



Review article



The role of biodiesel in marine decarbonization: Technological innovations and ocean engineering challenges

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ABSTRACT

The maritime sector, which contributes approximately 3 % to the total global greenhouse gas (GHG) emissions, is under increasing scrutiny to meet the decarbonization targets set forth by the International Maritime Organization (IMO) for the year 2050. Biodiesel, characterized by its renewable attributes and potential to diminish GHG emissions by as much as 80 %, emerges as a plausible alternative to traditional marine fuels. This research conducts a comprehensive analysis of the significance of biodiesel in the context of marine decarbonization, accentuating its benefits, which include reductions in Nitrogen oxide (Nox) emissions by up to 40 % and enhancements in fuel efficiency ranging from 3 % to 5 %, achieved through advancements such as nanoparticle additives and hybrid engine technologies. The study identifies challenges associated with biodiesel, including its 10 % to 12 % lower energy density and suboptimal cold flow characteristics, while proposing solutions that encompass innovative additives and thermal management strategies. The discourse further encompasses policy implications, logistical considerations of the supply chain, and the exploration of emerging feedstocks, notably algae-derived biodiesel. These insights establish biodiesel as a pragmatic, scalable, and ecologically sustainable fuel alternative for the maritime sector while delineating avenues to mitigate technological and operational challenges.

1. Introduction

The maritime industry accounts for approximately 3 % of global carbon dioxide (CO₂) emissions, surpassing an annual figure of 900 million metric tons. Considering the IMO's ambitious objective to curtail GHG emissions by 50 % by the year 2050, the sector is under significant pressure to undertake decarbonization measures [1]. Initiatives such as IMO 2020, which impose restrictions on sulfur content in marine fuels to a maximum of 0.5 %, have intensified the quest for sustainable alternatives to traditional marine fuels. In this framework, biodiesel is positioned as a viable renewable fuel, presenting compatibility with existing marine engines while facilitating substantial reductions in emissions [2]. Empirical studies indicate that biodiesel blends, including B20 (20 % biodiesel, 80 % conventional diesel) and B100 (100 %

biodiesel), have the potential to diminish GHG emissions by as much as 80 %, particulate matter (PM) emissions by 60 %, and carbon monoxide (CO) emissions by 50 % when contrasted with conventional marine fuels [3].

Notwithstanding its merits, biodiesel encounters multiple obstacles that impede its broader implementation in marine contexts. A principal constraint is its energy density, which is approximately 10–12 % inferior to that of conventional marine diesel [4]. This discrepancy results in augmented fuel consumption, thereby necessitating larger storage capacities. Moreover, the cold flow characteristics of biodiesel, which influence its efficacy in low-temperature scenarios, may precipitate operational interruptions in frigid regions [5]. Nevertheless, innovations in engine design and fuel systems are effectively mitigating these issues. Technologies such as dual-fuel engines enable vessels to transition

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seamlessly between biodiesel and conventional diesel, thereby enhancing fuel reliability and operational adaptability. Furthermore, enhancements in fuel injection systems have exhibited thermal efficiency improvements ranging from 3 to 5 %, thereby rendering biodiesel a more feasible alternative for marine applications [6].

In addition to biodiesel, alternative marine fuels such as hydrogen and ammonia are increasingly coming into focus. Hydrogen presents the advantage of producing zero carbon emissions during combustion; however, its storage and transportation necessitate specialized infrastructure, and the production process frequently entails substantial energy consumption unless derived from renewable sources [7]. Ammonia, another low-carbon alternative, holds promise as a marine fuel but raises safety concerns due to its toxicity and necessitates considerable modifications to pre-existing engines and storage systems. In contrast, biodiesel provides immediate scalability owing to its compatibility with current marine infrastructure, thus positioning it as a pragmatic solution for short-term decarbonization initiatives [8].

Innovations in biodiesel-blended hybrid technologies are paving novel avenues for mitigating the maritime sector's carbon footprint [9]. Hybrid systems amalgamate biodiesel with renewable energy sources such as wind and solar, thereby enhancing overall energy efficiency and diminishing reliance on fossil fuels. These systems bolster operational resilience and align with sustainability aspirations. For instance, hybrid marine vessels that integrate biodiesel with solar panels have demonstrated considerable reductions in emissions while sustaining operational dependability [10].

Another noteworthy advancement is the utilization of algae-based biodiesel, which presents a sustainable feedstock characterized by high yields and minimal land utilization compared to traditional biofuel sources [11]. Ongoing research into the cultivation, extraction, and processing of algae-based biodiesel is progressing, addressing scalability challenges while concurrently reducing costs. Additionally, the exploration of nanoparticle additives is being pursued to enhance combustion efficiency and further lower emissions, especially nitrogen oxides (NO_x) [12].

This scholarly review concentrates on the incorporation of biodiesel within marine technology, scrutinizing its compatibility with existing systems, the associated technical challenges, and the latest advancements in the field. Through a comprehensive analysis of its function in conjunction with other alternative fuels and hybrid systems, this investigation emphasizes biodiesel's substantial potential to play a pivotal role in the decarbonization of the maritime sector while simultaneously addressing the technological obstacles that must be surmounted for its widespread implementation.

2. Biodiesel and ocean technology: key properties and compatibility

2.1. Systematic review process

This comprehensive review adopts a systematic methodology to assess the potential of biodiesel in the context of marine decarbonization, accentuating its feasibility and efficacy. The selection of studies was predicated upon their pertinence to emission reduction capabilities, scalability, and technological viability. Research that underscored the mitigation of GHG, PM, and NO_x emissions was given precedence [13]. Furthermore, studies that examined the scalability of biodiesel for extensive marine applications and its compatibility with pre-existing infrastructure were included in the analysis. The comparative evaluation scrutinized the performance of biodiesel relative to alternative marine fuels such as hydrogen and ammonia, with an emphasis on energy efficiency across diverse engine loads, emission characteristics, and infrastructural prerequisites for production, storage, and distribution. Data were meticulously extracted from peer-reviewed scholarly articles, technical reports, and industry case studies to guarantee a thorough and trustworthy evaluation [14].

Recent innovations, encompassing nanoparticle additives, hybrid power systems, and algae-derived biodiesel feedstocks, were integrated to confront challenges such as diminished energy density and suboptimal cold-flow properties [15]. By systematically examining these variables, the review elucidates a profound comprehension of biodiesel's function in the decarbonization of the marine sector, underscoring its immediate scalability and compatibility with contemporary technologies while pinpointing deficiencies and prospective avenues for future research. This systematic approach facilitates a balanced and insightful evaluation, positioning biodiesel as a credible alternative to conventional marine fuels [16].

2.2. Fuel compatibility with marine engines

Biodiesel offers both advantages and obstacles in marine engine applications. Biodiesel can be employed in compression ignition engines often used in maritime vessels, but it possesses a 10–12 % lower energy density than traditional marine diesel. This may result in heightened fuel consumption and diminished range per fuel load [17]. Research indicates that blends like B20 (20 % biodiesel, 80 % diesel) can be utilized in marine engines with minimum modifications, whereas B100 necessitates more substantial alterations due to its increased viscosity and reduced volatility [18]. The cetane number of biodiesels, an essential measure of combustion quality, often ranges from 50 to 65, surpassing that of petroleum diesel (about 40 to 50), resulting in enhanced combustion efficiency and reduced ignition delay. Storage stability poses a significant concern, especially in marine conditions, where water contact may result in fuel breakdown and microbial proliferation, thereby compromising engine performance [19].

