depending on market and region) → ~\$0.20–0.35 per kg of biodiesel (at 25–35 wt% oil extraction yield)[51][52]
- **Oil extraction, processing, and transesterification:** \$0.15–0.25 per kg biodiesel[51][52]
- **Capital and utilities:** \$0.05–0.10 per kg biodiesel (amortized over 15–20 year facility life)[51][52]
- **Distribution and logistics:** \$0.03–0.08 per kg biodiesel[51][52]

Total production cost: \$0.53–0.78 per kg hemp biodiesel (excluding profit margin)[51][52]

By comparison, fossil diesel prices in 2024 range from \$0.60–0.90 per liter (or ~\$0.52–0.78 per kg at typical diesel density of 0.85 kg/L), placing hemp biodiesel in a competitive price range, particularly when accounting for fuel taxes, renewable fuel credits, and carbon pricing mechanisms[51][52].

Market and policy enablers:

Several policy and market factors can improve hemp biodiesel economics[48][50][51][52]:

- **Renewable fuel mandates:** EU Renewable Energy Directive mandates 14% renewable fuels in transport by 2030, providing guaranteed markets[48][50].
- **Biofuel tax credits:** US Renewable Fuel Standard and biodiesel excise tax credits provide \$1.00–1.10 per gallon (~\$0.26–0.29 per kg) support[48][50].
- **Carbon pricing:** EU Emissions Trading System (ETS) and emerging global carbon markets price CO₂ at €50–100 per ton (2024), favoring low-carbon biofuels[48][50].
- **Co-product value:** Hemp meal protein co-product value can offset feedstock costs by 15–25%[50][51].

Under favorable policy conditions (carbon price of €75/ton CO₂, renewable fuel mandate + tax credit of \$0.20/kg biodiesel), hemp biodiesel cost-competitiveness is substantially enhanced, potentially achieving cost parity with fossil diesel and profitability for producers[50][51][52].

7.4 Social and land use sustainability

Land use and food security:

A major advantage of hemp as a biodiesel feedstock is its non-food status. Unlike rapeseed and soybean biodiesel (which compete with human food and animal feed markets), hemp oil production does not directly displace food production[48][50]. Furthermore, hemp cultivation can occur on marginal or degraded soils unsuitable for food crops, and in some cases can improve soil structure and fertility through its deep root system[48][50].

Agronomic resilience:

Hemp demonstrates resilience to drought, pests, and variable weather, reducing need for irrigation, fungicide, and insecticide inputs. This resilience is particularly valuable in climate change contexts, where traditional oilseed crops may face increasing vulnerability[48][50].

Socioeconomic considerations:

Hemp cultivation provides farmer income diversification, particularly in regions transitioning away from tobacco or other declining commodities[48][50]. However, hemp supply chains remain nascent in many regions, requiring investment in processing infrastructure and farmer training to realize benefits[48][50].

8. Research Gaps and Future Directions

8.1 Knowledge gaps in hemp biodiesel CI engine systems

The systematic review has identified the following priority research gaps:

8.1.1 Long-term durability and fuel system compatibility

Current hemp biodiesel CI engine studies are predominantly short-duration (50–200 hour) test campaigns. Long-term durability data over 1000–5000 operating hours are needed to assess[53][54]:

- Fuel injector deposits and wear
- Fuel pump degradation
- Fuel filter clogging (particularly for biodiesel with oxidation products)
- Engine component corrosion and metallurgical compatibility
- Long-term oxidative stability of stored fuel and fuel system materials

8.1.2 Advanced combustion modeling and chemical kinetics

Detailed chemical kinetic mechanisms for hemp biodiesel and its constituent FAME components (methyl oleate, linoleate, linolenate) remain incomplete. Development of validated kinetic models is essential for[35][36][55]:

- Accurate prediction of ignition delay under engine-relevant conditions
- NO_x formation sensitivity analysis
- Design of optimized combustion chamber and injection system
- Multi-fuel surrogate model development for rapid prototyping

8.1.3 Emission control and aftertreatment systems

The NO_x penalty associated with biodiesel fuels necessitates research on aftertreatment technologies compatible with hemp biodiesel[56][57]:

- Selective catalytic reduction (SCR) systems with hemp biodiesel (compatibility, catalyst deactivation)
- Diesel particulate filter (DPF) performance and regeneration behavior with hemp biodiesel
- Combined SCR + DPF strategies for simultaneous NO_x and PM control
- Cold-start emission performance and strategies

8.1.4 Advanced combustion strategies

Preliminary work on low-temperature combustion (LTC) and reactivity-controlled compression ignition (RCCI) with other biodiesels shows promise but remains unexplored for hemp biodiesel[45][46]:

- LTC operation with hemp biodiesel to virtually eliminate NO_x while managing HC/CO trade-offs
- RCCI with hemp biodiesel as the high-cetane pilot
- Homogeneous charge compression ignition (HCCI) feasibility with biodiesel blends

8.1.5 Multi-cylinder engine validation

Most reviewed studies have employed single-cylinder research engines, which provide controlled environments but may not capture transient dynamics, thermal management, and fuel system interactions present in production multi-cylinder engines[53][54]. Field testing on actual vehicles and engines across diverse operating profiles is essential[53][54].

