

## GREENER OPTIONS FOR FOSSIL DIESEL SDG 7.2

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### Abstract

Diesel engines remain essential to electricity generation, on- and off-road transport, and particularly maritime operations, where rapid or cost-effective fleet turnover is impractical. Decarbonization therefore requires transitional pathways that lower emissions while leveraging the existing fleet. This study conducts an integrative literature review to assess hydrotreated vegetable oil (HVO, “renewable diesel”), fatty acid methyl ester biodiesel (FAME), and fuel additives as options for diesel-dependent sectors. The analysis is structured around four criteria: (i) economic cost, (ii) feedstock availability, (iii) technical performance and engine compatibility, and (iv) environmental impact, especially greenhouse-gas (GHG) emissions. Evidence indicates that HVO is fully miscible with fossil diesel and can be used at any blend ratio, including as neat fuel (HVO100), subject to manufacturer approval. Its paraffinic composition ensures a high cetane number, excellent storage stability, and reductions of 50–90% in life-cycle CO<sub>2</sub>, though current production costs are 25–90% higher than fossil diesel. FAME biodiesel provides meaningful benefits at blends up to B20, with typical GHG reductions of 30–60%, but faces constraints from oxidation instability, deposits, and cold-weather performance. Environmentally, HVO consistently lowers particulate matter, CO, and hydrocarbons, with generally favorable NO<sub>x</sub> outcomes, while biodiesel blends deliver moderate reductions, though results vary by feedstock. Additives emerge as a pragmatic bridge: they improve lubricity, stability, and combustion efficiency with marginal cost increases of 1–3%, delivering incremental GHG reductions. Together, these options contribute directly to the Sustainable Development Goals—SDG 7 (energy diversification), SDG 12 (waste-based feedstock use), and SDG 13 (climate action). From a temporal perspective, biodiesel and additives provide immediate, low-cost improvements; HVO stands out as the most technically robust medium-term pathway; and renewable matrices such as electrification and natural gas represent long-term strategies once infrastructure expands. Overall, HVO is highlighted as a feasible decarbonization option for the medium term, while biodiesel and additives prepare the ground for its broader deployment.

**Keywords:** Diesel; Energy transition; HVO; Biodiesel; Greenhouse gases.

## 1 Introduction

Fossil diesel, also referred to as mineral diesel or simply diesel, is a liquid energy carrier widely used across transport and industry. Derived from petroleum refining, its combustion releases greenhouse gases (GHG) and air pollutants that contribute to climate change and adverse health impacts (SOUTHERN et al., 2021; SONTALIA; KUMAR, 2023). Despite advances in alternative technologies such as electrification and renewable energy systems, the global prevalence of diesel-powered assets makes their complete replacement technologically and economically challenging in the short term, particularly in sectors such as maritime transportation and heavy-duty applications (NORDELÖF; ROMARE; TIVANDER, 2019; XIAO et al., 2022). Fleet turnover demands high capital expenditure (CAPEX), infrastructure readiness, and technological maturity, which remain barriers to rapid substitution (WOJCIESZYK et al., 2019).

In this context, biofuels represent transitional solutions that can reduce emissions while using existing fleets and, in some cases, recycle materials that might otherwise harm the environment. Biodiesel, typically produced from feedstocks such as algae, vegetable oils, used cooking oil, or animal fats, has been widely adopted in low to medium blends (WEI et al., 2021). Its main limitation is that fatty acid methyl ester (FAME) biodiesel is not fully compatible with conventional engines, as higher blends may lead to injector deposits, filter clogging, fuel tank corrosion, and poor oxidation stability (ZHANG et al., 2019; SUKMONO et al., 2023). These issues restrict its share in blends, commonly capped at 20% (B20) in most markets (AVARSKII et al., 2019).

