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ENGINE EMISSION CONTROL USING ALTERNATIVE BIOFUELS

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ABSTRACT The rapid expansion of the global transportation sector has intensified concerns regarding air pollution, greenhouse gas emissions, and the depletion of fossil fuels. Conventional petroleum-based fuels, although efficient, contribute significantly to carbon monoxide (CO), nitrogen oxides (NOx), unburned hydrocarbons (HC), and particulate matter (PM), all of which adversely affect human health and the environment. Alternative biofuels—such as biodiesel, bioethanol, biogas, bio-butanol, hydrogen-enriched biofuels, and advanced second-generation fuels—have emerged as promising solutions for emissions reduction and sustainable energy transitions. This paper examines engine emission characteristics when using biofuels, focusing on combustion behavior, physicochemical fuel properties, and engine modifications required for improved performance. It also synthesizes global trends in biofuel adoption, emission control technologies, lifecycle environmental benefits, and operational challenges. Experimental results from multiple studies demonstrate that biodiesel blends reduce CO and HC by up to 60–70% due to inherent oxygenation, whereas bioethanol significantly enhances combustion efficiency in spark-ignition engines. Hydrogen-enriched fuels further reduce PM and CO due to flame-speed enhancement. Despite advantages, issues such as higher NOx emissions in biodiesel, cold flow properties, and oxidation stability continue to limit large-scale adoption. This paper concludes that hybrid strategies—including fuel reformulation, exhaust after-treatment systems, and biofuel-specific engine calibration—offer an optimized pathway for emission control.

Keywords Alternative biofuels, engine emissions, biodiesel, bioethanol, NOx reduction, combustion efficiency, sustainability, particulate matter, renewable fuels, hydrogen-enriched biofuels.

1. INTRODUCTION

The global transportation sector contributes nearly **24% of energy-related CO_2 emissions** (IEA, 2022). Fossil fuels not only degrade air quality but also accelerate climate change,

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pushing researchers to explore **clean, renewable, and sustainable** alternatives. Biofuels—liquid, gaseous, or solid fuels derived from biomass—offer a promising pathway due to their **carbon-neutral nature, compatibility with existing engines, and socio-economic benefits** (Demirbas, 2018). Unlike fossil fuels, biofuels contain inherent oxygen molecules that promote cleaner combustion and reduced byproducts such as CO and HC. However, biofuels can also influence NOx formation, ignition delay, and engine wear depending on their properties. The aim of this paper is to analyze alternative biofuels and their role in reducing harmful engine emissions while maintaining vehicle performance and sustainability.