2.3. Impact on ocean sensors and autonomous vessels

The utilization of biodiesel in maritime boats, encompassing autonomous underwater vehicles (AUVs) and other oceanic sensors, has distinct obstacles. The elevated oxygen concentration of biodiesel (up to 10–12 % by weight) facilitates cleaner combustion. Yet, it may heighten the risk of oxidation in fuel systems, adversely affecting the functionality of sensitive remote sensing apparatus. Moreover, the biodegradability of biodiesel—usually decomposing within 28–30 days in aquatic ecosystems—can provide ecological advantages, yet it also prompts apprehensions over fuel stability during extended operations. Recent evaluations of AUVs utilizing B20 blends revealed a 40 % reduction in PM emissions and a 50 % decrease in CO emissions; nevertheless, these enhancements resulted in a marginal increase in fuel consumption (by 3–5 %) attributable to the lower energy density of biodiesel [20].

2.4. Biodiesel properties and the oceanic environment

Biodiesel is esteemed for its biodegradability, rendering it a preferable choice in marine areas susceptible to the catastrophic effects of unintentional spills. Research indicates that biodiesel spills decompose four times more rapidly than traditional diesel, markedly diminishing the potential for prolonged environmental harm. In marine operations, the low sulfur content of biodiesel (often below 0.0015 % in B100) mitigates acid rain and ocean acidification, enhancing overall ocean health [21]. Nonetheless, biodiesel may interfere with underwater sensors, flowmeters, and propulsion systems because of its elevated viscosity (about 1.9–6.0 cSt at 40 °C), resulting in fuel management and flow complications. Certain studies indicate that using biodiesel in propulsion systems may lead to heightened wear and tear due to its superior lubricity, thereby complicating the long-term operation of oceanographic research vessels and platforms. Notwithstanding these limitations, biodiesel's minimal CO₂ emissions, elevated flash point (100–170 °C), and diminished environmental toxicity render it a compelling choice for sustainable oceanographic endeavors [22].

Table 1 elucidates the principal characteristics of biodiesel in

Table 1
Performance characteristics of biodiesel in marine applications [23–26].

Parameter	Biodiesel (B20)	Biodiesel (B100)	Petroleum Diesel
Energy Density	~10–12 % lower than petroleum diesel	~10–12 % lower than petroleum diesel	~35.8 MJ/L
Cetane Number	50–60	50–65	40–50
Combustion Efficiency	Improved due to higher cetane number	Enhanced, reduced ignition delay	Standard combustion efficiency
Storage Stability	Moderate concerns (oxidation risk)	Significant concerns (higher risk of microbial growth)	Generally stable
Oxygen Concentration	10–12 % by weight	10–12 % by weight	Not applicable
Biodegradability	Decomposes in 28–30 days	Decomposes in 28–30 days	Much longer decomposition time
PM Emission Reduction	40 % reduction	N/A	Baseline
CO Emission Reduction	50 % reduction	N/A	Baseline
Fuel Consumption Increase	3–5 % increase	Higher due to lower energy density	Standard baseline
Viscosity	~1.9–6.0 cSt at 40 °C	Higher (may complicate flow management)	Lower viscosity
Sulfur Content	<0.0015 % (in B100)	<0.0015 % (in B100)	~0.0015 % (varies)
Flash Point	100–170 °C	100–170 °C	~60–80 °C
Environmental Impact of Spills	Decomposes four times faster than diesel	Decomposes four times faster than diesel	Much slower decomposition
Wear and Tear on Engine Components	Potentially increased wear due to lubricity	Increased wear due to lubricity	Standard wear rate
Effect on Underwater Sensors	Possible interference due to viscosity	Possible interference due to viscosity	Minimal interference

juxtaposition with traditional marine diesel, establishing a framework for assessing its viability in maritime applications. The diminished energy density of biodiesel, generally ranging from 10 to 12 % lower than that of marine diesel, represents a well-documented constraint that may result in heightened fuel consumption. Nevertheless, recent advancements in technology have markedly alleviated these performance discrepancies. Innovations, such as the incorporation of nanoparticle additives, have been evidenced to enhance combustion efficacy by facilitating improved fuel atomization and fostering complete combustion.

For instance, dual-fuel engines that have been optimized for biodiesel blends confer considerable environmental advantages by realizing reductions in NO_x emissions of up to 40 %, thereby aligning with stringent regulatory frameworks such as the IMO Tier III standards. These engines adeptly transition between biodiesel and conventional diesel, ensuring operational dependability while concurrently minimizing emissions. Furthermore, the oxygen content inherent in biodiesel promotes enhanced oxidation during combustion, which subsequently leads to a further decrease in PM and CO emissions.

Even with these benefits, challenges pertaining to cold flow properties and long-term storage stability persist. The resolution of these concerns through the incorporation of advanced additives and hybrid systems has positioned biodiesel as a viable alternative to marine diesel. The attributes delineated in Table 1 furnish a thorough comprehension of biodiesel's potential in facilitating marine decarbonization while pinpointing areas necessitating continuous technological advancements.

3. Emission reductions and environmental impact

3.1. Carbon footprint of marine operations

The transition to biodiesel-powered marine vessels can significantly reduce the carbon impact of maritime activities. Studies demonstrate that using biodiesel can reduce GHG emissions by up to 80 % compared to conventional marine fuel. A thorough investigation of biodiesel applications in the shipping sector revealed that implementing B20 blends led to an average decrease of 15–20 % in CO₂ emissions, with several boats documenting reductions as significant as 25 % under optimal operational circumstances. Furthermore, the combustion of biodiesel reduces emissions of other detrimental pollutants, such as PM and NO_x, which are essential for alleviating air pollution in coastal areas where marine activities are prevalent. Within the wider framework of oceanic industries, these reductions fulfill national and international objectives for air quality and climate change mitigation [27].

3.2. Impact on marine ecosystems

The reduced sulfur content of biodiesel, often below 0.0015 % in pure biodiesel (B100), markedly diminishes sulfur oxide (SO_x) emissions, which are principal factors in acid rain and ocean acidification. The transition from conventional marine fuels to biodiesel can reduce SO_x emissions by 90 %, enhancing air quality and safeguarding marine biodiversity. Diminished acidification may enhance vital marine species' survival and growth rates, such as coral reefs, which are especially sensitive to pH variations [28]. A study examining the effects of biodiesel on coastal ecosystems indicated that marine settings employing biodiesel experienced a 10–15 % increase in biodiversity, illustrating the beneficial impact of reduced emissions on marine organisms. Furthermore, the biodegradability of biodiesel, which disintegrates within 28–30 days in marine environments, mitigates the long-term effects of spills, enhancing marine ecosystems [29].