A more recent alternative is hydrotreated vegetable oil (HVO), also referred to as renewable diesel. HVO is produced via hydrotreatment of waste fats, oils, and other biomass feedstocks, resulting in a paraffinic fuel with properties comparable—or in some respects superior—to fossil diesel (SIMACEK et al., 2019; ZEMAN et al., 2019). Unlike FAME, HVO presents high cetane numbers, excellent oxidation stability, favorable cold-flow behavior, and lower density than EN590 diesel, while maintaining compatibility with diesel engines when approved by manufacturers under EN 15940 standards (BJØRGEN; EMBERSON; LØVÅS, 2020; FATHURRAHMAN et al., 2023). The largest producer, Neste, currently reports renewable fuel production capacity of about 5.5 million tons annually across three continents (SIMACEK et al., 2019).

Given the urgent need to reduce emissions, international policy targets are reshaping the energy landscape. The European Union, for example, has raised its renewable energy target to at least 42.5% of total consumption by 2030, with an aspirational goal of 45% (KARLSSON POTTER; YACOUT; HENRYSON, 2023). Similarly, the International Maritime Organization (IMO) updated its greenhouse gas strategy in 2023, now aiming for net-zero emissions from international shipping by or around 2050, with intermediate milestones such as the adoption of zero or near-zero GHG fuels by 2030 (XIAO et al., 2022). These developments place increasing emphasis on alternatives like HVO, alongside more immediate measures such as biodiesel blending, additives, and engine upgrades.

Thus, the objective of this article is to analyze, through an integrative literature review, the technical, environmental, and economic feasibility of using HVO in diesel engines, in comparison with conventional biodiesel and incremental solutions such as additives. This analysis is directly aligned with the Sustainable Development Goals, particularly SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action). The comparison is structured around four criteria: economic feasibility, feedstock availability, technical performance, and environmental impact, providing a systematic basis for assessing the role of these fuels in the diesel transition.

## 2 Literature Review

### 2.1 The Energy Transition

The energy transition is driving global efforts to reduce greenhouse gas (GHG) emissions and mitigate climate change. A key milestone was the 2015 Paris Agreement, in which nations committed to limit global warming to well below 2 °C above pre-industrial levels, with continued efforts to pursue a 1.5 °C pathway (SOUTHERN et al., 2021). While the primary focus is on reducing GHG, air pollution is also closely associated with fossil fuel combustion. Pollutants emitted together with GHG have direct links to adverse health outcomes, particularly cardiovascular and respiratory diseases (SONTHALIA; KUMAR, 2023). Consequently, stricter policies and regulations are being implemented worldwide to improve both engine technologies and fuel quality (RODRÍGUEZ-FERNÁNDEZ et al., 2019; SAISIRIRAT et al., 2024).

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Diesel remains particularly relevant because of its high thermodynamic efficiency and lower fuel consumption relative to gasoline engines (FATHURRAHMAN et al., 2023), making it the dominant fuel in freight, maritime, and industrial sectors. However, diesel combustion produces a mixture of CO<sub>2</sub>, NO<sub>x</sub>, CO, particulate matter (PM), and unburned hydrocarbons (GREN et al., 2021). While electrification and alternative powertrains are emerging, full replacement of diesel engines remains a complex challenge, particularly in heavy-duty applications (NORDELÖF; ROMARE; TIVANDER, 2019). The continued growth in diesel demand also raises concerns over energy security and exposure to fluctuations in fossil fuel supply (WEI et al., 2021).

## 2.2 Biodiesel

Biodiesel has long been considered a partial substitute for fossil diesel. Fatty acid methyl ester (FAME) biodiesel is produced primarily via the transesterification of vegetable oils or animal fats, and can also be derived from waste cooking oils and algae (ZHANG et al., 2019). It offers clear environmental benefits, including reductions in CO, PM, and hydrocarbons relative to fossil diesel, and can partially close the carbon loop by recycling waste feedstocks (AVARSKII et al., 2019). In socio-economic terms, biodiesel production also supports rural economies by generating employment and diversifying agricultural markets (AVARSKII et al., 2019).

