REFINING DIESEL: PETRODIESEL, BIODIESEL, AND RENEWABLE DIESEL COMPARED

As heavy industry and transportation seek to move away from petroleum-derived diesel due to high carbon emissions, particle pollutants, and non-renewable constraints, biomass-based alternatives are rising in popularity and have gained prominent market focus. This paper provides a comparative review of petroleum diesel (petrodiesel), biodiesel (fatty acid methyl/ethyl esters, or FAME), and renewable diesel (hydrotreated vegetable oil, or HVO). Their chemical structures, refinement processes, physical properties, cold-flow behaviors, and lifecycle environmental impacts are compared. While biodiesel offers biodegradability and restores lubricity lost in Ultra-Low Sulfur Diesel (ULSD), its low energy density, poor oxidation stability, and cold-flow limits restrict it primarily to applications as a blend with petrodiesel. In contrast, renewable diesel consists of oxygen-free, saturated hydrocarbons that match petrodiesel's energy density and performance, allowing it to act as a direct "drop-in" fuel. Finally, the paper covers commercial trends, highlighting how regulatory mandates and growing international trade dynamics, specifically U.S. export markets, are shaping the adoption of these low-carbon fuels.

Introduction

The choice of heavy-duty fuel remains a critical factor across global transportation and industrial sectors. Petroleum diesel has long been the reliable choice, providing the necessary energy density and operational reliability, but its toxic byproducts and non-renewable nature has driven many industries to rapidly shift towards alternatives. Two commercial biomass-based solutions lead this transition: biodiesel and renewable diesel. Both biomass-based fuels significantly reduce environmental toxicity, but due to their distinct chemical structures have stark differences in engine compatibility, storage stability, and thermal performance.

This paper summarizes three forms of diesel and compares them. It covers the chemical identity of the above diesels and the basic mechanics behind their different production steps, as well as their different properties resulting from the divergence in synthesis steps. It touches upon the environmental impact of the fuels and what goes into minimizing this impact. The paper also establishes global and US specific commercial trends. The goal of the paper is to bring together all the components of this summary to inform upon these fuels and allow a direct comparison between them.

Chemical Identity and Production Mechanics

Petroleum diesel:

Petroleum diesel, often referred to as petrodiesel, is a complex mixture derived from crude oil that contains alkanes, aromatics, and sulfur compounds. Figure 1 shows crude oil's components and their structures. Refineries will limit or process aromatics through hydrotreating depending on the intended fuel specifications, while non-hydrocarbon impurities—such as sulfur, nitrogen, and metals—are systematically removed via catalytic separation processes. The removal of sulfur components will be further discussed below. The ideal components of refined petrodiesel are straight-chain alkanes, with hexadecane (or cetane) being the high-quality reference compound on the cetane scale.

The cetane scale measures diesel fuels ignition quality. It indicates how quickly and smoothly the fuel ignites under the high heat and pressure of a diesel engine's cylinder. The scale ranges from 0 to 100, where higher numbers represent faster and more complete combustions. Cetane is assigned a rating of 100, as it serves as the high-quality reference compound, whereas highly branched or aromatic compounds exhibit significant ignition delays and low CN ratings. For example, cyclic alkanes have ring structures that resist breaking apart and possess higher ignition resistance, so they tend to have low to moderate cetane numbers [1, 2].

The components of petrodiesel also affect other properties. The presence of large branched-alkanes dicyclic-alkanes ,and cycloalkanes have the potential to strongly increase the kinematic viscosity of a fuel [1, 3]. The viscosity determines how much the fuel resists flowing, which is an important consideration in engine design and application.

A myriad of additives are incorporated in modern petrodiesel. An additive is an engineered chemical substance mixed into diesel to improve engine performance, clean internal parts, and/or protect the fuel system, and is generally defined in fuel as a component added at less than 1% w/w. Anything added to fuels at a greater amount are considered blending components. Fuel additives are used as combustion modifiers, antioxidants, corrosion inhibitors and deposit control detergent [4, 5]. A few common additives are described in Table 1, although other important additives include conductivity improvers and biocides.