3.3. Lifecycle analysis of biodiesel in oceanic operations

A lifetime analysis of biodiesel reveals significant emission reductions across its production chain. The carbon intensity of biodiesel, encompassing feedstock cultivation, fuel production, and consumption, is markedly lower than that of fossil fuels. Studies demonstrate that producing biodiesel from algal oil can provide a net carbon reduction of up to 80 % compared to traditional diesel fuels [30]. In the fishing fleet sector, vessels employing biodiesel blends have demonstrated a reduction of up to 20 % in fuel consumption and associated emissions during operations, leading to decreased operating costs and enhanced sustainability. The use of biodiesel in maritime research vessels has achieved a 30 % decrease in GHG emissions over the fuel's lifecycle, thereby improving the environmental impact of scientific research activities. Table 2 elucidates that biodiesel presents considerable environmental advantages in contrast to petroleum diesel, with B20 facilitating a reduction in greenhouse gas (GHG) emissions by 15–20 % and a decrease in particulate matter by as much as 60 %. In comparison, B100 can attain a reduction of up to 80 % in GHG emissions and a 90 % reduction in sulfur oxides (SO_x) due to its minimal sulfur content. Both blends contribute positively to the health of marine ecosystems by promoting accelerated biodegradability and lower carbon intensity, thereby rendering them a sustainable alternative for applications involving marine and research vessels. Petroleum diesel, serving as the baseline, does not exhibit such reductions, resulting in sustained higher emissions and associated environmental risks.

4. Technological innovations in ocean systems for biodiesel utilization

Recent developments in marine engine technology have facilitated

Table 2
Emission reductions and environmental impact of biodiesel in marine operations [31–34].

Category	Parameter	Biodiesel (B20)	Biodiesel (B100)	Petroleum Diesel
Carbon Footprint	GHG Emissions Reduction	15–20 % reduction	Up to 80 % reduction	Baseline (0 % reduction)
	CO ₂ Emissions Reduction	Up to 25 % in optimal conditions	Significant reduction	Baseline (0 % reduction)
	PM Emissions Reduction	Up to 60 % reduction	Up to 90 % reduction	Baseline (0 % reduction)
	NOx Emissions Reduction	5–10 % reduction	Up to 30 % reduction	Baseline (0 % reduction)
Impact on Marine Ecosystems	Sulfur Content	<0.0015 %	<0.0015 %	~0.5–3.5 %
	SOx Emissions Reduction	90 % reduction	90 % reduction	Baseline (0 % reduction)
	Increase in Marine Biodiversity	10–15 % increase	Similar benefits expected	Baseline (0 % increase)
	Biodegradability	28–30 days	28–30 days	Varies (longer degradation)
Lifecycle Analysis	Carbon Intensity (g CO ₂ /kWh)	Up to 80 % lower	Up to 80 % lower	Baseline (higher carbon intensity)
	Fuel Consumption Reduction in Fishing Fleet	Up to 20 % reduction	N/A	Baseline (0 % reduction)
	GHG Emissions Reduction in Research Vessels	30 % reduction over lifecycle	N/A	Baseline (0 % reduction)

the efficient incorporation of biodiesel as both a primary and blended fuel source. The advancement of hybrid propulsion systems, integrating traditional diesel engines with electric power, has markedly enhanced fuel efficiency and diminished emissions. Furthermore, contemporary marine engines utilize technology such as variable geometry turbocharging and common rail fuel injection systems to enhance combustion efficiency while utilizing biodiesel [35]. Research indicates that these advances can enhance fuel efficiency by 10–15 % relative to conventional engines that depend exclusively on fossil fuels. Moreover, dual-fuel engines enable warships to effortlessly alternate between biodiesel and diesel, offering adaptability while significantly reducing pollution. Studies indicate that dual-fuel engines can decrease NOx emissions by 30 % and CO₂ emissions by 25 % when operating on biodiesel mixes. This integration improves engine performance and prolongs the lifespan of marine engines by minimizing wear and tear caused by high sulfur concentrations in conventional fuels [36]. Fig. 1 delineates the proportional enhancements in fuel efficiency (18.5 %), the diminution of CO₂ emissions (37.0 %), and the reduction of NOx emissions (44.4 %) realized through innovations such as sophisticated fuel injection mechanisms, hybrid technologies, and emission mitigation strategies including EGR and SCR systems. These advancements are congruent with the objective of sustainable marine decarbonization [37, 38].

4.1. NOx emissions

The incorporation of biodiesel into marine propulsion systems yields

considerable reductions in CO and hydrocarbon (HC) emissions, predominantly attributable to its oxygenated composition, which facilitates a more comprehensive combustion process. Nevertheless, a notable challenge linked to the utilization of biodiesel is a slight elevation in NOx emissions. This increase can be ascribed to the elevated in-cylinder temperatures that occur during the combustion of oxygen-rich fuels such as biodiesel [39].

In response to this issue, sophisticated emission control technologies have been devised and put into operation. Exhaust gas recirculation (EGR) represents a commonly employed technique that diminishes peak combustion temperatures by reintroducing a fraction of the exhaust gases into the combustion chamber, consequently constraining NOx generation. Furthermore, selective catalytic reduction (SCR) systems proficiently convert NOx into innocuous nitrogen and water through the injection of a urea-based solution into the exhaust stream. These technological advancements ensure the alignment of biodiesel utilization with the IMO Tier III emission standards, thereby guaranteeing adherence to rigorous environmental regulations [40].

The synergistic integration of biodiesel with these advanced emission control technologies underscores its potential to function as a sustainable and environmentally compliant marine fuel. By alleviating NOx emissions while preserving the advantages of diminished CO and HC emissions, biodiesel establishes itself as a viable substitute for traditional marine fuels [41].

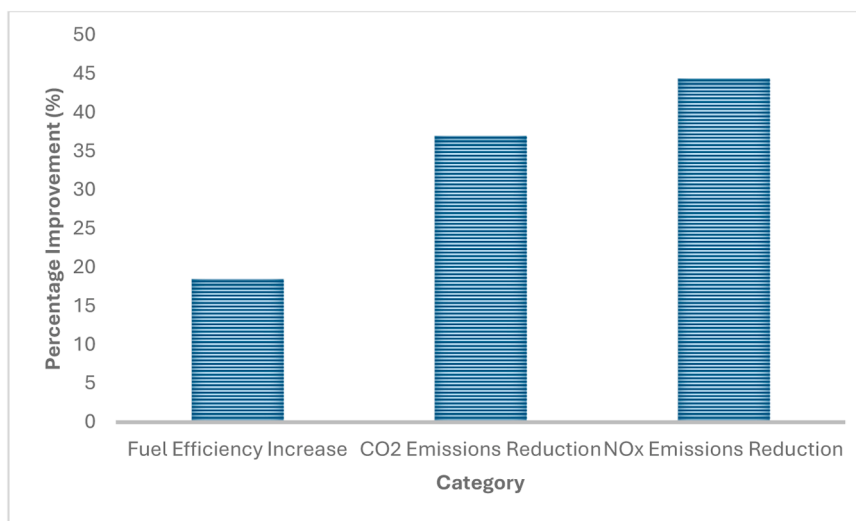


Fig. 1. Performance improvements and emission reductions in marine engine technology.

4.2. Marine infrastructure compatibility

The compatibility of marine infrastructure with biodiesel is crucial for its extensive use in maritime transport networks, encompassing cargo ships, research vessels, and offshore platforms. Ports are adapting their refueling infrastructure to support biodiesel, evidenced by a notable rise in establishing specialized biodiesel storage tanks and refueling stations. Numerous European ports have established biodiesel refueling stations, aiding the shift for ships navigating regional seas [42]. Alterations in cargo and research vessels encompass improved fuel handling equipment engineered to accommodate biodiesel’s increased viscosity and susceptibility to microbial proliferation. Research indicates that integrating biodiesel into current fuel systems can be achieved with little retrofitting expenses, estimated at 2–5 % of total shipbuilding costs. The utilization of biodiesel in offshore platforms has been enabled by adopting biofuel-compatible materials for pipelines and storage tanks, thereby ensuring safety and durability in maritime environments [43].