Nonetheless, biodiesel is limited by blend compatibility. Typical commercial blends include B2, B5, and B20, with B100 restricted to controlled contexts due to its poor oxidation stability and tendency to generate injector deposits, filter clogging, and elastomer degradation (SIMACEK et al., 2019). Additional drawbacks include higher viscosity, lower energy content compared to diesel, and susceptibility to hydrolysis and polymer degradation in the presence of water (WEI et al., 2021). In cold climates, biodiesel's high cloud and pour points necessitate blending with fossil diesel to ensure operability (ZEMAN et al., 2019). These technical limitations explain why biodiesel is seen more as a transitional and partial solution rather than a long-term replacement (SUKMONO et al., 2023).

These benefits, particularly when using waste-based feedstocks such as used cooking oil, align directly with SDG 12 (Responsible Consumption and Production), by promoting circular economy practices and reducing environmental burdens associated with waste disposal.

## 2.3 Hydrotreated Vegetable Oil (HVO)

Hydrotreated vegetable oil (HVO), also called renewable diesel, has emerged as one of the most promising alternatives. Produced by hydrotreating biomass-derived oils and fats, HVO yields a paraffinic fuel with properties that are highly compatible with diesel engines (SONDORS et al., 2019). Unlike FAME, HVO presents a lower density than fossil diesel (typically 6–7% lower), a high cetane number, excellent storage stability, and favorable cold-flow characteristics (BJØRGEN; EMBERSON; LØVÅS, 2020; FATHURRAHMAN et al., 2023). These properties enable superior ignition quality, cleaner combustion, and reduced engine noise (SIMACEK et al., 2019).

HVO is also free of oxygen and aromatics, which contributes to lower particulate emissions compared to fossil diesel (GREN et al., 2021). Studies consistently report reductions in CO, hydrocarbons, and PM, with mixed but generally favorable results for NO<sub>x</sub> (SAISIRIRAT et al., 2024). Importantly, some experimental work indicates that blends of HVO with biodiesel may increase aerosol emissions; however, aerosols are not greenhouse gases, but atmospheric particulates with distinct health and climate effects (DOBRZYŃSKA et al., 2020).

From a practical perspective, HVO can be blended with fossil diesel in any proportion and, where approved by manufacturers, can be used as neat fuel (HVO100) under EN 15940 standards (WOJCIESZYK et al., 2019). One consideration is lubricity: neat HVO has lower inherent lubricity compared to fossil diesel, but this is addressed through mandatory lubricity additives required by EN 15940, ensuring safe operation without modifications (ZEMAN et al., 2019).

The main limitation for HVO remains economic rather than technical. Its production cost is currently 25–90% higher than fossil diesel, depending on feedstock and region (ŽAGLINSKIS; RIMKUS, 2023). Expansion also depends on the scalability of waste-based feedstocks and the availability of hydrogen for processing (WEI et al., 2021). Nonetheless, the largest producer, Neste, now reports a renewable production capacity of about 5.5 million tons annually across three continents (SIMACEK et al., 2019).

By enabling diversification of the energy matrix and significant reductions in life-cycle CO<sub>2</sub> emissions, HVO contributes directly to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), reinforcing its role as a medium-term pathway within the diesel transition.

### **3 Method**

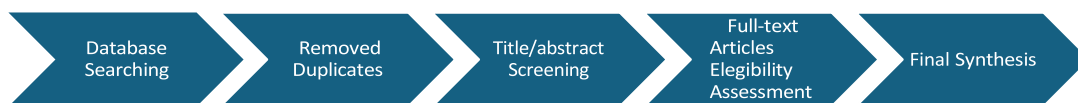
This study employed an integrative literature review to synthesize current knowledge about the technical, environmental, and economic feasibility of hydrotreated vegetable oil (HVO) as an alternative to fossil diesel and conventional biodiesel. Unlike systematic reviews, which are limited to predefined protocols, integrative reviews enable the combination of empirical, theoretical, and review studies, allowing for a broader and more flexible understanding of the research topic (SOUZA; SILVA; CARVALHO, 2010).

The review process involved several stages. First, a search was conducted in Scopus and ScienceDirect databases between March and July 2024. Keywords used included: “hydrotreated vegetable oil”, “renewable diesel”, “HVO100”, “biodiesel blends”, “diesel emissions”, “GHG reduction”. Searches were restricted to open-access publications in English, from 2019 onwards, to capture the most recent technological and environmental evidence.