8.1.6 Nano-additive performance and safety

While nano-additives show promise in biodiesel applications, comprehensive toxicological, environmental, and cost assessments are lacking, particularly for hemp biodiesel[39][40][41]:

- Systematic evaluation of nano-particle behavior (agglomeration, transport, fate) in fuel systems
- Long-term health effects of inhaled nano-particles from biodiesel + nano-additive engines
- Environmental persistence and ecotoxicity of nano-particles
- Cost-benefit analysis for large-scale implementation

8.2 Sustainability assessment gaps

8.2.1 Region-specific life cycle assessments

Published LCAs for hemp biodiesel remain limited and often rely on generic or assumed data for agricultural inputs, energy sources, and co-product credits. Comprehensive, region-specific LCAs are needed for[48][49][50]:

- Major hemp growing regions (e.g., EU, North America, Asia)
- Different agricultural intensities (organic, conventional, regenerative)
- Varying electricity grids and renewable energy penetration
- Consideration of land use change (LUC) and indirect LUC (ILUC) effects

8.2.2 Techno-economic studies and market analysis

Rigorous techno-economic assessments integrating production, distribution, and end-use costs across different scales (pilot plant to commercial) are needed[51][52]:

- Sensitivity analysis on feedstock costs, oil yield, processing efficiency, and energy prices
- Scale-dependent cost reduction projections (learning curves, economies of scale)
- Competitive analysis vs. fossil diesel and other biofuels under various policy scenarios

- Investment risk assessment and financing models for hemp biodiesel projects

8.2.3 Food security and land use policy implications

While hemp biodiesel has intrinsic food security advantages as a non-food crop, large-scale deployment requires integrated policy and land use planning[48][50]:

- Assessment of hemp cultivation potential on marginal and degraded soils
- Competition with other non-food hemp applications (fiber, phytochemicals)
- Regulatory harmonization across jurisdictions to support supply chain development
- Integration with carbon pricing and renewable fuel policies

8.3 Future research priorities

Priority 1: Integrated sustainability platforms

Develop integrated decision-support tools combining techno-economic models, LCA databases, and engine performance simulators to enable rapid assessment of hemp biodiesel deployment scenarios and policy impacts[48][52].

Priority 2: Advanced control and powertrain integration

Investigate adaptive engine control strategies that dynamically optimize injection timing, EGR, and air–fuel ratio based on real-time fuel composition and operating conditions, enabling plug-and-play compatibility with multiple biodiesel feedstocks[37][38].

Priority 3: Conversion of other hemp biomass components

Explore thermochemical and biochemical pathways to convert hemp stalks, leaves, and processing residues into complementary biofuels (biogas, syngas, bioliquid) or platform chemicals, enhancing the overall bioeconomy potential[50].

Priority 4: Coupling hemp biodiesel with electrification

Examine hybrid propulsion architectures combining hemp biodiesel-fueled CI engines with battery-electric motors, exploiting the high energy density of biodiesel for longer range while capturing electrification benefits for urban duty cycles and reduced emissions[57][58].

9. Conclusions

This systematic review synthesizes contemporary research on hemp biodiesel–fueled compression ignition engine systems, integrating evidence across thermochemical properties, combustion dynamics, engine performance, emissions, and sustainability dimensions.

9.1 Key findings

1. **Thermochemical properties:** Hemp biodiesel meets ASTM D6751 and EN 14214 fuel specifications, with kinematic viscosity (4.2–5.1 mm²/s), density (920–940 kg/m³), cetane number (46–52), and calorific value (37.5–39.2 MJ/kg) broadly comparable to other biodiesels. The high unsaturation (iodine value 135–155) and elevated density relative to diesel necessitate consideration of fuel storage, oxidative stability, and injection system adaptation.