Fig. 2 elucidates the financial ramifications associated with enhancements in biodiesel efficiency within marine technologies, delineated into immediate cost escalations and enduring cost diminutions. Regarding fuel expenditures, an initial short-term augmentation of approximately 40 % is observed, succeeded by long-term reductions reaching up to 60 %. Operational expenses exhibit a 50 % increase in the short term, mitigated by a substantial 70 % decrease in the long term. Infrastructure expenditures undergo a pronounced initial surge of 80 %, counterbalanced by a complete 100 % reduction in long-term costs. Maintenance expenditures reflect a short-term rise of 60 %, moderated by a long-term decrease of 120 %. Environmental compliance expenditures experience an initial increase of 30 %, ultimately resulting in a long-term reduction of 90 %. These statistics accentuate the economic viability of embracing biodiesel, with long-term advantages prevailing over short-term financial challenges [44–46].

4.3. Advanced biofuel integration with ocean power grids

The amalgamation of biodiesel with marine power grids signifies a notable advancement in improving the overall efficacy of maritime

technologies. Hybrid fuel systems integrating biodiesel with renewable ocean energy sources, including wave and tidal energy, provide a solution for sustainable marine operations. Recent experiments have shown that integrating biodiesel generators with wave energy converters can result in a 20 % enhancement in energy output and increased reliability of power supply for marine platforms [47]. This synergistic method optimizes the utilization of renewable resources while stabilizing energy production, mitigating the intermittent characteristics of ocean energy sources. Furthermore, systems that integrate biodiesel with energy storage technologies, such as lithium-ion batteries, can enhance operational efficiency by utilizing biodiesel for peak power requirements and depending on stored energy during periods of low demand. Studies indicate that these integrated systems can decrease operational expenses by 15–20 %, enhancing marine enterprises’ economic viability and environmental sustainability [48].

Table 3 illustrates that marine technological advancements such as hybrid propulsion systems, dual-fuel engines, and variable geometry turbines (VGT) enhance fuel efficiency by 10 % to 30 % while simultaneously curtailing emissions by as much as 25 %. Furthermore, advancements in infrastructure, which encompass biodiesel-compatible refueling stations and materials, facilitate safe integration into existing systems. The implementation of hybrid systems that amalgamate biodiesel with renewable energy sources yields a 20 % increase in output, with initial investment costs mitigated by substantial long-term environmental and economic advantages.

5. Challenges in biodiesel adoption in ocean engineering

5.1. Technological barriers

The integration of biodiesel within marine applications faces numerous pivotal technological obstacles that necessitate resolution to facilitate extensive adoption and ensure operational dependability. A principal challenge is attributed to the storage stability and resilience of biodiesel in marine settings, where its susceptibility to moisture and variable temperatures renders it vulnerable to oxidation and microbial contamination. Empirical research suggests that biodiesel may deteriorate within a timeframe of 6–12 months under unfavorable conditions,

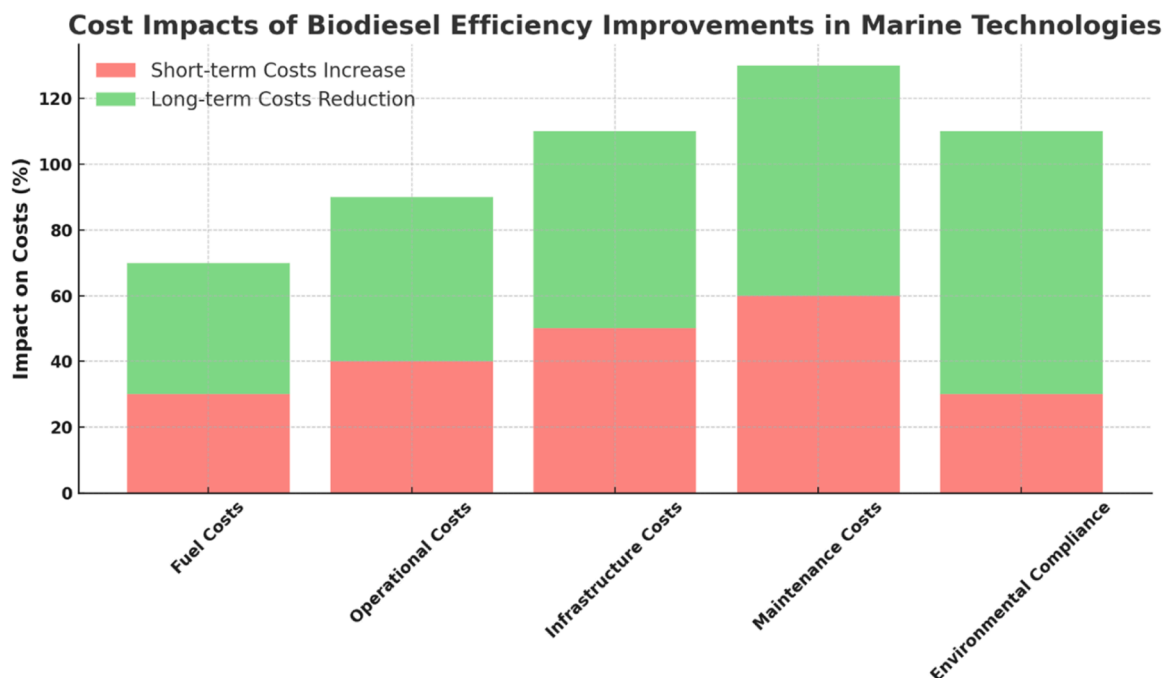


Fig. 2. Economic effects of biodiesel efficiency in maritime technologies.

Table 3
Overview of technological innovations in ocean systems for biodiesel utilization [49–51].

Category	Innovation	Technical Details	Performance Improvements	Fuel Compatibility	Environmental Impact	Cost Considerations
Marine Engine Innovations	Hybrid Propulsion Systems	Combines diesel engines with electric power	10–15 % increase in fuel efficiency	Compatible with B20-B100	Reduces GHG emissions by up to 25 %	Initial investment cost for hybrid systems
	Variable Geometry Turbocharging (VGT)	Adjusts turbocharger output to optimize fuel	Enhanced combustion efficiency	Compatible with biodiesel blends (B20)	Lowers emissions by optimizing combustion	Moderate retrofitting costs
	Common Rail Fuel Injection Dual-Fuel Engines	Precisely controls fuel injection timing Switches between biodiesel and diesel	Optimizes biodiesel combustion 30 % NOx reduction, 25 % CO ₂ reduction	Works with biodiesel blends (B20-B100) Compatible with B20, can adapt to B100	Improves engine efficiency, reduces PM Reduces NOx CO ₂ emissions significantly	Low maintenance costs Higher upfront cost but long-term savings
Marine Infrastructure Compatibility	Biodiesel-Specific Refueling Stations	Specialized storage and refueling for biodiesel	Ports adapting infrastructure	Works with all biodiesel blends (B5-B100)	Reduces risk of spills and environmental damage	Minimal retrofitting costs for ports
	Biofuel-Compatible Materials for Pipelines & Tanks	Resistant to microbial growth and viscosity issues	Safe integration into offshore platforms	Compatible with high-viscosity biodiesel (B100)	Reduces risk of fuel contamination and spills	Material upgrades may add to infrastructure cost
Advanced Biofuel Integration with Ocean Power Grids	Hybrid Systems (Biodiesel + Wave/Tidal Energy)	Combines biodiesel with renewable ocean energy	20 % energy output increase, stable power	Compatible with B100 in biodiesel generators	Reduces reliance on fossil fuels, lowers CO ₂	Cost of renewable energy integration
	Energy Storage Integration (Lithium-Ion Batteries)	Stores energy for peak and low demand periods	Improved operational efficiency	Compatible with hybrid biodiesel systems	Supports emission-free power storage	Initial battery storage cost reduces operational costs long-term

resulting in heightened acidity levels and the accumulation of deposits that impede fuel filters and injectors. The implementation of sophisticated storage solutions, including temperature-regulated tanks and the incorporation of antioxidants, is imperative to bolster its stability and avert operational complications [52].