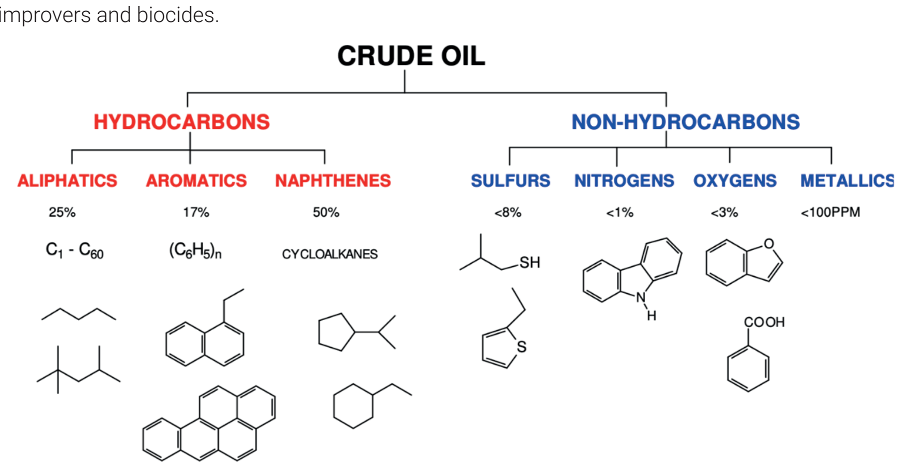

Figure 1. Composition of crude oil [6].

Table 1. Common fuel additives [4, 5, 7].

Additive	Purpose	Description
Monoacids or esters	Lubricity improver	Prevent friction inside high-pressure fuel pumps and injectors
Polyether amine (PEA)	Detergents	Disperse carbon deposits in injector openings
Copolymers (Wax anti-settling agents (WASA) and cloud point depressants)	Cold flow improvers	Break up heavy paraffin waxes that crystalize and freeze in cold weather
Phenol or amine-based antioxidants	Fuel Stabilizers and Antioxidants	Extend shelf-life by preventing degradation and oxidation

Biodiesel:

Biodiesel is a long chain of fatty acid methyl/ethyl esters produced via the transesterification process, where triglyceride and alcohol (commonly methanol or ethanol) react under catalytic conditions to produce biodiesel and glycerol. Figure 2 shows the chemical structures in this process, including the product produce mono-alkyl ester, or biodiesel. The triglyceride can be derived from a multitude of feedstocks, including edible and non-edible plants, animal fats, used cooking oils, and algae [8]. Of these feedstocks algae proves to be the most interesting, as algae is relatively easy to grow and does not impede on food consumption, although it requires a tremendous amount of water and space to produce in mass. Despite the potential of algae-based biodiesel, much research still must be done on improving the process of harvesting algae [9].

To achieve the most desirable outcome for a biodiesel, producers can select specific feedstocks, change the type of alcohol used, apply chemical additives, and blend it with petrodiesel. When selecting feedstock, producers choose feedstocks based on their fatty acid chains because longer carbon chains increase the fuel's cetane number, but also its viscosity. The degree of saturation within the chains affects stability and cold-flow properties. Methanol is most used in transesterification to produce Fatty Acid Methyl Esters (FAME), which is cheap and efficient to make. Heavier/branched alcohols can also be used to improve cold properties, but they raise production costs as well as increasing viscosity. Chemical additives are mostly similar to those added to petrodiesel, although the importance of biocides and stabilizers is increased [10]. Most biodiesels are blended with standard diesel fuel to optimize the chemical properties by inheriting the superior lubricity and low sulfur of biodiesel while maintaining the excellent cold-weather fluidity of petrodiesel.

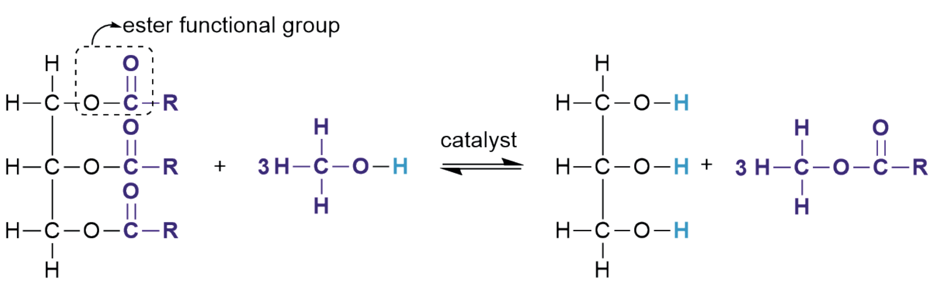

Figure 2. Transesterification of triglyceride and methanol to produce mono-alkyl ester (biodiesel) [11].