Inclusion criteria were: (i) studies analyzing HVO production processes, properties, or applications in diesel engines; (ii) studies comparing HVO with fossil diesel or biodiesel in terms of emissions, performance, or costs; (iii) review papers and reports addressing renewable diesel in the context of energy transition. Exclusion criteria were: (i) articles not available in full text; (ii) studies not focused on energy or transportation applications; and (iii) works published before 2019, unless they were widely cited seminal references.

The selection process followed three steps: (i) screening of titles and abstracts; (ii) full-text reading of eligible studies; (iii) organization of the final sample in thematic categories. The articles were then analyzed qualitatively, with findings grouped into three dimensions: (a) technical and operational aspects; (b) environmental and emissions outcomes; and (c) economic and implementation challenges, per Figure 1.

Figure 1 – Flow diagram of the integrative review process



Source: Adapted from PRISMA methodology (PAGE et al., 2021).

#### 4 Discussion

The reviewed literature can be organized into three main themes: technical performance and compatibility in diesel engines, environmental and health impacts, and economic and implementation challenges (SONTHALIA; KUMAR, 2023; FATHURRAHMAN et al., 2023).

Biodiesel is more broadly available and may represent a more immediate opportunity for emission reduction, with the literature frequently indicating that a 20% blend (B20) provides a balance between emission benefits and the mitigation of technical risks (ZEMAN et al., 2019; SONTHALIA; KUMAR, 2023). Where possible, adopting more efficient engines such as Euro 6 can also contribute to reducing emissions without altering the fuel supply chain. However, this alternative poses a CAPEX challenge due to the need for fleet renewal (NORDELÖF; ROMARE; TIVANDER, 2019). Even so, Euro 6 engines can benefit from the use of HVO, which has been shown to provide high compatibility and strong performance (SIMACEK et al., 2019; BJØRGEN; EMBERSON; LØVÅS, 2020; FATHURRAHMAN et al., 2023).

While SIMACEK et al. (2019) emphasize the absence of blending issues between HVO and fossil diesel, SONTHALIA and KUMAR (2023) suggest that combining HVO with biodiesel can generate additional performance benefits, pointing to potential synergies. On the other hand, BJØRGEN, EMBERSON and LØVÅS (2020) reported differences in soot behavior between HVO and diesel, highlighting the need for further engine testing under real-world conditions. These contrasts demonstrate that although there is broad consensus on HVO's technical feasibility, debates remain on its cost-effectiveness and comparative performance against biodiesel.

The inclusion of additives highlights not only their role in improving biodiesel and HVO properties, but also their potential to upgrade fossil diesel itself. ZEMAN et al. (2019) and FATHURRAHMAN et al. (2023) suggest that lubricity and fuel stability are central for performance. Extending these findings, SONTHALIA and KUMAR (2023) argue

that additive development can contribute to combustion efficiency and lower emissions. This provides a gradual transition pathway: fleets that cannot yet adopt HVO may still benefit from additives in conventional diesel, thereby reducing emissions and improving efficiency while infrastructure and supply chains for HVO are scaled up.

To illustrate the comparative trade-offs, Table 1 summarizes approximate values drawn from the reviewed literature.

Table 1 - Estimated trade-offs by potential solution

Criterion	HVO (Renewable Diesel)	Biodiesel (FAME)	Additives
CO <sub>2</sub> reduction (life cycle)	50–90%	30–60% (feedstock dependent)	5–10% (via improved combustion)
Production cost vs. fossil diesel	+25–90%	+10–30%	+1–3%
Storage stability	High (years)	Moderate (3–6 months, oxidation risk)	High (maintains stability)
Engine compatibility	Full (up to 100%, EN 15940)	Limited ( $\leq$ 20% blends)	Full (any proportion)

Source: elaborated from the integrative literature review

These values reinforce the structured comparison across economic, availability, technical, and environmental criteria, showing that biodiesel and additives deliver accessible short-term gains, HVO stands out as the most robust medium-term option, and renewable matrices remain a long-term pathway. This perspective is directly aligned with SDG 7, SDG 12, and SDG 13, underscoring the contribution of each alternative to the broader energy transition.