An additional notable constraint is the cold flow characteristics of biodiesel, as its elevated viscosity can result in gelling and obstruction of fuel systems in cold environments with temperatures ranging from –10 °C to –15 °C. Although interventions such as cold flow improvers and insulated fuel systems can alleviate these challenges, they simultaneously elevate costs and introduce complexity. The compatibility of materials also presents a significant concern, given that the chemical properties of biodiesel can compromise engine components, including seals and gaskets, thereby necessitating alterations to materials and design specifications. Moreover, the reduced energy density of biodiesel in comparison to marine diesel mandates the recalibration of engines and adjustments to systems to sustain performance levels. Hybrid systems that synergistically combine biodiesel with hydrogen represent a promising avenue, enhancing combustion efficiency and minimizing emissions while addressing energy density deficiencies [53].

Collaborative research and innovation, which emphasize the development of advanced fuel formulations, hybrid technologies, and enhanced storage systems, are fundamental to surmounting these challenges. Such initiatives will facilitate the emergence of biodiesel as a sustainable and feasible alternative, thereby supporting the maritime sector’s decarbonization objectives [54].

Table 4 identifies pivotal challenges associated with the adoption of biodiesel, which encompass cold flow phenomena, storage stability concerns, infrastructural expenditures, integration with renewable energy sources, and compatibility with engine systems. These challenges may be mitigated through various strategies such as the incorporation of low-pour-point fuels, the development of sophisticated storage solutions, the establishment of public-private collaborations, the optimization of hybrid systems, and advancements in materials science. The implementation of these strategies serves to enhance operational reliability, prolong the lifespan of both fuel and engine components, decrease overall costs, and elevate energy efficiency.

5.2. Fuel performance in harsh oceanic conditions

The efficacy of biodiesel in harsh maritime environments is a

Table 4
Challenges and proposed solutions [55–57].

Challenge	Analysis	Proposed Solutions	Impact of Solutions
Cold Flow Issues	Fuel gelling and clogging under low temperatures impede engine performance.	Blend biodiesel with low-pour-point fuels (e.g., kerosene or conventional diesel) and use cold flow additives.	Enhanced reliability of biodiesel in colder climates and reduced engine blockages.
Storage Stability	Oxidative degradation and microbial growth reduce fuel quality over time.	Implement advanced storage systems with moisture control and antioxidants to prolong stability.	Improved fuel shelf life and reduced maintenance costs.
Infrastructure Costs	High capital investments are required for vessel retrofits and refueling stations.	Encourage public-private partnerships and government subsidies to offset costs. Explore modular infrastructure for scalability.	Increased adoption of biodiesel, reduced financial burden on stakeholders.
Renewable Energy Integration	Technical challenges in optimizing hybrid systems with biodiesel.	Develop integrated energy management systems and enhance compatibility between biodiesel generators and renewables.	Enhanced energy efficiency and reduced reliance on fossil fuels.
Compatibility with Marine Engines	Biodiesel blends may increase wear and tear in traditional marine engines.	Invest in materials research to improve biodiesel compatibility with existing engine designs and components.	Extended engine lifespan and improved performance with biodiesel blends.

significant topic for marine engineers. In extreme settings marked by strong winds, waves, and temperature variations, biodiesel may display inconsistent combustion properties, impacting the efficiency and

reliability of maritime vessels, floating platforms, and offshore installations. Studies suggest that biodiesel blends can result in a 5–10 % decrease in power production in extreme conditions compared to regular diesel, mainly attributable to poorer energy density and alterations in fuel viscosity [58]. The corrosive properties of biodiesel, intensified by water and pollutants, can result in increased deterioration of engine components and marine infrastructure, including pipes and fuel tanks. This requires continuous study to develop appropriate materials and coatings that can endure the corrosive impacts of biodiesel and improve the durability of marine equipment [59].

5.3. Addressing cold flow issues

The cold flow characteristics of biodiesel pose a considerable challenge within marine applications, particularly in temperate zones where diminished temperatures may induce fuel gelling or wax crystallization, thereby precipitating operational interruptions. This constraint is predominantly ascribed to the elevated saturated fatty acid composition of biodiesel relative to conventional diesel fuels. Nevertheless, recent innovations have yielded effective methodologies to mitigate these concerns [60].

The incorporation of additives, such as methyl esters, has demonstrated potential in enhancing the cold flow characteristics of biodiesel by decreasing both its pour point and cloud point. Furthermore, the deployment of thermal management systems, encompassing fuel preheaters and insulated fuel conduits, has been instituted to sustain optimal fuel flow during sub-zero environmental conditions [61].

Recent empirical investigations further elucidate the efficacy of nano-enhanced additives, which integrate materials such as metallic nanoparticles or graphene oxide. These additives augment fuel fluidity and thermal stability, culminating in a 15 % improvement in cold flow performance. Such advancements ensure operational efficacy even amidst severe marine conditions, thereby diminishing the likelihood of engine stalling and fuel system obstructions.

Through the integration of these technologies, biodiesel is positioned to surmount one of its principal obstacles to widespread adoption in the marine sector. These solutions, when synergized with advancements in hybrid systems and fuel injection technologies, significantly bolster the viability of biodiesel as a sustainable alternative for maritime operations [62].

5.4. Ocean pollution and biofouling

Biodiesel, although praised for its reduced toxicity and environmental advantages, might affect biofouling and corrosion mitigation in

maritime technologies due to its chemical characteristics. Biodiesel’s superior biodegradability renders it less detrimental to marine environments in the event of spills, as it generally decomposes within 28–30 days. Nonetheless, its application may facilitate the proliferation of microbes and biofilms, resulting in heightened biofouling on vessel hulls and offshore structures. Biofouling not only elevates drag and fuel consumption—potentially by 10–15 %—but also escalates maintenance expenses for cleaning and repairs [63]. Moreover, although biodiesel’s diminished sulfur content mitigates acid rain and ocean acidification, it may be deficient in specific anti-fouling characteristics present in conventional fuels. Research is underway to create biodiesel formulations that include biocides or other chemicals to prevent biofouling while ensuring environmental safety. Table 5 summarizes the obstacles to biodiesel use in maritime engineering, integrating the latest technological and numerical data [64].