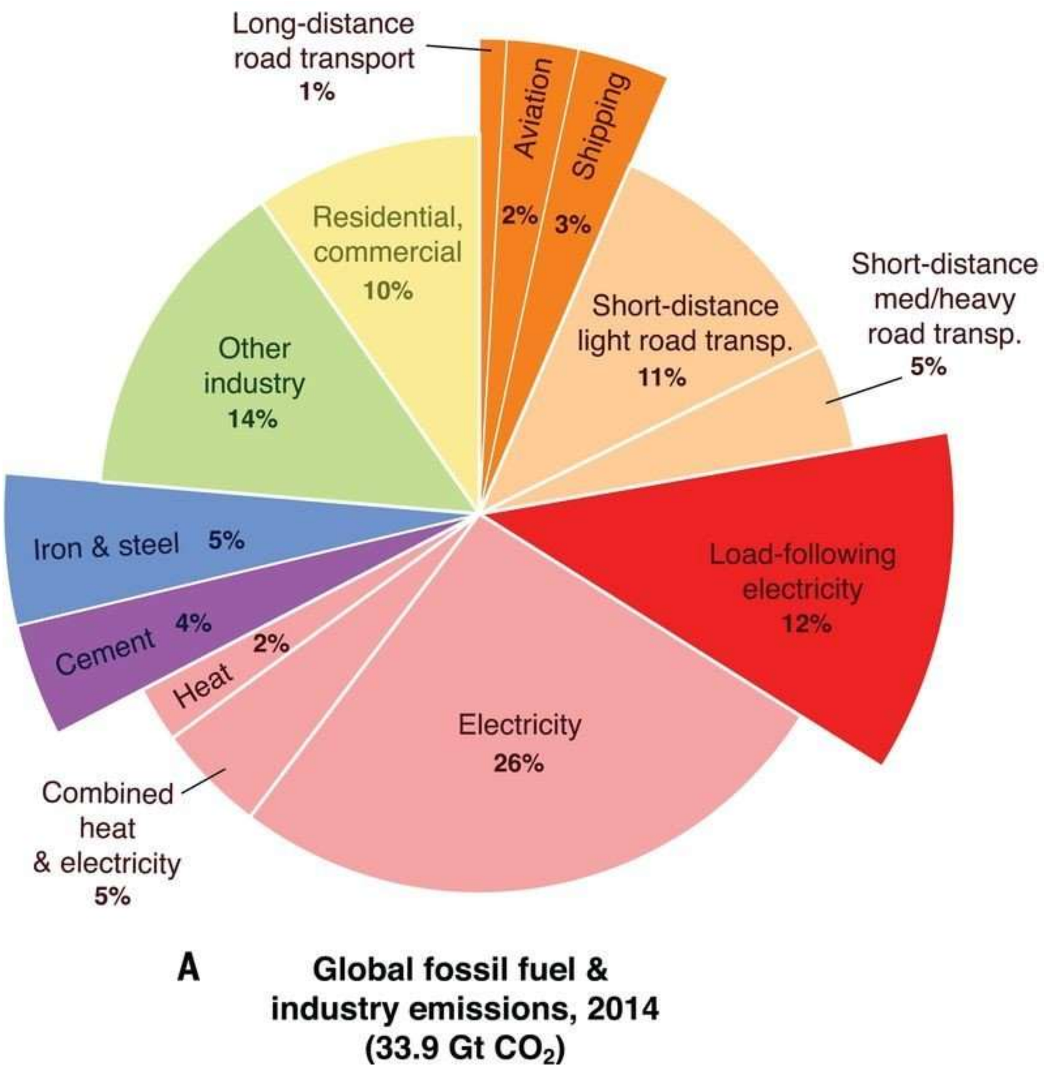

Figure 1.1 – Global Contribution of Transportation Sector to CO_2 Emissions

2. TYPES OF ALTERNATIVE BIOFUELS

2.1 First-Generation Biofuels

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First-generation fuels originate from edible biomass such as sugarcane, corn, and vegetable oils. Bioethanol and biodiesel are the most widely adopted examples. Bioethanol is produced through fermentation of sugars and starches and is blended with gasoline for spark ignition (SI) engines (Zhang et al., 2020). Biodiesel is synthesized through transesterification of vegetable oils and animal fats and can replace diesel in compression ignition (CI) engines without significant modifications (Knothe, 2017).

2.2 Second-Generation Biofuels

Second-generation biofuels use non-edible feedstocks such as agricultural waste, lignocellulosic residues, algae, and forestry biomass. These fuels overcome the food-versus-fuel conflict associated with first-generation fuels (Naik et al., 2019). Cellulosic ethanol and algal biodiesel possess improved environmental credentials and lower life-cycle carbon emissions.

2.3 Third-Generation and Advanced Biofuels

Third-generation fuels focus on microalgal biomass, offering high lipid productivity and CO_2 fixation rates. Advanced fuels include **bio-butanol, Fischer–Tropsch diesel, renewable diesel, dimethyl ether (DME), and hydrogen-enriched biofuels** (Hosseini & Wahid, 2020). These fuels demonstrate superior combustion characteristics and compatibility with modern engines and after-treatment systems.

