

Green diesel and its role as a drop-in renewable diesel alternative to FAME-based biodiesel

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Abstract

Fatty acid methyl ester (FAME) biodiesel has been widely adopted as a renewable alternative to fossil diesel due to its relatively simple production process and established blending frameworks. Nevertheless, intrinsic limitations associated with its oxygenated ester structure such as oxidative instability, hygroscopicity, cold-flow constraints, and restricted blend ratios, continue to limit its long-term suitability for advanced diesel engines and fuel systems. Green diesel, also known as renewable diesel, is a hydrocarbon fuel produced from renewable and waste lipid feedstocks through catalytic deoxygenation pathways, yielding paraffinic hydrocarbons that closely resemble conventional petroleum diesel.

Keywords: Green diesel; Renewable diesel; FAME biodiesel; Catalytic deoxygenation; Drop-in fuel

1. Reconsidering Renewable Diesel beyond FAME Biodiesel

The transition toward low-carbon energy systems has placed renewable liquid fuels at the center of efforts to decarbonize the transportation sector [1]. Among these fuels, FAME biodiesel has been the most extensively implemented, largely due to its compatibility with existing diesel engines at low blending ratios and the maturity of transesterification technology [2], [3]. Despite these advantages, FAME biodiesel remains an oxygenated fuel whose ester functional groups fundamentally distinguish it from petroleum diesel. This structural difference governs many of the well-documented challenges associated with FAME biodiesel, including limited oxidation stability, affinity for water, reduced energy density, and unfavorable cold-flow behavior [4], [5]. As diesel engines continue to evolve toward higher injection pressures, tighter tolerances, and longer service lifetimes, these constraints become increasingly relevant. Consequently, there is growing interest in renewable fuels that can more closely replicate the chemical and physical characteristics of fossil diesel.

To address these limitations, green diesel has been proposed as a drop-in renewable diesel fuel that more closely matches the physicochemical characteristics of petroleum diesel. Produced through catalytic deoxygenation of triglycerides and fatty acids, green diesel consists predominantly of straight-chain and branched paraffinic hydrocarbons within the diesel boiling range [6]. Unlike FAME biodiesel, green diesel is not an oxygenated fuel, enabling it to function as a true drop-in replacement rather than merely a blending component.

2. Fuel Property Advantages of Green Diesel

The hydrocarbon nature of green diesel underpins its favorable fuel properties relative to FAME biodiesel. Numerous studies report higher cetane numbers for green diesel, which contribute to improved ignition quality and more stable combustion behavior [7], [8]. The absence of oxygen-containing functional groups also mitigates issues related to oxidative degradation, polymerization, and long-term storage instability. From a practical perspective, green diesel exhibits negligible hygroscopicity and excellent compatibility with elastomers, seals, and high-pressure fuel injection systems. These characteristics reduce risks associated with corrosion, microbial growth, and fuel system deterioration, which are commonly reported for ester-based fuels at elevated blending levels. Importantly, green diesel can be used at high blend ratios or even as a neat fuel without requiring modifications to existing diesel engines or distribution infrastructure (Figure 1).

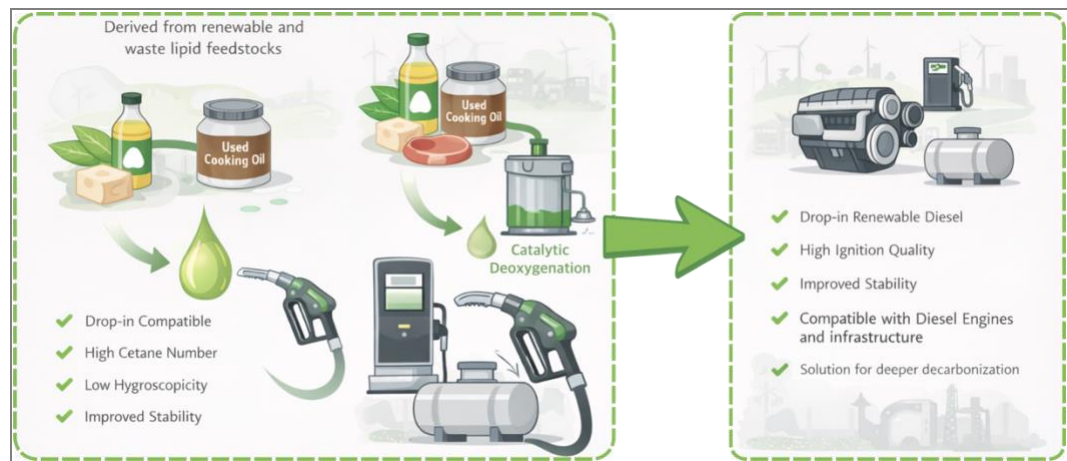


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Figure 1.
Green diesel:
Renewable fuel