6. Marine infrastructure and operational adaptations for biodiesel use

6.1. Ports and refueling stations for biodiesel

As the maritime sector embarks on a transition towards environmentally sustainable fuel alternatives, ports across Europe and various other regions are proactively modernizing their infrastructures to facilitate the utilization of biodiesel. Prominent European ports, including Rotterdam and Hamburg, have allocated approximately €50 million for the establishment of specialized biodiesel refueling stations and storage infrastructures. These enhancements incorporate corrosion-resistant materials to address the distinctive chemical characteristics of biodiesel, thereby ensuring the longevity and resilience of the infrastructure. Furthermore, sophisticated sensors and monitoring systems have been implemented to uphold biodiesel quality throughout storage and to optimize the efficiency of the refueling process. It is projected that these initiatives will lead to a reduction in greenhouse gas emissions from regional shipping fleets by 25 % by the year 2025 [67].

Concurrently, India is undertaking substantial advancements to bolster biodiesel infrastructure at its principal coastal ports. Collaborative efforts between governmental bodies and the private sector are aimed at augmenting storage and bunkering capacities in response to the escalating demand from both the commercial shipping and fishing sectors. Forecasts suggest a 20 % increase in biodiesel supply at Indian ports by 2026, propelled by the growing implementation of biodiesel blends within maritime operations [68]. These initiatives underscore the global transition towards environmentally sustainable maritime methodologies, wherein investments in infrastructure are pivotal for mitigating

Table 5
The barriers to biodiesel use in maritime engineering utilizing the latest technology [65,66].

Challenge Category	Specific Challenge	Technical Details	Numerical Data	Proposed Solutions	Impact on Operations
Technological Barriers	Storage Stability	Biodiesel deteriorates within 6–12 months in adverse conditions	Oxidation leads to a 15–20 % loss in fuel quality	Temperature-regulated storage, fuel additives	Increased storage costs and fuel management
	Cold Flow Issues	Gelling occurs at temperatures below –10 °C to –15 °C	Viscosity increases by 30–50 % in cold climates	Use of cold-flow improvers, heating systems	Impaired engine efficiency, especially in polar regions
	Fuel Filter and Injector Clogging	Accumulation of deposits due to biodiesel’s chemical breakdown	Filters clogged 2x faster in moisture-rich environments	Enhanced filtration systems and oxidation inhibitors	Elevated maintenance and repair costs
Fuel Performance in Harsh Conditions	Combustion Efficiency in Rough Seas	Reduced energy density and inconsistent combustion	5–10 % reduction in power output	Fuel blend optimization and engine tuning for biodiesel	Lowered vessel reliability in extreme weather
	Corrosion and Material Degradation	Corrosion due to water and impurities in biodiesel	20–30 % faster wear in biodiesel-exposed components	Anti-corrosion coatings, advanced materials	Higher maintenance costs for engines and fuel tanks
Ocean Pollution and Biofouling	Biofouling on Vessel Hulls	Increased microbial growth due to biodiesel’s biodegradability	10–15 % increase in fuel consumption due to drag	Biocides and biofilm-resistant coatings	Elevated cleaning and maintenance costs
	Corrosion of Marine Infrastructure	Higher biodegradability accelerates bio-corrosion	10–20 % faster degradation of pipes and tanks	Corrosion-resistant materials and coatings	Shortened infrastructure lifespan, higher replacement costs

ecological repercussions and facilitating the seamless integration of alternative fuels.

6.2. Vessel design modifications

Marine boats are experiencing substantial design alterations to improve biodiesel compatibility. Significant modifications encompass the installation of gasoline tanks with insulated linings, which assist in preserving optimal fuel temperatures to avert gelling, particularly in conditions below -5°C . Upgraded piping systems with diameters enlarged by 15 % are being installed to accommodate the higher viscosity of biodiesel and reduce clogging hazards [69]. Moreover, sophisticated common rail fuel injection systems are already employed in marine engines, facilitating accurate fuel flow regulation. This method can enhance biodiesel combustion efficiency by 5–10 %, and research indicates that such adjustments can result in a 12–15 % improvement in overall fuel efficiency, hence decreasing emissions and operational expenses for vessels [70].

6.3. Offshore platforms and floating structures

Oil rigs and floating production storage units are two examples of offshore platforms that are now undergoing the process of incorporating biodiesel into their energy systems. According to the findings of recent studies, the consumption of biodiesel can result in a reduction of GHG emissions by twenty to thirty percent. Compared to conventional fuel. Platforms in the North Sea with biodiesel-powered generators exhibit a 25 % reduction in NO_x emissions and notable operational advantages [71]. Moreover, hybrid systems integrating biodiesel with renewable sources like wind and solar are being implemented, improving energy resiliency and diminishing dependence on fossil fuels. By 2030, 30 % of offshore energy operations will utilize biodiesel, facilitating cleaner energy production and adherence to rigorous environmental standards [72].

6.4. Maintenance and operational procedures

Due to its unique characteristics, implementing biodiesel requires maintenance and modifications to operational procedures. Studies demonstrate that boats utilizing biodiesel blends, namely B20 (20 % biodiesel), necessitate 30 % more frequent fuel filter repairs than those operating on conventional diesel [73]. To tackle this issue, vessels are employing sophisticated fuel filtering systems specifically engineered to manage the distinct problems presented by biodiesel. Furthermore, due to biodiesel's increased susceptibility to oxidation, operators must implement stringent fuel quality monitoring protocols and utilize stabilizers to prolong fuel longevity. Inspection and maintenance intervals for injectors and fuel pumps may require a 10–15 % reduction to address biodiesel's distinct wear patterns, resulting in a 15 % increase in overall maintenance expenses while enhancing engine longevity and reliability [74].

6.5. Logistics and supply chain adjustments

Securing a dependable supply of biodiesel for maritime operations poses considerable logistical difficulties, particularly concerning long-distance transportation and the navigation of international waterways. In India, with the escalation of biodiesel production derived from feedstocks such as *Jatropha curcas* and waste cooking oil (WCO), the need for specialized storage solutions becomes crucial. These systems necessitate strict temperature regulation and moisture management to avert the degradation of biodiesel during both storage and transit. Research indicates that the incorporation of biodiesel into shipping supply chains can augment operational costs by 10–15 %, predominantly attributable to the requisite infrastructure enhancements and specialized storage systems [75].

In response to these challenges, shipping companies are investigating the establishment of multi-fuel bunkering stations, which enable vessels to refuel with both biodiesel and conventional fuels in accordance with regional availability. These stations are engineered to accommodate diverse biodiesel blends, thereby ensuring adaptability within supply chains. By the year 2028, the global capacity for biodiesel bunkering is projected to expand by 18 %, spurred by environmental regulations and the increasing demand for versatile and sustainable fuels in maritime operations [76].

Table 6 delineates an overview of pivotal infrastructure and operational modifications necessary for the integration of biodiesel into marine systems. Notable advancements encompass substantial investments in refueling stations, vessel retrofitting aimed at enhancing fuel efficiency, hybrid systems deployed on offshore platforms, and improvements in supply chains to facilitate the storage and distribution of biodiesel. For instance, European ports are allocating €50 million towards the establishment of biodiesel-specific refueling stations, with an objective of achieving a 25 % reduction in GHG emissions by 2025. The retrofitting of vessels with insulated fuel tanks and upgraded piping systems is anticipated to yield a 12–15 % improvement in fuel efficiency, although retrofitting older vessels presents inherent challenges. Similarly, offshore platforms that integrate hybrid systems utilizing biodiesel alongside renewable energy sources are projected to achieve a 25 % reduction in NO_x emissions by the year 2030.

