Dipak K. Dond, 2026, 14:3
ISSN (Online): 2348-4098
ISSN (Print): 2395-4752

International Journal of Science, Engineering and Technology
An Open Access Journal

Hydrogen and Nanoparticle Enhanced Waste Cooking Oil Biodiesel in Diesel Engines: A Literature Survey

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Abstract- The continuous depletion of fossil fuel reserves and the enforcement of stringent emission norms have accelerated the need for sustainable alternatives in compression ignition engines. Biodiesel derived from waste cooking oil (WCO) presents a viable solution by addressing both energy demand and waste disposal concerns. However, its inherent drawbacks—such as higher viscosity and lower calorific value compared to diesel—can negatively influence engine performance and emissions. To overcome these limitations, recent research has focused on enhancing combustion through hydrogen supplementation and nanoparticle additives. Hydrogen, due to its high diffusivity and rapid flame propagation, improves combustion efficiency, while nanoparticles act as catalysts that promote oxidation reactions. Additionally, fuel injection parameters such as pressure, timing, and quantity significantly influence combustion characteristics. This review examines previous studies on WCO biodiesel enhanced with hydrogen and nanoparticles, with emphasis on injection system optimization and its effects on engine performance, combustion behaviour, and emission characteristics.

Keywords— Hydrogen enrichment, Injection Pressure and timing, Injection quantity, Waste Cooking oil, Nanoparticle.

I. INTRODUCTION

Diesel engines remain widely utilized across transportation, agricultural machinery, and power generation applications owing to their superior thermal efficiency, durability, and ability to operate on a wide range of fuels. Their reliable performance and adaptability make them a preferred choice in both stationary and mobile systems. However, increasing concerns over the rapid depletion of conventional fossil fuel reserves, along with the environmental impact of greenhouse gas emissions, have driven the need for cleaner and more sustainable energy alternatives. Additionally, stringent emission regulations imposed by regulatory bodies have further accelerated research into environmentally friendly fuels.

In this context, biodiesel has emerged as a viable alternative to conventional petroleum diesel. It is derived from renewable biological sources such as vegetable oils, animal fats, and waste cooking oil, making it a sustainable energy option. Biodiesel is characterized by its biodegradable and non-toxic nature, which minimizes environmental hazards in case of spills or leakage. Furthermore, its inherent oxygen content promotes more complete combustion, leading to reduced emissions of harmful pollutants such as carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter. These advantages position biodiesel as a promising substitute for conventional diesel fuel in compression ignition engines. [1].

Waste cooking oil (WCO) is unique among biodiesel feedstocks because of its abundance, low cost, and combined benefits of energy recovery and waste management [2]. Particularly in blended form like B20, biodiesel made from WCO can be utilized directly in diesel engines with little to no modification. However, a number of studies have shown negative aspects of WCO biodiesel, such as increased emissions of nitrogen oxides (NO_x), decreased brake thermal efficiency (BTE), and greater brake specific fuel consumption (BSFC) [3]. Advanced combustion enhancement methods, such as hydrogen enrichment and fuel additives using nanoparticles, have been extensively studied to overcome these issues [4–7]. When utilized as an additional fuel, hydrogen increases combustion efficiency due to its wide flammability limits and fast flame speed. In a similar vein, nanoparticles increase fuel atomization and reduce emissions by acting as oxygen buffers and combustion catalysts. To get the most out of these cutting-edge fuel compositions, injection system parameter tuning is also essential [8]. Figure 1 presents different sources from which waste cooking oil is obtained.

Figure 1 Waste cooking oil sources

II. WASTE COOKING OIL BIODIESEL: PROPERTIES AND ENGINE BEHAVIOUR

Waste cooking oil biodiesel is generally produced through a transesterification reaction that converts triglycerides into fatty acid methyl esters (FAME). Compared with mineral diesel, this fuel possesses greater density and viscosity, slightly lower heating value, and inherent oxygen content within its molecular structure [8]. The embedded oxygen improves oxidation during combustion, often resulting in lower carbon monoxide (CO) and hydrocarbon (HC) emissions. However, increased viscosity can negatively influence spray breakup and droplet evaporation, especially under lower injection pressures. This may extend ignition delay and affect combustion uniformity depending on engine load conditions [9]. Experimental studies consistently report that moderate blends such as B20 provide a practical compromise between emission benefits and acceptable efficiency losses. Higher blend ratios, however, may increase brake specific fuel consumption due to reduced calorific value. The typical transesterification process for WCO biodiesel production is illustrated in Fig. 2