Engine and emission studies further indicate that green diesel generally leads to reductions in particulate matter, carbon monoxide, and unburned hydrocarbons, while nitrogen oxides emissions may vary depending on engine calibration and operating conditions [9], [10]. These findings suggest that the full benefits of green diesel are most effectively realized when fuel formulation is considered alongside combustion optimization strategies.

3. Technological Readiness and Production Pathways

The technological feasibility of green diesel production has advanced significantly in recent years. Thermochemical routes, particularly hydrodeoxygenation, decarboxylation, and decarbonylation, are widely regarded as the most mature pathways for converting lipid feedstocks into diesel-range hydrocarbons [6], [11]. These processes can achieve high conversion efficiencies and product selectivity when supported by appropriately designed catalysts.

Catalyst development remains a central research focus. Transition metal phosphides have attracted considerable attention due to their tunable selectivity, resistance to water, and noble-metal-like behavior under hydrodeoxygenation conditions [12]. In parallel, nickel-based and other non-noble metal catalysts have been extensively investigated as cost-effective alternatives, particularly for fatty-acid deoxygenation reactions [13]. While catalyst deactivation due to coke formation, sintering, and leaching remains a challenge, ongoing research into regeneration strategies and support optimization continues to improve long-term performance.

A notable advantage of green diesel production lies in its tolerance toward diverse feedstocks. Unlike transesterification-based biodiesel, green diesel processes can accommodate feedstocks with high free fatty acid content, including used cooking oil, animal fats, and industrial lipid residues. This flexibility enhances both the technical robustness and sustainability profile of green diesel systems [14].

4. Feedstock Diversity and Circular Economy Implications

Feedstock availability and sustainability are critical considerations in the long-term deployment of renewable diesel fuels [15], [16]. Green diesel offers particular advantages in this regard due to its ability to valorize non-food and waste-derived lipid resources. The conversion of used cooking oil and industrial residues into high-quality diesel-range hydrocarbons aligns closely with circular economy principles, transforming low-value waste streams into valuable energy carriers. Life cycle assessments consistently demonstrate that green diesel derived from waste feedstocks can achieve substantial greenhouse gas emission reductions compared to both fossil diesel and conventional FAME biodiesel [17]. Moreover, the absence of esterification and washing steps simplifies downstream processing and reduces wastewater generation.

Feedstock composition, especially fatty acid saturation level, also influences both process performance and fuel quality. Oils rich in monounsaturated fatty acids, such as oleic acid, tend to offer a favorable balance between conversion efficiency, cold-flow behavior, and combustion characteristics [18], [19]. Advances in feedstock pretreatment and selective hydrogenation further expand the range of suitable raw materials.

5. Research Opportunities and Remaining Challenges

Despite its promising attributes, green diesel production continues to face several technical and research challenges. Catalyst durability under prolonged operation remains a key issue, necessitating deeper understanding of deactivation mechanisms and more effective regeneration protocols [20]. In addition, hydrogen consumption in conventional hydrodeoxygenation routes has important economic and environmental implications, particularly in regions where low-carbon hydrogen is not readily available.

Emerging research on hydrogen-efficient and hydrogen-free deoxygenation pathways offers potential solutions to these challenges, aiming to reduce hydrogen demand while maintaining acceptable fuel quality [21]. Furthermore, advances in process integration, refinery co-processing, and real-time optimization are expected to enhance overall system efficiency and economic viability [22]. From a broader perspective, the development of green diesel exemplifies the convergence of catalysis, reaction engineering, fuel science, and sustainability assessment. This interdisciplinary character positions green diesel as a fertile area for continued academic and industrial research.

6. Concluding Remarks

Green diesel represents a significant evolution in renewable diesel fuel development. By overcoming many of the molecular and operational limitations associated with FAME biodiesel, it offers a technically robust and fully compatible alternative for diesel engines and infrastructure. Continued progress in catalyst design, feedstock utilization, and process optimization will be essential to fully realize its potential. As research advances, green diesel is well positioned to play an increasingly important role in the diversification and decarbonization of diesel fuel systems.

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