Renewable diesels:

Renewable diesels are fuels that simulate the composition of petrodiesel. They consist of paraffinic hydrocarbons synthesized from the same lipid feedstocks biodiesels are derived from, but go through a different process of catalytic hydroprocessing, pyrolysis, decarboxylation, or gasification [1]. As illustrated in Figure 3, hydrodeoxygenation (HDO) serves as the primary commercial processing pathway, wherein hydrogen reacts with triglycerides over heterogenous catalysts under elevated temperatures and pressures to strip oxygen atoms and saturate double bonds. Unlike biodiesel production, which generates glycerol as a waste stream, HDO's byproduct is propane (C3H8), a valuable, high-energy co-product that can be captured and utilized as a secondary fuel source or refinery feedstock [1]. Renewable diesel's structure is chemically incredibly similar to petrodiesel and is made up of the aliphatics shown in Figure 1, but does not contain any of the aromatics, naphthenes, or impurities present in petrodiesel. Figure 4 exemplifies this general process. Depending on which process is used in the synthesis of renewable diesel, the oxygens can be removed in the form of water, carbon dioxide, or carbon monoxide.

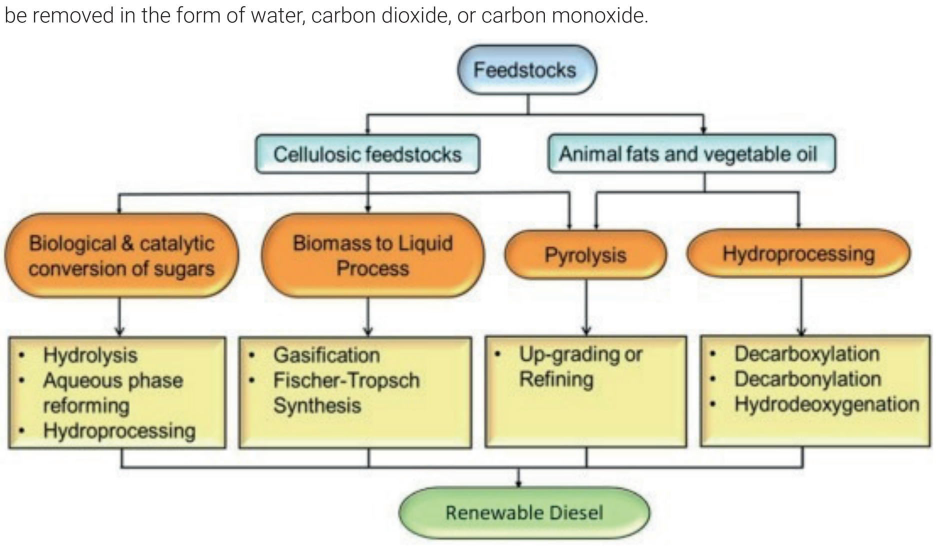

Figure 3. Process paths to synthesize renewable diesel [12].

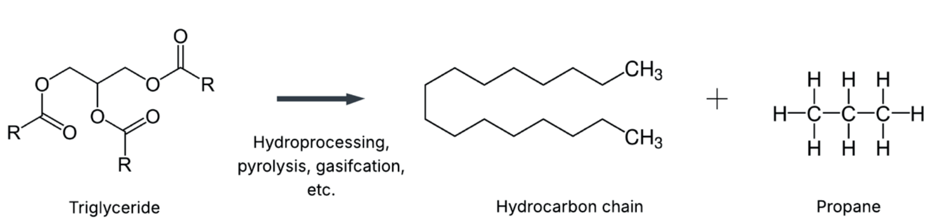

Figure 4. Triglyceride to renewable diesel and propane.

Property and performance comparisons:

Table 2. Property and performance comparisons [13, 14].

Fuel property	Petrodiesel	Biodiesel	Renewable diesel
Chemical structure	Alkanes + Aromatics/ PAHs	Fatty Acid Esters	Iso- & Normal Alkanes
Cetane number (CN)	40-50	50-65	70-90
Energy density (per kg)	100% (baseline)	10-12% lower	Nearly identical to petrodiesel
Density at 15℃ (g/mL)	0.831	0.880	0.785
Oxidation stability	High	Low	High
Cold flow	Varies	Poor	Excellent (With isomerization)
Engine compatibility	Direct use	Blends with petrodiesel	Drop-in fuel

Table 2 summarizes the properties of the different types of fuels. Higher cetane number, good stability, high energy density, and direct engine compatibility are desirable for quality fuel. Chemical structure plays a large role in these properties. Cold flow properties determine the functionality of fuel under cold weather.

