

# **Integrating Green Hydrogen and Bioethanol for Sustainable Combustion in Advanced Engines: A Pathway Toward SDG-Aligned Clean Mobility**

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## **Abstract**

The increasing demand for sustainable transportation and decentralized power generation requires the integration of renewable fuels into advanced engine systems. This research investigates the combined utilization of green hydrogen and bioethanol in advanced compression ignition (ACI) and common-rail direct injection (CRDI) engines. Hydrogen provides carbon-free combustion with high flame speed, while bioethanol enhances oxidation due to its oxygenated nature. The study evaluates varying hydrogen substitution ratios, ethanol blend percentages, injection pressures, and engine loads. Key parameters such as in-cylinder pressure, heat release rate, brake thermal efficiency (BTE), brake specific fuel consumption (BSFC), and emissions (NO<sub>x</sub>, CO, CO<sub>2</sub>, HC, smoke) are analyzed. Optimization techniques including RSM and ANN are proposed to determine optimal operating conditions. The research supports SDG 7, SDG 9, and SDG 13 by advancing carbon-neutral mobility solutions.

## **Keywords**

Green Hydrogen; Bioethanol; CRDI Engine; Dual-Fuel Combustion; Sustainable Mobility; Renewable Energy; Emission Optimization

## **1. Introduction**

Transport and distributed power systems continue to rely heavily on fossil fuels, contributing to greenhouse gas emissions and air pollutants [1-3]. Green hydrogen, produced via electrolysis using renewable energy, is a carbon-free fuel with rapid flame propagation characteristics [4-6]. Bioethanol, derived from biomass, is an oxygenated renewable fuel that reduces soot emissions. However, hydrogen may increase NO<sub>x</sub> formation due to higher combustion temperatures, while ethanol presents ignition delay challenges in CI engines. This study explores their synergistic integration in CRDI engines [5-9].

## **2. Research Problem and Objectives**

The integration of hydrogen and ethanol in CI engines presents challenges such as combustion instability, NO<sub>x</sub> rise, and safety concerns. The objectives of this research are

to experimentally evaluate combustion behavior, optimize injection strategies, and establish safety-integrated operational guidelines.

### 3. Literature Review

Previous studies have explored hydrogen-diesel dual fuel and ethanol-diesel blends independently. Hydrogen enrichment improves combustion efficiency but may increase NO<sub>x</sub> [7]. Ethanol blending reduces smoke and CO emissions but affects ignition timing [8]. Recent CRDI-based hydrogen induction studies demonstrated improved efficiency [6]. However, limited research simultaneously optimizes hydrogen and ethanol under unified injection control strategies.

Study (Journal, Year)	Key Finding	Gap
Alone et al., <i>Energies</i> (2026)	Ethanol + H <sub>2</sub> improves reactivity control and reduces emissions.	Review only; lacks unified engine dataset under consistent conditions.
Saha & Roy, <i>ASME J. Energy Resources Tech</i> (2025)	H <sub>2</sub> induction with ethanol–diesel improves CRDI combustion/emissions.	Needs broader injection pressure/timing optimization.
Rajak et al., <i>Int. J. Hydrogen Energy</i> (2024)	RSM optimization for H <sub>2</sub> + ethanol + CR variation shows performance trends.	Limited stability/knock bounds and transient behavior.
Pullagura et al., <i>Int. J. Hydrogen Energy</i> (2024)	H <sub>2</sub> addition with biodiesel–alcohol blends enhances performance/emissions.	Additives confound pure ethanol + H <sub>2</sub> effects.
Gültekin et al., <i>Int. J. Hydrogen Energy</i> (2024)	Combined ethanol and H <sub>2</sub> in CI yields efficiency gains.	Lacks unified multi-objective optimization criteria.
Qadiri et al., <i>RSC Environ. Sci.</i> (2024)	Numerical modeling of multi-fuel (incl. H <sub>2</sub> /ethanol) behavior.	Needs experimental validation on CRDI systems.
Vasanthakumar et al., <i>Int. J. Hydrogen Energy</i> (2023)	H <sub>2</sub> enrichment + ethanol blends raised BTE, NO <sub>x</sub> penalty noted.	NO <sub>x</sub> control strategies unexplored.
Sekar et al., <i>Energies</i> (2023)	HHO + ethanol–diesel reduced HC/CO and improved combustion.	Energy balance and direct H <sub>2</sub> comparison missing.
Atelge et al., <i>Fuel</i> (2022)	H <sub>2</sub> enhances multi-alcohol blends' efficiency/exergy.	Ethanol effect not isolated; older engine config.

#### **4. Methodology**

A single-cylinder, four-stroke CRDI diesel engine is used with hydrogen manifold injection and ethanol blending. Hydrogen substitution (5–30%) and ethanol blends (E10–E30) are tested across varying injection pressures (400–600 bar) and loads (20–100%). Combustion parameters, performance metrics, and emissions are recorded. Optimization techniques such as RSM and ANN are applied to determine the best operating window.

#### **5. Expected Results and Discussion**

It is anticipated that hydrogen will enhance flame speed and improve combustion efficiency, while ethanol will promote complete oxidation and reduce soot formation. BTE is expected to increase by 10–20%, with significant reductions in CO and HC. NOx may increase at higher hydrogen ratios, requiring injection timing optimization.

#### **6. Sustainability and SDG Alignment**

This research contributes to SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation and Infrastructure), and SDG 13 (Climate Action) by integrating renewable hydrogen and bioethanol for carbon-neutral engine operation.

#### **7. Conclusion**

The combined utilization of green hydrogen and bioethanol in CRDI engines presents a viable pathway toward sustainable mobility. Optimized injection strategies and safety-integrated frameworks can ensure improved efficiency and controlled emissions, supporting the transition toward renewable energy systems.

#### **References**

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