Finally, pursuing the replacement of the current energy matrix with alternatives such as electricity, natural gas, solar, or wind requires not only additional CAPEX but also a complete rethinking of the energy supply chain (NORDELÖF; ROMARE; TIVANDER, 2019; WOJCIESZYK et al., 2019). Table 1 presents a qualitative assessment of available technological alternatives for asset managers seeking options to replace fossil diesel. Each option is rated on a scale from 1 to 5, where 5 indicates the best performance or easiest implementation and 1 represents the lowest performance or the highest implementation challenge. In terms of availability, Euro 6 engines and Biodiesel (B20) are relatively accessible in the current market (ZEMAN et al., 2019), while HVO and renewable energy matrices remain limited due to cost and infrastructure challenges (FATHURRAHMAN et al., 2023). Additives to fossil diesel present high availability since they can be blended directly into existing fuels (SONTHALIA; KUMAR, 2023).

Compatibility also differs: Euro 6 engines are designed to meet strict standards (ZEMAN et al., 2019), but biodiesel blends present technical challenges such as injector deposits (SUKMONO et al., 2023). HVO demonstrates high compatibility with existing engines (BJØRGEN; EMBERSON; LØVÅS, 2020), while new matrices such as electrification require completely different platforms (NORDELÖF; ROMARE; TIVANDER, 2019). Additives maintain full compatibility with current diesel engines (ZEMAN et al., 2019).

Regarding CAPEX, new Euro 6 fleets and renewable matrices demand high investments (NORDELÖF; ROMARE; TIVANDER, 2019). Conversely, HVO and biodiesel require moderate to high CAPEX depending on supply (ŽAGLINSKIS; RIMKUS, 2023). Additives require minimal or no capital investment, since they can be integrated into existing distribution chains (SONTHALIA; KUMAR, 2023).

On OPEX, operation costs for Euro 6 and biodiesel remain moderate (ZEMAN et al., 2019), while HVO is still expensive per liter (ŽAGLINSKIS; RIMKUS, 2023). Renewable matrices such as solar and electric may offer lower costs per kilometer once infrastructure is available (NORDELÖF; ROMARE; TIVANDER, 2019). Additives offer the lowest OPEX impact since they marginally increase fuel cost while reducing wear and maintenance (FATHURRAHMAN et al., 2023).

Implementation feasibility varies as well: Euro 6 and HVO require infrastructure adaptation (WOJCIESZYK et al., 2019), while biodiesel is easier to implement in limited blends (AVARSKII et al., 2019). Electrification requires a completely new ecosystem, making it one of the hardest solutions (NORDELÖF; ROMARE; TIVANDER, 2019). Additives present the lowest challenge as they integrate directly into fossil diesel supply chains (ZEMAN et al., 2019).

Concerning air pollution, HVO and renewable matrices provide greater reductions in pollutants (GREN et al., 2021; FATHURRAHMAN et al., 2023). Biodiesel shows moderate reductions but may increase NO<sub>x</sub> (DOBRZYŃSKA et al., 2020). Additives have a limited effect, improving combustion efficiency but not eliminating pollutants (SONTHALIA; KUMAR, 2023).

Regarding greenhouse gas (GHG) emissions, renewable matrices and HVO contribute to significant reductions (SIMACEK et al., 2019; FATHURRAHMAN et al., 2023). Biodiesel presents moderate benefits but may vary depending on feedstock (ZHANG et al., 2019). Additives provide only incremental reductions, mainly by improving combustion efficiency (SONTHALIA; KUMAR, 2023).