Biodiesel completely differs from petrodiesel in chemical makeup but nonetheless has similar density. Due to the presence of vegetable oils or animal fat and the process of transesterification, biodiesel lacks long storage life. First, it is more susceptible to microbial contamination than other diesels, which can cause the injectors to clog. It is also vulnerable to attack and breakdown from oxygen exposure [15]. Another key drawback with biodiesel is that it has about a 10–12% lower energy density than traditional petrodiesel, which means more biodiesel is required to achieve the same outcome as fossil fuels [16]. Fortunately, because biodiesel has similar properties as petrodiesel, they can be combined at around a 1:4 ratio to achieve a cleaner product with less carbon dioxide and sulfur emissions, that also improves the lubricity of desulfurized petrodiesel [17].

Renewable diesel has the benefit of being a drop in fuel that requires no addition with petrodiesel. Although, because renewable diesel is synthesized to consist mainly of normal (straight chain) saturated hydrocarbons in the C_{15}–C_{18} range, they have poor cold flow properties with a high freezing point above 15 °C despite also having a high cetane number. Renewable diesel can just be combined with petrodiesel to eliminate this issue, but it can also undergo hydro isomerization of the normal saturated hydrocarbons into branched chain isomers, resulting in a lower freezing point appropriate for use in engines under cold weather and cold start conditions. Hydro isomerization is a chemical process that converts straight-chain alkanes into branched-chain isomers using hydrogen and specialized catalysts that rearrange the molecular skeleton of the fuel's components. The trade-off is lowering the CN from near 100 down to 70-90, which does not cost renewable diesel the advantage of having the highest CN [15].

Environmental impact

The combustion of petrodiesel leads to the production of sulfur-containing compounds, which are incredibly harmful to human health and the environment, and are known to cause acid rain. Due to this result, the Environmental Protection Agency (EPA) regulates the amount of sulfur allowed in fuels to a limit of 15 part per million [18]. Companies that use or produce diesels must find ways to be below these limits.

Hydrodesulfurization is an energy-intensive chemical technique often employed in refineries to remove sulfur-containing compounds from petrodiesel. It is performed at high temperature and pressure in the presence of a transition metal catalyst. Other methods such as adsorptive desulfurization and biodesulfurization are less common, as they have drawbacks in stability and reusability [14]. Removing sulfur from oil is a necessary extra step to ensure environmental and human safety, but it increases the energy required for fuel production, therefore adding a new drawback to petrodiesel.

Biofuels, which includes biodiesel and renewable diesel, contain less sulfur components, and release less sulfur oxide into the atmosphere [15]. They also contain fewer polycyclic aromatic hydrocarbons (PAHs) than petrodiesel. The absence of these undesirable components is due to the renewable sources of biofuels, which are derived from biological plant oils and animal fats rather than ancient fossil deposits. The fossil matter from which petrodiesel is derived contains heavy organic compounds holding trace minerals, sulfur, and aromatics that turn into PAHs [19]. PAHs contribute to particulate emissions, so bio and renewable diesels lower particulate matter, as well as sulfur oxides and greenhouse gas (GHG) emissions. Studies performed by Yage Di et al. demonstrated that blends with biodiesels lower the particulate matter in emissions, with more biodiesel resulting in less unwanted emissions [20]. Although they still release emissions, they are less toxic and at a lower scale, making them valuable from an environmental perspective.

While biodiesel's rapid decomposition proves to be an issue in its storage as a fuel that results in more fuel wasted, it turns into a benefit when looked at through an environmental lens. Figure 5 shows how much faster biodiesel experiences mass loss percentage in artificial weathering over time. The breakdown that results in mass loss makes biofuel desirable in the instance of a maritime oil spill, where regular petrodiesel or renewable diesel would take far longer to degrade and do more damage on the environment.