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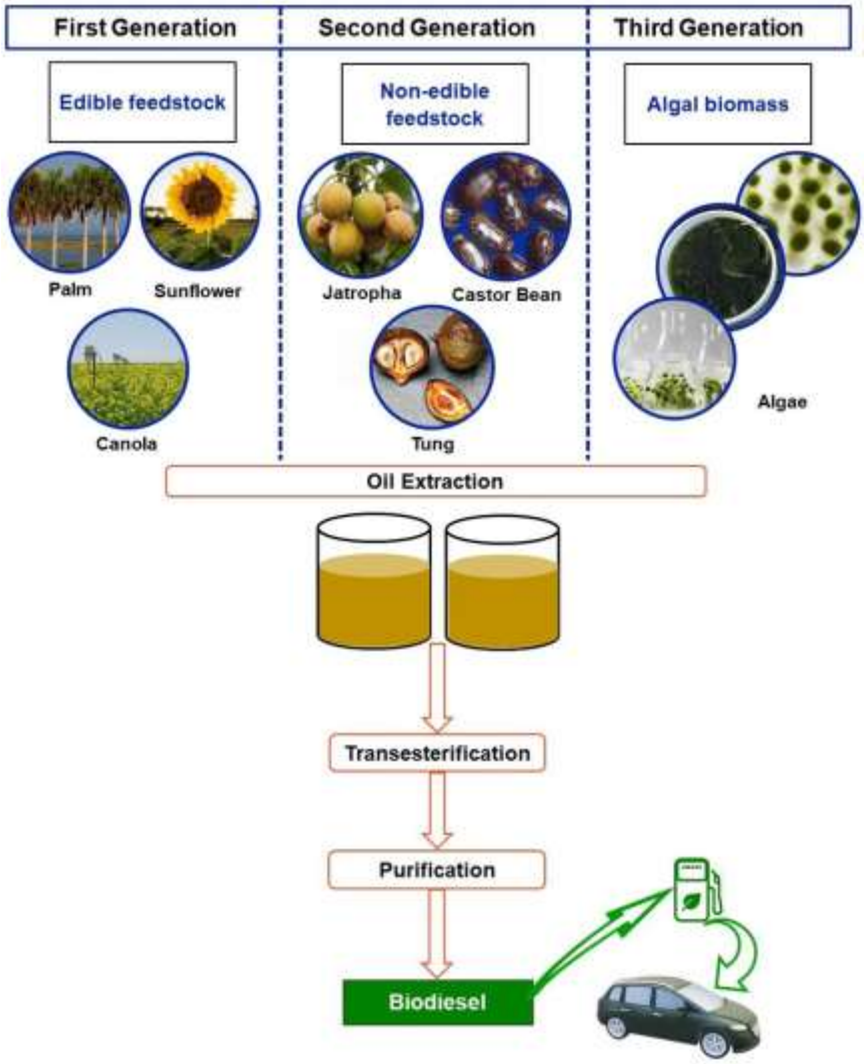

Figure 2.1 – Classification of Alternative Biofuels (1st, 2nd, 3rd Generation)

3. PHYSICOCHEMICAL PROPERTIES OF BIOFUELS AND THEIR RELEVANCE TO EMISSIONS

Biofuels differ significantly from fossil fuels in **density, viscosity, calorific value, cetane number, oxygen content, volatility, and ignition characteristics**. These factors influence combustion temperature, spray pattern, fuel–air mixing, and flame propagation. Biodiesel typically contains **10–12% oxygen**, leading to complete combustion and reduced CO and HC emissions, but elevated combustion temperatures sometimes increase NOx formation (Lapuerta et al., 2019). Bioethanol has high latent heat of vaporization, which may reduce combustion temperatures, resulting in lower NOx levels in SI engines (Costa & Sodré, 2018).

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Table 1: Comparison of Key Properties of Fossil Fuels and Major Biofuels

Property	Diesel	Biodiesel	Gasoline	Bioethanol
Density (kg/m^3)	830	860–900	740	790
Viscosity (mm^2/s)	2.5–3.5	4–6	0.4–0.8	1.2
Calorific Value (MJ/kg)	42–43	37–39	44–46	26–28
Oxygen Content (%)	0	10–12	0	35
Cetane Number	45–55	50–65	<10	—

These fuel properties directly influence combustion efficiency, ignition delay, and tailpipe emissions.

4. ENGINE EMISSION MECHANISMS AND FORMATION OF POLLUTANTS

4.1 Carbon Monoxide (CO)

CO is primarily generated due to **incomplete combustion**. Biofuels reduce CO due to better oxidation pathways, especially biodiesel's oxygen-rich molecular structure (Qi et al., 2020).

4.2 Unburned Hydrocarbons (HC)

HC emissions arise from flame quenching and poor atomization. Ethanol blends improve flame propagation and reduce HC significantly (Yao et al., 2017).

4.3 Nitrogen Oxides (NOx)

NOx is formed at high temperatures through thermal and prompt pathways. Biodiesel tends to increase NOx due to higher combustion temperatures, whereas ethanol blends typically lower NOx (Lapuerta et al., 2019).

4.4 Particulate Matter (PM)

Biofuels reduce PM because oxygenated fuels promote soot oxidation. Hydrogen-enriched fuels drastically reduce soot due to higher flame speed and shorter ignition delay (Verhelst & Wallner, 2009).

5. EMISSION CHARACTERISTICS OF MAJOR BIOFUELS

5.1 Biodiesel Emissions

Biodiesel blends (B10–B20) consistently show **40–70% reductions in CO and HC**, along with a **20–50% decline in PM** due to inherent oxygen content (Knothe, 2017). However, NOx may increase by 2–8%. Cold flow, oxidation stability, and storage issues remain challenges.