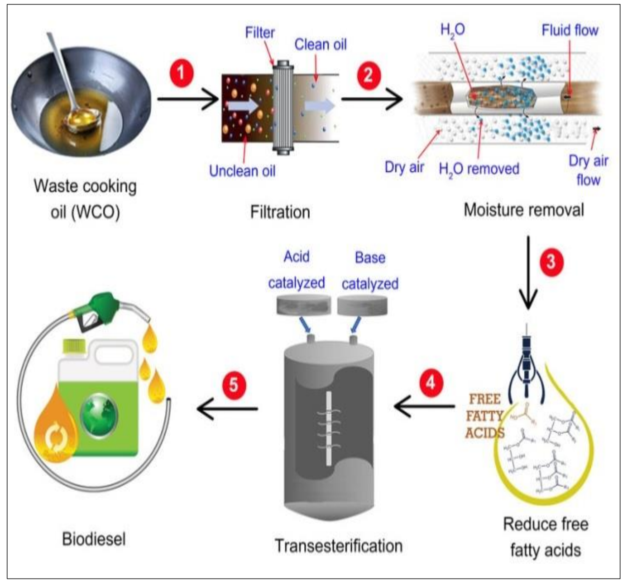

Figure 2 Typical trans esterification process for WCO biodiesel production

Table I: Summary of studies on WCO biodiesel in diesel engines

Author(s)	Blend	Major Findings
Lin et al. [3]	B20	Reduced CO & HC, higher NO_x
Utlu & Koçak [10]	B10–B50	Increased BSFC
Atabani et al. [4]	Neat biodiesel	Lower efficiency

III. HYDROGEN ENRICHMENT IN DIESEL ENGINE

Hydrogen is considered an ideal supplementary fuel due to its carbon-free nature and excellent combustion properties [10]. Hydrogen enrichment is generally achieved through intake manifold induction, ensuring homogeneous mixing with intake air. Hydrogen addition reduces ignition delay and enhances flame propagation, resulting in increased peak in-cylinder pressure and heat release rate [11]. Studies indicate that hydrogen-enriched WCO biodiesel blends exhibit improved BTE and reduced BSFC compared to neat biodiesel operation. Despite performance benefits, hydrogen enrichment often leads to increase NO_x emissions due to elevated combustion temperatures, highlighting the need for injection parameter optimization. Fig. 3 shows the schematic of the hydrogen-enriched diesel engine system.

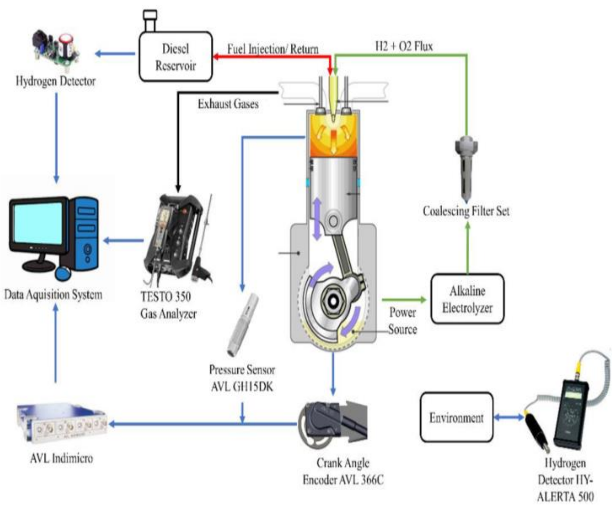

Figure 3 Schematic of hydrogen-enriched diesel engine system

Table II: Hydrogen enrichment studies with biodiesel fuels

Author(s)	Fuel	H_2 Rate	Key Outcomes
Saravanan et al. [11]	Biodiesel	5–15 L/min	↑ BTE, ↓ CO
Kumar et al. [12]	WCO B20	Intake	↓ Smoke, ↑ NO_x

IV. NANOPARTICLE ADDITIVES AND THEIR ROLE

Nanoparticles have emerged as effective fuel additives due to their high surface area-to-volume ratio and catalytic behavior [12]. Common nanoparticles used include cerium oxide (CeO_2), titanium dioxide (TiO_2), zinc oxide (ZnO), and carbon nanotubes (CNTs). Nanoparticles improve atomization, enhance micro-explosion phenomena, and promote complete combustion [13].