Table 2 - Qualitative assessment of options for technology options

Alternative	Availability	Compatibility	CAPEX	OPEX	Implementation	Air Pollution	GHG Emissions
<b>Euro 6 engines</b>	4 – Available in the market.	5 – Designed to meet strict standards.	1 – High investment for fleet renewal.	3 – Moderate costs.	2 – Requires fleet substitution and infrastructure	4 – Significant pollutant reduction	4 – Reduces GHG relative to older fleets (ZEMAN <i>et al.</i> , 2019)
<b>Biodiesel (B20)</b>	4 – Widely available blends (ZEMAN <i>et al.</i> , 2019)	3 – Moderate issues (injector deposits, clogging) (SONTHALIA; KUMAR, 2023)	3 – Moderate investment (FATHURRAHMAN <i>et al.</i> , 2023)	3 – Moderate operating costs (ZEMAN <i>et al.</i> , 2019)	4 – Easier to implement in existing fleets (SONTHALIA; KUMAR, 2023)	3 – Reduces PM, CO, HC but may increase NOx (ZEMAN <i>et al.</i> , 2019)	3 – Moderate reductions, feedstock dependent (ZEMAN <i>et al.</i> , 2019)
<b>HVO (Renewable diesel)</b>	2 – Limited availability due to supply (FATHURRAHMAN <i>et al.</i> , 2023)	5 – Fully compatible with existing engines (FATHURRAHMAN <i>et al.</i> , 2023)	3 – Moderate to high depending on region (FATHURRAHMAN <i>et al.</i> , 2023)	2 – Currently expensive per liter (FATHURRAHMAN <i>et al.</i> , 2023)	3 – Requires adaptation of logistics and supply chains (ZEMAN <i>et al.</i> , 2019)	5 – Strong reductions in PM, CO, HC, NOx (FATHURRAHMAN <i>et al.</i> , 2023)	5 – Significant GHG reduction (SONTHALIA; KUMAR, 2023)
<b>Renewable matrices (electric, solar, etc.)</b>	1 – Still limited by infrastructure (FATHURRAHMAN <i>et al.</i> , 2023)	1 – Requires new vehicle platforms (NORDELÖF; ROMARE; TIVANDER, 2019)	1 – Very high capital requirements (ZEMAN <i>et al.</i> , 2019)	4 – Low costs per km once infrastructure is deployed (FATHURRAHMAN <i>et al.</i> , 2023)	1 – Demands systemic ecosystem changes (NORDELÖF; ROMARE; TIVANDER, 2019)	5 – Eliminates local pollutants (FATHURRAHMAN <i>et al.</i> , 2023)	5 – Near-zero GHG at point of use (SONTHALIA; KUMAR, 2023)
<b>Additives</b>	5 – High availability, easy integration (SONTHALIA; KUMAR, 2023)	5 – Fully compatible with current diesel (SONTHALIA; KUMAR, 2023)	5 – Minimal investment needed (SONTHALIA; KUMAR, 2023)	4 – Very low additional cost, reduces maintenance (SONTHALIA; KUMAR, 2023)	5 – Easiest to implement in current fuel chains (SONTHALIA; KUMAR, 2023)	2 – Limited impact, improves combustion (SONTHALIA; KUMAR, 2023)	2 – Incremental GHG reduction only (SONTHALIA; KUMAR, 2023)

Source: Elaborated by the authors from the integrative literature review (2025).

## 5 Conclusion

Diesel-powered assets will continue to coexist with emerging technologies for the foreseeable future, not only due to the techno-economic challenges of scaling alternatives, but also because of the persistent high energy demand that prevents a full abandonment of fossil fuels in the short term (NORDELÖF; ROMARE; TIVANDER, 2019). Within this context, Euro 6 engines provide an immediate route to reduce pollutant emissions, although their large-scale adoption entails significant capital investment. Importantly, this option is most viable when fleet renewal is already planned, since its adoption requires substantial CAPEX (WOJCIESZYK et al., 2019).

From a policy and industrial perspective, the inclusion of additives emerges as a pragmatic and highly compatible incremental alternative. Unlike biodiesel or HVO, which depend on feedstock availability and infrastructure readiness, additives can deliver near-term benefits by improving combustion, reducing maintenance, and lowering emissions without requiring fleet replacement or fuel supply restructuring (ZEMAN et al., 2019; SIMACEK et al., 2019; SONTHALIA; KUMAR, 2023; FATHURRAHMAN et al., 2023). This positions additives not as competitors, but as complementary solutions—able to upgrade fossil diesel while also enhancing biodiesel blends already in use, thereby bridging the transition toward broader deployment of HVO.