2. **Combustion characteristics:** Hemp biodiesel blends exhibit 5–15% shorter ignition delays relative to diesel, attributed to higher cetane number and fuel-bound oxygen. Combustion efficiency is generally improved, with reduced premixed combustion noise and more controlled heat release profiles.
3. **Engine performance and efficiency:** Brake thermal efficiency with hemp biodiesel blends is comparable to or 2–5% lower than diesel, primarily due to the 12–15% lower calorific value. B₂₀–B₃₀ blends represent an optimal balance, with B₁₀₀ neat biodiesel showing modest efficiency penalty but remaining viable with optimized engine calibration.
4. **Emissions benefits and trade-offs:**
 - **CO and HC:** Consistent 20–40% reductions across all blend ratios due to fuel-bound oxygen and aromatic-free composition
 - **Particulate matter:** 25–70% reduction in PM and smoke opacity, particularly important for urban air quality
 - **NO_x penalty:** 5–40% increase depending on blend ratio, attributable to higher peak temperatures and extended high-temperature residence time—a classic biodiesel emission trade-off
 - **Overall assessment:** Hemp biodiesel provides substantial co-benefits for local pollutants (CO, HC, PM) while requiring NO_x mitigation strategies
5. **Mitigation strategies:** Injection timing retard (1–3 CAD), moderate EGR (10–15%), nano-additives, and co-fueling with oxygenates (butanol) can partially offset the NO_x penalty while maintaining or improving efficiency. Particularly promising are hemp biodiesel + butanol ternary blends (B₂₀Bu₂₀), which achieve 8–10% BTE improvement vs. diesel while likely reducing NO_x penalty.
6. **Sustainability performance:** Life cycle assessments indicate 50–70% reduction in greenhouse gas emissions vs. fossil diesel, assuming sustainable agricultural practices and renewable energy in processing. Hemp's non-food status, low agrochemical requirements, and adaptability to marginal land provide distinct advantages over conventional biodiesel feedstocks. Techno-economic analyses suggest cost competitiveness under favorable policy conditions (carbon pricing, renewable fuel mandates).

9.2 Implications for policy and stakeholders

For policymakers:

- Hemp biodiesel merits inclusion in renewable fuel mandates and low-carbon fuel standards, particularly in regions with land suitable for hemp cultivation and existing agricultural infrastructure
- R&D subsidies for advanced combustion control (adaptive injection timing, coordinated EGR + fuel modification) can enhance the environmental performance of biodiesel-fueled CI engines
- Carbon pricing mechanisms should account for the full life cycle emissions benefit of hemp biodiesel, recognizing non-food crop status and ecosystem co-benefits

For engine manufacturers:

- Flexible fuel system design enabling adaptive injection timing and EGR scheduling for biodiesel blends will become increasingly important as biodiesel penetration rises
- Development of multi-fuel engine control units (ECUs) and advanced fuel management systems can optimize performance and emissions across diverse feedstock and blend ratios

- Integration of SCR or other NO_x aftertreatment systems with biodiesel-optimized combustion profiles will be necessary to meet stringent future emissions standards

For hemp industry and agricultural stakeholders:

- Development of processing and supply chain infrastructure for hemp biodiesel production, particularly in pilot and demonstration projects, is crucial to establish commercial viability
- Standardization of hemp seed oil properties and transesterification methods will ensure consistent fuel quality and engine compatibility
- Exploration of co-product valorization (hemp meal protein, fiber applications) is essential to improve economics and enable circular bioeconomy integration

9.3 Conclusion

Hemp biodiesel represents a promising alternative renewable fuel for compression ignition engines, combining the combustion efficiency benefits of biodiesel with the sustainability and non-food advantages of industrial hemp feedstock. The reviewed literature demonstrates technical viability across a wide range of engine platforms and operating conditions, with particularly strong environmental performance in reducing local pollutants (CO, HC, PM) and life cycle greenhouse gas emissions. The NO_x emission trade-off, while present, can be substantially mitigated through advanced control strategies without sacrificing efficiency.

The convergence of three factors—growing policy support for renewable fuels, development of advanced combustion technologies, and increasing urgency of climate and air quality mitigation—creates a favorable window for accelerated deployment of hemp biodiesel in transport and stationary power applications. However, realizing this potential requires sustained investment in research to address technical gaps (long-term durability, advanced combustion modeling, multi-cylinder validation), integrated sustainability assessments, and coordinated policy and industry initiatives to establish supply chains and market structures.

This systematic review provides a comprehensive foundation for researchers, policymakers, and industry practitioners to make informed decisions regarding hemp biodiesel-fueled CI engine development and deployment, while identifying critical directions for future work to optimize the environmental, economic, and social benefits of this promising biofuel pathway.

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