Table III: Nanoparticle additives used with biodiesel

Author(s)	Nanoparticle	ppm	Observations
Sajith et al. [13]	CeO_2	25–50	↓ CO, ↓ BSFC
Karthikeyan et al. [14]	TiO_2	30	↑ BTE
Venu & Madhavan [15]	CNT	100	Best overall performance

V. INJECTION SYSTEM PARAMETERS

Injection Pressure: Injection pressure governs atomization quality and air–fuel interaction inside the combustion chamber. Elevating injection pressure promotes finer droplet formation and improved spray dispersion, which is particularly beneficial when using high-viscosity biodiesel fuels. Enhanced atomization accelerates evaporation and supports more uniform premixed combustion, leading to improved brake thermal efficiency and lower incomplete combustion products.[14]. However, extremely high pressures may increase mechanical stress on fuel system components and should therefore be optimized rather than maximized.

Injection Timing: The timing of fuel delivery determines the phasing of combustion relative to piston position. Advancing the start of injection increases the duration of the premixed combustion phase, often resulting in higher peak pressure and improved efficiency. Conversely, this advancement also raises combustion temperature, potentially intensifying nitrogen oxide formation [15]. Retarded injection timing tends to reduce peak temperature and NO_x emissions but may compromise thermal efficiency if excessively delayed. Therefore, identifying an optimal crank angle position is essential to balance efficiency and emission trade-offs.

Injection Quantity: Fuel quantity directly influences equivalence ratio and heat release characteristics. When hydrogen is inducted as a supplementary fuel, careful adjustment of diesel injection quantity becomes critical to prevent excessive heat release and abnormal combustion phenomena. Proper calibration ensures stable combustion, prevents knocking, and maintains target power output while minimizing fuel consumption. Optimized injection quantity thus contributes significantly to emission control and performance stability [14].

VI. COMBINED EFFECTS ON COMBUSTION CHARACTERISTICS

The simultaneous application of WCO biodiesel, hydrogen supplementation, nanoparticle additives, and optimized injection parameters creates a synergistic enhancement in combustion characteristics. Hydrogen accelerates flame development and shortens ignition delay, while nanoparticles facilitate catalytic oxidation and improve micro-scale fuel dispersion. Improved injection pressure enhances spray–air interaction, producing more homogeneous combustion zones. Consequently, peak cylinder pressure and heat release rates increase near top dead center, reflecting more effective energy conversion. The oxygenated structure of biodiesel further assists complete combustion and reduces cyclic variability. Overall, the synergistic interaction of advanced fuel formulations and injection system optimization leads to stable combustion, reduced ignition delay, and enhanced thermal energy conversion.

VII. ENGINE PERFORMANCE CHARACTERISTICS

The key indicators for assessing a diesel engine fueled with WCO-based blends are brake thermal efficiency (BTE) and brake specific fuel consumption (BSFC). Compared to neat biodiesel operation, the combined use of fuel modification techniques leads to a noticeable rise in combustion efficiency, resulting in a 5–15% increase in brake thermal efficiency and a corresponding reduction in BSFC. Among the conventional blends, WCO B20 exhibits a small reduction in BTE of approximately 3.5% relative to diesel fuel, accompanied by a moderate increase in BSFC of about 4–6%. Despite this marginal performance penalty, WCO B20 remains the most practical blend for unmodified diesel engines due to its stable combustion behavior and acceptable efficiency. The hybrid blend of WCO B10 with Jatropha biodiesel B10 demonstrates a significant improvement in BTE, with a rise of nearly 6% at 75% engine load, along with a 5% reduction in BSFC. This improvement is attributed to enhanced fuel atomization and improved energy density achieved through feedstock hybridization. Further enhancement in engine performance is observed with the addition of oxygenated alcohol fuels such as pentanol to WCO biodiesel. The WCO–pentanol blend (B30 + P20) results in an increase in BTE of approximately 9.9% and a reduction in BSFC by about 10.5% compared to diesel operation. The improved performance can be attributed to reduced fuel viscosity, better vaporization characteristics, and improved air–fuel mixing during combustion. The most pronounced improvement in performance is achieved with the incorporation of nanoparticle additives into WCO biodiesel. The WCO blend containing copper oxide (CuO_2) nanoparticles exhibits a BTE enhancement of 12.43% and a BSFC reduction of 12.73%, highlighting the strong catalytic role of nanoparticles in promoting oxidation reactions and heat release. In contrast, the use of pure WCO biodiesel (B100) results in a substantial decline in BTE, ranging from 9.5% to 29.3%, along with a significant increase in BSFC of up to 17.8%. This deterioration in performance is primarily attributed to its lower calorific value and increased viscosity, and inferior spray characteristics of neat biodiesel. Overall, the results clearly indicate that appropriate fuel blending and additive strategies play a crucial role in achieving superior engine performance while utilizing WCO biodiesel as a sustainable alternative fuel.