The analysis also highlights that no single solution is universally optimal. As shown in Table 1, biodiesel blends represent a widely available and proven first step, though limited by maximum blending percentages and technical restrictions such as injector deposits and oxidation instability (SUKMONO et al., 2023; ZHANG et al., 2019). HVO, in turn, is highly compatible with existing engines and offers strong environmental benefits, but requires cost reductions and expanded production capacity to achieve commercial scale (SIMACEK et al., 2019; BJØRGEN; EMBERSON; LØVÅS, 2020; ŽAGLINSKIS; RIMKUS, 2023). Meanwhile, renewable energy matrices such as electrification and natural gas remain long-term pathways due to infrastructure and CAPEX barriers (NORDELÖF; ROMARE; TIVANDER, 2019; XIAO et al., 2022).

Finally, this integrative review identifies five main opportunities for future research: (i) reducing costs and scaling HVO production, particularly through alternative feedstocks and process optimization (SIMACEK et al., 2019); (ii) developing techno-economic models for blended fuels (diesel, biodiesel, and HVO) to minimize fossil use (SONTHALIA; KUMAR, 2023); (iii) conducting lifecycle and comparative assessments between HVO, electrification, and other alternatives (GREN et al., 2021); (iv) testing compatibility across different engine generations, including Euro 6 and legacy fleets (ZEMAN et al., 2019); and (v) analyzing regional supply chains and infrastructure readiness (KARLSSON POTTER; YACOUT; HENRYSON, 2023). Addressing these gaps will be critical to support both academic inquiry and industrial decision-making in advancing the energy transition.

In temporal terms, the findings confirm that biodiesel blends (up to B20) and additives provide the most accessible short-term solutions; HVO represents the most technically robust medium-term option, provided that production costs and supply constraints are addressed; and renewable matrices such as electrification, natural gas, and hydrogen remain long-term strategies dependent on systemic infrastructure. This staged perspective not only strengthens the comparative framework but also directly supports SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action), highlighting the role of transitional fuels in a gradual, multi-layered diesel decarbonization pathway.

## 6 Final Considerations

The findings of this integrative review suggest that the decarbonization of diesel-reliant fleets will not be achieved by a single disruptive solution, but rather through a portfolio of strategies deployed at different time horizons.

- Short term: Biodiesel blends (B20) and fuel additives offer immediate, cost-effective options to reduce emissions without demanding structural changes (AVARSKII et al., 2019; SONTHALIA; KUMAR, 2023).
- Medium term: HVO represents the most technically robust pathway, capable of full substitution for fossil diesel, provided that production costs and supply chain limitations are addressed (SIMACEK et al., 2019; FATHURRAHMAN et al., 2023).
- Long term: Electrification, natural gas, and other renewable energy matrices will become central once infrastructure and ecosystems are developed, enabling deeper decarbonization (NORDELÖF; ROMARE; TIVANDER, 2019; XIAO et al., 2022).

Thus, the energy transition in diesel-dependent sectors must be viewed as a gradual and multi-layered process. Additives and biodiesel blends serve as transitional tools, ensuring near-term improvements in emissions while preparing the ground for HVO expansion. Over time, as structural barriers are overcome, renewable matrices can complement or even replace liquid fuels entirely.

These staged strategies also reinforce alignment with the Sustainable Development Goals—SDG 7 (Affordable and Clean Energy), SDG 12 (Responsible Consumption and Production), and SDG 13 (Climate Action)—highlighting that decarbonization of diesel fleets is not only a technical challenge but also part of a global sustainability agenda.

For policymakers and industry leaders, the challenge is to design incentives, regulatory frameworks, and investments that encourage both incremental and structural solutions. For researchers, advancing the understanding of synergies among fuels,

additives, and emerging technologies will be essential to ensure that the diesel transition remains technically feasible, economically viable, and environmentally aligned with global climate goals (SONTHALIA; KUMAR, 2023; SOUTHERN et al., 2021).

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