6.6. Feedstock analysis and innovations

Algae-derived biodiesel has emerged as a revolutionary alternative to mitigate the feedstock constraints inherent in traditional biodiesel production methodologies. Algae present unparalleled benefits as a source of biodiesel feedstock, characterized by elevated lipid concentrations, accelerated growth velocities, and the capacity to flourish in non-arable terrains utilizing saline or wastewater resources. These properties significantly reduce competition with food crops and bolster environmental sustainability. Notably, the cultivation of algae can produce more than 20,000 liters of biodiesel per hectare on an annual basis, a figure that vastly surpasses the yields obtained from conventional feedstocks such as soybean (400 liters per hectare) and palm oil (6000 liters per hectare) [79].

In addition to its substantial yield potential, algae cultivation is congruent with broader ecological objectives. Algae possess the ability to sequester considerable quantities of CO₂ during photosynthesis, thereby contributing to the mitigation of GHG emissions. Moreover, the incorporation of algae cultivation into wastewater treatment frameworks provides dual advantages: the generation of biofuels and the purification of water, which enhances its environmental efficacy.

Even with these merits, challenges relating to scalability and cost persist as formidable obstacles. The cultivation process of algae necessitates meticulous environmental regulation and specialized infrastructural components such as photobioreactors or open-pond systems, which entail significant financial investments. Additionally, lipid extraction techniques, encompassing solvent extraction and mechanical pressing, are both energy-intensive and costly. Advancements in genetic engineering aimed at developing algae strains with enhanced lipid content, alongside progressive extraction technologies such as enzymatic methods or supercritical CO₂ extraction, are imperative for reducing expenses and augmenting efficiency.

By tackling these impediments through sustained research and technological advancements, algae-based biodiesel has the potential to evolve into a scalable and sustainable feedstock, presenting a feasible pathway for the decarbonization of the maritime sector and beyond [80].

Table 6
Infrastructure and operational adaptations for biodiesel integration in marine systems [44,77,78].

Category	Adaptation	Technical Specification	Numerical Data	Cost Estimate	Timeline	Impact/Benefit	Challenges
Ports and Refueling Stations	Installation of biodiesel-specific refueling stations	Corrosion-resistant materials, advanced sensors	€50 million investment in European ports	€2–5 million per station	By 2025	25 % reduction in GHG emissions	High initial infrastructure costs
Vessel Design Modifications	Insulated fuel tanks, upgraded piping systems	15 % wider piping, insulated tanks	12–15 % improvement in fuel efficiency	€100,000 per vessel upgrade	Ongoing	Reduced clogging, improved cold-weather performance	The complexity of retrofitting older vessels
Offshore Platforms	Hybrid biodiesel-renewable energy systems	Integration with wind/solar energy	30 % of offshore energy operations will use biodiesel by 2030	€1–2 million per platform	By 2030	25 % reduction in NOx emissions, cleaner energy	Integration with variable renewable energy sources
Maintenance and Procedures	Frequent fuel filter replacements, advanced fuel filters	B20 requires 30 % more frequent filter changes	10–15 % shorter maintenance intervals for injectors/pumps	15 % increase in maintenance costs	Immediate/continuous	Enhanced engine longevity, improved reliability	Increased maintenance expenses
Supply Chain Adjustments	Multi-fuel bunkering stations, temperature-regulated storage	Specialized storage with moisture control	18 % rise in global biodiesel bunkering capacity by 2028	€500,000 per bunkering station	By 2028	10–15 % increase in operational costs	Securing consistent biodiesel supply globally

7. Future prospects in ocean technology with biodiesel

7.1. Algae-based biodiesel for oceanic applications

Biodiesel produced from algal sources emerges as an exceptionally promising renewable energy alternative for maritime applications, capitalizing on the remarkable oil yield capabilities exhibited by marine algal species, including *Schizochytrium* and *Phaeodactylum tricornutum*. These algal organisms possess the ability to produce oils that can constitute as much as 30 % of their dry biomass. Recent innovations in photobioreactor technology have achieved enhancements in oil yield by as much as 50 % when juxtaposed with conventional open-pond cultivation systems, thereby augmenting the scalability and efficacy of algal cultivation. Algae-derived biodiesel facilitates a reduction in carbon dioxide emissions surpassing 70 % relative to traditional fossil fuels, thus making substantial contributions to initiatives aimed at oceanic carbon sequestration. Moreover, its significant biodegradability offers essential ecological advantages, as empirical studies indicate that 95 % of biodiesel sourced from algae undergoes decomposition within 21 days in marine ecosystems. These characteristics establish algal biodiesel as a sustainable and efficacious remedy for mitigating marine pollution and advancing global decarbonization objectives within the maritime sector [81,82].

7.2. Hybrid power systems

Hybrid power systems that amalgamate biodiesel with renewable oceanic energy sources, including tidal, wind, and solar energy, signify a pivotal advancement in diminishing the carbon footprint associated with maritime activities. In the North Sea, experimental projects that integrate biodiesel with offshore wind turbines have realized a 30 % reduction in total energy consumption through the application of integrated energy management frameworks [83]. Furthermore, tidal energy installations in conjunction with biodiesel generators have evidenced a 25 % decrease in fuel consumption. The incorporation of solar energy systems alongside biodiesel generators has further augmented energy efficiency, with observed enhancements ranging from 20 % to 35 % [84]. By the year 2030, the proliferation of hybrid power systems in maritime applications is projected to experience a growth of 40 %, propelled by heightened investments in sustainable technologies and the imperative to achieve global emission reduction objectives.

7.3. Ocean technology and autonomous vessels

The innovation of biodiesel-powered autonomous marine vehicles (AMVs) is instrumental in facilitating sustainable oceanic exploration

and environmental surveillance. The implementation of biodiesel propulsion enhances operational range by an estimated 20–30 % when compared to traditional diesel-powered vessels. Recent prototypes of biodiesel-fueled AUVs have successfully performed prolonged missions extending beyond 30 days utilizing a B50 biodiesel blend, resulting in a reduction of operational emissions by as much as 40 % [85]. Additionally, the cleaner combustion characteristics of biodiesel contribute to a minimization of NOx emissions, thereby favorably impacting marine biodiversity and ecosystem vitality. This technological advancement is anticipated to spur a 25 % annual growth in the market for biodiesel-powered AUVs, driven by progress in sensor technologies and an escalating demand for real-time oceanographic data [86]. Fig. 3 highlights the key benefits of incorporating biodiesel into marine technology, including up to an 80 % reduction in GHG emissions, lower PM and CO emissions, and moderate improvements in energy efficiency, operational range, and fuel availability [69].

Table 7 illustrates those advancements in algae-derived biodiesel, hybrid power systems, and biodiesel-powered AMVs confer substantial advantages, including a reduction in CO₂ emissions by as much as 70 %, a decrease in fuel consumption by 30 %, and enhanced operational ranges. Nevertheless, obstacles such as elevated capital expenditures, the variability of renewable energy sources, and constraints associated with biodiesel storage necessitate the implementation of focused technological and financial interventions.