Table IV: BTE and BSFC Comparison by WCO Combination

Combination / Blend	BTE Comparison (Relative to Diesel)	BSFC Comparison (Relative to Diesel)
WCO B20 (Standard)	Slight reduction (~3.5% decrease)	Slight increase (~4–6% higher)

WCO B10 + Jatropha B10	6% increase (at 75% load)	5% reduction (at 75% load)
WCO + Pentanol (B30+P20)	9.9% increase	10.5% reduction
WCO + Nano-additives	12.43% increase	12.73% reduction
WCO B100	Significant decrease (9.5–29.3% lower)	Significant increase (up to 17.8% higher)

VIII. ENGINE EMISSION CHARACTERISTICS

The exhaust emission characteristics of a diesel engine running on waste cooking oil (WCO) biodiesel, hydrogen enrichment, and nanoparticle additives are significantly influenced by fuel properties, combustion behavior, and injection system parameters. The availability of oxygen within WCO biodiesel supports improved combustion performance, resulting in a noticeable reduction in carbon monoxide (CO) and unburned hydrocarbon (HC) emissions relative to engines running on standard diesel fuel. Hydrogen enrichment further enhances combustion due to its high flame speed and wide flammability limits, leading to improved oxidation of carbon-based species and additional reductions in CO and HC emissions. The presence of hydrogen also shortens ignition delay and accelerates flame propagation, which contributes to lower smoke opacity and particulate matter formation. Nanoparticle additives such as aluminum oxide, cerium oxide, and titanium dioxide act as oxidation catalysts and oxygen buffering agents, enhancing micro-explosion phenomena and improving fuel–air mixing, thereby further suppressing incomplete combustion products.

A notable reduction in smoke emissions is observed with the combined use of hydrogen and nanoparticles, as hydrogen contains no carbon and nanoparticles promote soot oxidation during the diffusion combustion phase. However, nitrogen oxides (NO_x) emissions generally exhibit rising trend due to elevated in-cylinder temperatures, enhanced premixed combustion, and greater availability of oxygen associated with biodiesel and hydrogen enrichment. The increase in peak combustion temperature and faster heat release rates favor thermal NO_x formation. Nevertheless, optimized injection system parameters play a crucial role in controlling NO_x emissions. Elevated injection pressure leads to finer spray formation and reduces locally rich zones, thereby lowering smoke and CO emissions, while slight retardation of injection timing effectively mitigates NO_x formation without significantly compromising brake thermal efficiency. Additionally, optimized injection quantity ensures stable combustion when hydrogen partially replaces diesel fuel, preventing excessive temperature rise and abnormal combustion. Overall, the synergistic combination of WCO biodiesel, hydrogen enrichment, nanoparticle additives, and optimized injection parameters results in substantial reductions in CO, HC, and smoke emissions, with controlled NO_x levels, making this approach a promising pathway toward cleaner and more sustainable diesel engine operation.

IX. RESEARCH GAP AND FUTURE SCOPE

Although significant research has been conducted on waste cooking oil biodiesel, hydrogen enrichment, and nanoparticle additives individually, limited studies have investigated their combined effects under optimized injection system parameters. The interactive influence of hydrogen flow rate, nanoparticle concentration, and injection timing on combustion and exhaust gas emission trade-offs remains insufficiently explored. Long-term durability aspects such as injector wear, fuel stability, and deposit formation due to nanoparticle usage require systematic investigation. Future research should focus on multi-objective optimization techniques such as RSM (response surface methodology) and machine learning approaches to achieve optimal performance–emission balance. Additionally, real-world operating conditions and transient engine behavior should be examined to assess practical feasibility.

X. CONCLUSION

This literature survey confirms that WCO biodiesel can be effectively utilized in single-cylinder diesel engines when combined with hydrogen enrichment, nanoparticle additives, and optimized injection system parameters. The synergistic approach significantly improves combustion efficiency, engine performance, and reduces harmful emissions. Future research should focus on multi-objective optimization and long-term engine reliability studies.

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