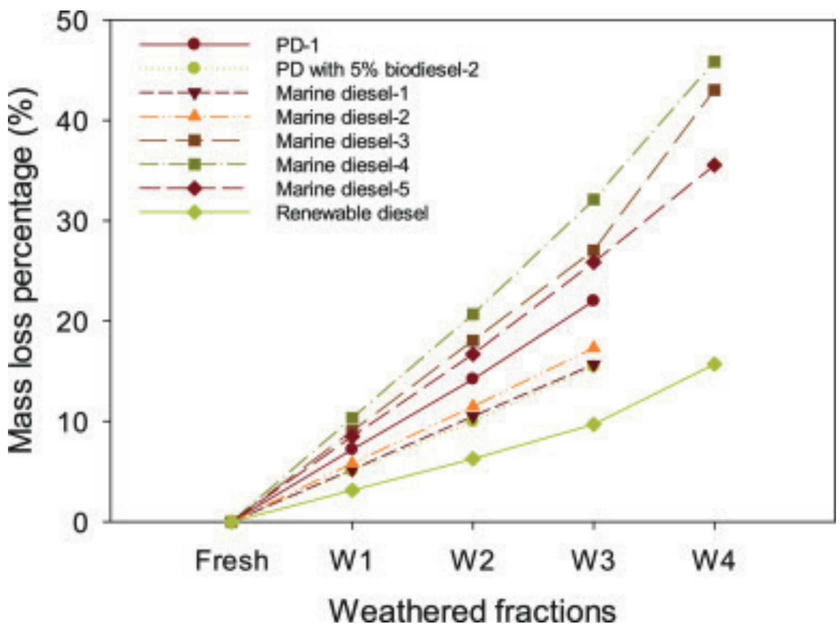

Figure 5. Mass loss percentage of oils with artificial weathering [13].

Commercial trends

The commercial landscape for biomass-based diesels has expanded rapidly, driven in the U.S. by national decarbonatization policies such as the Environmental Protection Agency's (EPA) Renewable Fuel Standard (RFS) and regional low-carbon fuel programs. Renewable diesel consumption has grown significantly in the last couple of years, despite brief domestic dips within the U.S. in the first quarter of 2025 . Domestic renewable diesel production capacity has surpassed biodiesel capacity due to its superior performance as a stand-alone "drop-in" fuel [18, 21]. In the second half of 2025 (2H25) the United States produced around 250,000 barrels per day and exported nearly 50,000 barrels of renewable diesel and other biofuels per day, as shown in figure 6. The majority of U.S. biofuel feedstock consists of corn and soybean oil. Of the exports, about half of these exports went to Canada, with the rest mostly going to Europe [22].

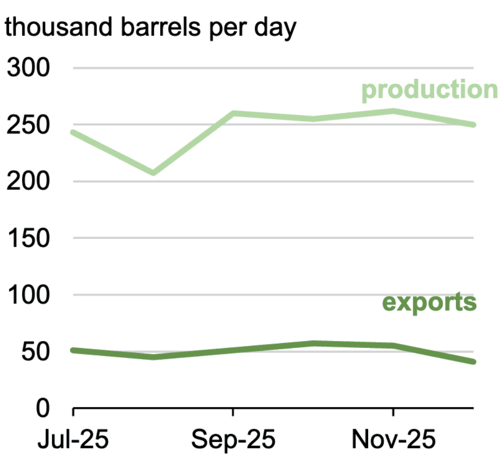

Figure 6. Monthly production and exports of U.S. renewable diesels and other biofuels (note sustainable aviation fuel (SAF) is included in these values but considered negligible compared to renewable diesel due to low U.S. SAF production) [22].

On a worldwide scale, Brazil, Indonesia, and India are emerging as biofuel consumers. Both renewable diesel and biodiesel have experienced trends of increased demand. Renewable diesel is set to increase demand by 20.4 billion from 2023-2028, thereby over doubling its demand of 18.6 billion in 2023. Biodiesel is also seeing a steady increase in demand and is set to experience a 20-billion-liter expansion between 2023 and 2028 [23]. Feedstocks used in biofuel production vary based on region, but include soybean, corn, cassava, sugarcane, palm oil, canola oil, and used cooking oil (UCO) [24].

While large-scale hydrotreating facilities benefit from integrated refinery pipelines and hydrogen infrastructure, small-scale producers face significant economic friction. Capital intensity for hydrodeoxygenation and catalytic isomerization units remains prohibitively high for localized operators, who frequently remain restricted to small-scale transesterification plants that produce biodiesel [25].

Conclusion

Petroleum diesel remains the historic benchmark for heavy transport due to its high volumetric energy density and established refining infrastructure. However, sulfur limitations, greenhouse gas mandates, and concern over long-term renewability of fossil fuels necessitate cleaner alternatives from new sources. Biodiesel serves as an effective biodegradable additive that restores lubricity to Ultra-Low Sulfur Diesel and reduces toxic particulate emissions, ideal for use in transportation, especially marine transportation. However, its low energy density, thermal instability, and cold-flow constraints restrict its utility to low-concentration blends (B5–B20).

Renewable diesel successfully overcomes the chemical limitations biodiesel faces. By utilizing hydrodeoxygenation and isomerization, renewable diesel produces clean, paraffinic hydrocarbons that match petrodiesel's energy content while delivering superior cetane ratings and cold-weather performance without engine modifications. Although its production requires significant energy and catalytic infrastructure, market data demonstrates that it is rapidly becoming the dominant bio-alternative. Future developments must focus on optimizing hydroprocessing catalysts, expanding non-food lipid feedstocks, and improving local processing economics for smaller industrial facilities.

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