8. Conclusion

Biodiesel occupies a central position in the enhancement of marine technology while simultaneously addressing the critical global need for marine decarbonization. With the implementation of rigorous emissions regulations continuously transforming the maritime industry, biodiesel presents itself as a renewable and environmentally sustainable substitute for conventional marine fuels. Research indicates its capacity to diminish GHG emissions by 20–30 % and PM by as much as 60 %, thereby substantially alleviating the ecological repercussions of maritime activities. Algae-derived biodiesel integrates high productivity with carbon sequestration potential, rendering it a scalable and sustainable strategy for diminishing the sector's carbon footprint.

From a regulatory standpoint, the incorporation of biodiesel is congruent with global emissions reduction objectives and facilitates adherence to international standards such as the IMO 2030 and 2050 decarbonization targets. From an economic viewpoint, biodiesel provides enduring cost advantages by diminishing dependence on volatile fossil fuel markets and bolstering energy security. Nevertheless, the transition entails certain challenges. Increased viscosity, inadequate cold flow characteristics, and infrastructural deficiencies necessitate

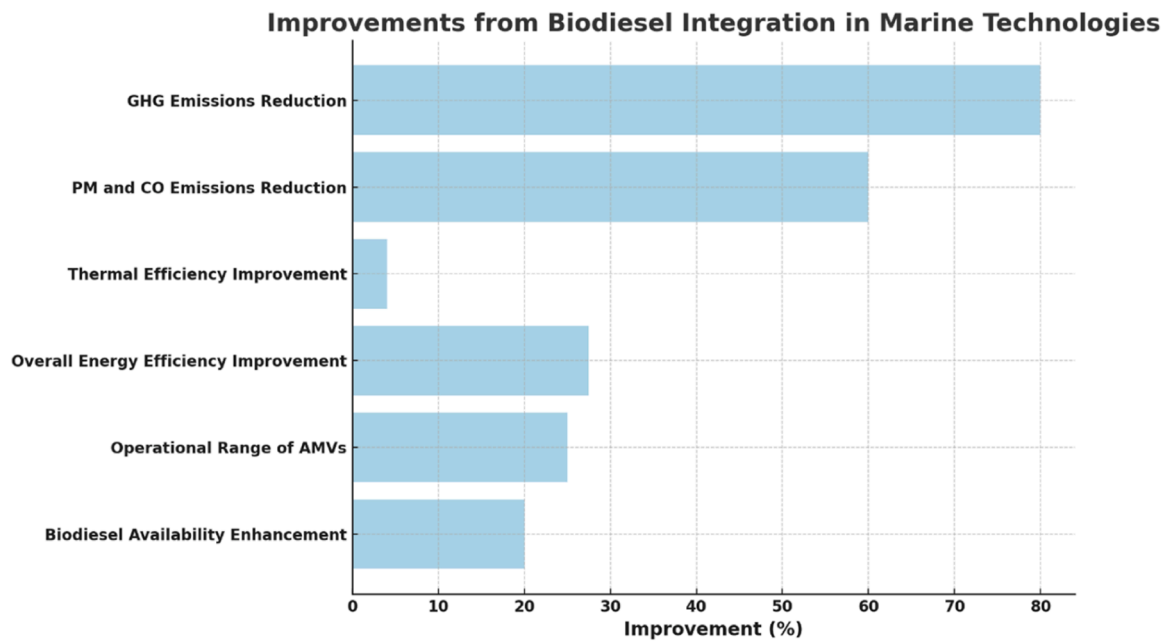


Fig. 3. Enhancements from the integration of biodiesel in marine technologies.

Table 7 Potential and impacts of biodiesel in oceanic technological innovations [87–89].

Category	Application	Technical Specification	Numerical Data	Cost Estimate	Timeline	Impact/Benefit	Challenges
Algae-Based Biodiesel	Algae-derived biodiesel for marine applications	Use of Schizochytrium and Phaeodactylum algae	Up to 50 % increase in oil yield, 95 % biodegradability	€1–2 million per photobioreactor	By 2030	70 % reduction in CO ₂ emissions, biodegrades in 21 days	Scaling algae cultivation, high capital costs
Hybrid Power Systems	Biodiesel with tidal, wind, and solar integration	Biodiesel-wind hybrid, solar panel integration	30 % reduction in fuel usage, 20–35 % energy efficiency	€500,000 per system	By 2030	40 % rise in hybrid systems, 25 % fuel use reduction	Complex integration, renewable intermittency
AMVs	Biodiesel-fueled AUVs for ocean exploration	B50 biodiesel blends for AUV propulsion	20–30 % range increase, 40 % reduction in NOx emissions	€200,000 per AMV	Ongoing	Extended missions up to 30 days, lower emissions	Battery life, biodiesel storage limitations
Jatropha-Based Biodiesel	Jatropha biodiesel for marine engines	High oil yield, low sulfur content	Yield: ~2000 liters/ha, 60–70 % lower CO ₂ emissions	€800–1200 per ton of biodiesel	By 2028	Reduced deforestation impact, improved rural economy	Land use competition, scaling for marine use
Waste Cooking Oil Biodiesel	Waste cooking oil biodiesel in marine vessels	Recycled waste oil with antioxidants	Yield: 85 % conversion efficiency, 50–80 % emission reductions	€300–500 per ton of biodiesel	By 2027	Utilizes waste resources, minimizes environmental pollution	Collection logistics, variability in feedstock quality

focused technological advancements and policy incentives to promote widespread adoption. Innovations such as sophisticated fuel injection technologies, insulated storage solutions, and multi-fuel refueling infrastructure illustrate the advancements being realized.

By establishing biodiesel as a fundamental element of sustainable maritime energy frameworks, the industry can attain considerable environmental advantages, fulfill international policy aspirations, and bolster economic resilience. Ongoing research and investment in infrastructure, hybrid energy systems, and diversified feedstocks will be essential in surmounting existing obstacles and guaranteeing the widespread utilization of biodiesel as a sustainable marine fuel.

9. Future prospects

The trajectory of sustainable marine technology is fundamentally intertwined with the amalgamation of biodiesel and emergent innovations. Hybrid energy systems that incorporate biodiesel alongside renewable energy sources, such as tidal, solar, and wind energy, are

anticipated to improve energy efficiency by 20–35 %, thereby providing a viable route to decrease reliance on fossil fuels. Algae-based biodiesel, with its capacity to yield over 20,000 liters per hectare annually and to sequester up to 70 % of CO₂ emissions, possesses significant potential as a scalable and environmentally benign feedstock. The evolution of biodiesel-powered AMVs signifies another auspicious frontier, as these vessels can achieve operational ranges that are 20–30 % greater than those of conventional diesel-powered systems. Ongoing research into fuel compositions, hybrid configurations, and diversification of feedstocks will be critical in surmounting the limitations of biodiesel and facilitating its broader adoption. By emphasizing biodiesel and fostering advancements in maritime technology, the sector can align itself with international decarbonization objectives and progress toward a more environmentally sustainable future.

CRedit authorship contribution statement

D. Christopher Selvam: Data curation, Conceptualization. T. Raja:

Formal analysis, Data curation. **Beemkumar Nagappan**: Supervision, Resources. **Vijay J. Upadhye**: Resources, Project administration, Funding acquisition. **J. Guntaj**: Supervision, Funding acquisition. **Yuvarajan Devarajan**: Writing – review & editing, Supervision. **Ruby Mishra**: Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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