5.2 Ethanol and Ethanol–Gasoline Blends

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Ethanol blends such as E10 and E20 improve combustion efficiency and enhance flame propagation. Studies show **25–50% reductions in CO and HC** and **5–20% reduction in NOx** in SI engines (Costa & Sodré, 2018).

5.3 Biogas and Biomethane Emissions

Biogas, primarily methane, produces significantly lower PM and CO than diesel. Lean combustion strategies can be applied to further reduce NOx (Sridharan & Kumar, 2021).

5.4 Hydrogen-Enriched Biofuels

Hydrogen addition improves flame speed and reduces ignition delay, resulting in **substantial PM and CO reduction** (Verhelst & Wallner, 2009). However, high NOx formation may occur if combustion is uncontrolled.

6. ENGINE MODIFICATIONS AND OPTIMIZATION FOR BIOFUELS

6.1 Fuel Injection and Combustion Optimization

Optimizing injection timing, injection pressure, and EGR (exhaust gas recirculation) is essential to control NOx for biodiesel. Retarding injection timing typically lowers NOx (Lapuerta et al., 2019).

6.2 Exhaust After-Treatment Systems

Three major systems include:

a) **Diesel Oxidation Catalysts (DOC)** – Reduce CO and HC
b) **Selective Catalytic Reduction (SCR)** – Reduces NOx using urea
c) **Diesel Particulate Filters (DPF)** – Reduce PM

Biofuels, due to lower sulfur content, increase catalyst life (Qi et al., 2020).

7. PERFORMANCE AND EMISSION TRENDS IN VARIOUS BIOFUEL BLENDS

Table 2: Summary of Emission Trends for Major Biofuel Blends

Fuel Blend	CO	HC	NOx	PM
B20 Biodiesel	↓ 50–70%	↓ 40–60%	↑ 2–8%	↓ 20–50%
E20 Ethanol	↓ 30–50%	↓ 25–40%	↓ 5–20%	↓ Slight
20% Biogas Dual-Fuel	↓ 40%	↓ 35%	Variable	↓ Significant
10% Hydrogen Enrichment	↓ 70%	↓ 60%	↑ Possible	↓ Drastic

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8. ENVIRONMENTAL AND LIFE-CYCLE IMPACTS OF BIOFUELS

Life-cycle assessments reveal that biodiesel reduces **CO_2 emissions by 60–80%**, while ethanol lowers GHG emissions by **40–60%** depending on feedstock (Hill et al., 2020). However, land use change, biodiversity loss, and water footprint must be considered for first-generation fuels. Algae-based biofuels have the lowest ecological footprint but face economic constraints.

9. CHALLENGES AND LIMITATIONS OF BIOFUELS IN EMISSION CONTROL

Major challenges include:

1. **Higher NOx emissions in biodiesel** due to thermal effects.
2. **Low energy density**, especially in ethanol, leading to increased fuel consumption.
3. **Food vs. fuel conflict** in first-generation biofuels.
4. **Cold flow properties** affecting biodiesel usability in winter.
5. **High production cost** of advanced biofuels.
6. **Engine durability concerns**, including deposit formation and injector fouling.

10. FUTURE PERSPECTIVES AND RESEARCH DIRECTIONS

Future developments point toward:

1. **Hybrid biofuel systems** such as ethanol–biodiesel blends.
2. **Advanced catalytic reforming** to reduce NOx.
3. **Algae biofuel commercialization** through genetic engineering.
4. **AI-based engine tuning** to optimize biofuel combustion.
5. **Hydrogen–biofuel hybrid engines** to achieve near-zero PM emissions.

The next decade may see integrated combustion strategies combining biofuels with **after-treatment and adaptive engine control**, paving the way for carbon-neutral transportation.

11. CONCLUSION

Alternative biofuels offer a viable and sustainable approach to reducing harmful emissions from internal combustion engines. Biodiesel, ethanol, biogas, and hydrogen-enriched fuels all contribute to lower CO, HC, and PM emissions due to their oxygenated nature and improved combustion efficiency. Challenges such as NOx increase, lower energy density, and high production costs must be addressed through engine calibration, hybrid fuel strategies, and after-treatment technologies. The future of emission control lies in **second- and third-generation biofuels** combined with **intelligent combustion and emission control systems**.

10.48047/jocaaa.2024.33.04.35

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