Journal of Marine Science and Application (2023) 22: 870-881
https://doi.org/10.1007/s11804-023-00382-2

RESEARCH ARTICLE

The Potential of Inedible Biodiesel as an Eco-Friendly and Sustainable Alternative Fuel for Marine Diesel Engines in India

Christopher Selvam Damian[1], Yuvarajan Devarajan[1] and Ravikumar Jayabal[1]

Received: 16 October 2023 / Accepted: 12 December 2023

Abstract

This article explores the possibilities of inedible biodiesel as a viable and environmentally friendly substitute fuel for marine diesel engines in India. This article encompasses on various crucial elements, including engine compatibility, biodiesel blends, fuel quality, emissions reduction, regulatory compliance, cost analysis, environmental advantages, and research and development. Implementing biodiesel in maritime operations within India presents favourable opportunities for mitigating carbon emissions, improving air quality, bolstering energy security, promoting sustainable agriculture, and harmonizing with international environmental objectives. Nevertheless, the effective incorporation of biodiesel necessitates a meticulous examination of multiple variables and an all-encompassing methodology that involves formulating policies, investment in infrastructure, research and development, and collaboration among relevant parties. Adopting biodiesel in India's maritime sector offers a promising prospect for substantially contributing to sustainability and environmental stewardship.

Keywords Biodiesel; Marine diesel engines; Engine compatibility; Emissions reduction; Regulatory compliance; Energy security; Sustainability; Environmental stewardship

1 Introduction

The maritime transportation industry is significant in facilitating India's economic development and enhancing its connectedness in global trade. Nevertheless, the industry's dependence on traditional diesel fuel from fossil sources carries noteworthy environmental consequences, such as greenhouse gas emissions and air pollution (Ampah et al., 2021). As India endeavors to achieve a harmonious equilibrium between economic progress and environmental conservation, there is a growing imperative for implementing sustainable and environmentally friendly solutions within the maritime industry (Tan et al., 2021). This extensive manuscript examines the possibilities of biodiesel as a feasible resolution to tackle these difficulties and promote sustainability in the realm of India. naval transportation (Panoutsou et al., 2021).

Biodiesel, commonly sourced from renewable feedstocks such as vegetable oils or animal fats, exhibits considerable potential as a substitute for conventional diesel fuel. This alternative fuel presents many environmental advantages, encompassing diminished carbon emissions, decreased sulfur content, and enhanced air quality (Hoang et al., 2022). The possible benefits of integrating biodiesel into Indian marine operations include reducing the industry's carbon emissions, improving energy security, promoting sustainable agriculture, and aligning with international environmental objectives (Mujtaba et al., 2020). Nevertheless, the effective incorporation of biodiesel into the maritime industry is a multifaceted undertaking that necessitates meticulous examination of numerous issues. The elements under consideration include engine compatibility, biodiesel blends, fuel quality, emissions reduction, regulatory compliance, cost analysis, environmental advantages, and research and development (Razzaq et al., 2021). Furthermore, using biodiesel as a marine fuel necessitates a comprehensive strategy that includes formulating policies, allocating resources for infrastructure development, undertaking research and development activities, and fostering collaboration among various stakeholders (Gray et al., 2021).

In the subsequent sections, we will thoroughly examine the crucial elements of implementing biodiesel in the con-

Article Highlights

- Importance of biodiesel in marine engine is explored;
- Biodiesel lowers Greenhouse Gases;
- Biodiesel lubricity requires meticulous engine maintenance.

✉ Yuvarajan Devarajan
dyuvarajan2@gmail.com

[1] Department of Mechanical Engineering, Saveetha School of Engineering, SIMATS, Chennai, Tamil Nadu, India

text of maritime transportation in India, providing a comprehensive analysis of each of these parameters (Wang and Li, 2023). Through thoroughly analysing the various prospects and obstacles linked to biodiesel, our objective is to offer a clear comprehension of the potential of this alternative fuel in fostering sustainability and environmental conservation within India's marine industry (Ogunkunle and Ahmed, 2019). This detailed review examines the integration of inedible biodiesel into marine diesel engines in India, with a focus on sustainable maritime operations. It explores new waters and presents a novel approach. This article explores various factors related to biodiesel's potential in the Indian maritime sector, including engine compatibility, emissions reduction, regulatory compliance, and economic viability. It also discusses the importance of policy formulation, infrastructure investment, and collaborative initiatives for the successful implementation of biodiesel in this sector. Adopting non-consumable biodiesel not only serves as an alternative fuel, but also acts as a guiding light leading India towards a future characterized by decreased carbon emissions, improved energy security, and global environmental balance.

2 Navigating engine compatibility for sustainable marine diesel engines

For sustainable marine diesel engines to have a minimal negative environmental impact on transportation, navigation engine compatibility is crucial. Sustainable marine diesel engines are designed to meet strict environmental standards, reduce greenhouse gas emissions, and maximize fuel efficiency (Soudagar et al., 2020b). Compatibility requires considering several variables, such as engine technologies, emission control systems, and fuel types. When navigating engine compatibility in the context of sustainable marine diesel engines, keep the following points in mind:

2.1 Selection of fuel

The choice of fuel for environmentally friendly marine diesel engines is crucial and can significantly affect both operating effectiveness and the environment. When making this decision, stability, lubricity, and the pros and downsides of biodiesel and other fuels are essential considerations (Gössling et al., 2021). In essence, adherence to regulatory requirements within the maritime sector plays a crucial role in ensuring the responsible functioning of marine diesel engines that are environmentally sustainable (Oloruntobi et al., 2023). By adhering to emission regulations and maintaining vigilance about emission control areas, individuals and organizations assure their compliance with local and international legislation and demonstrate their commitment to broader environmental objectives. Maritime operators significantly contribute to improving air quality, minimizing ecological effects, and fostering a sustainable future for the industry by embracing these requirements (Nunes, 2023).

The topic of sustainability and long-term planning is of great importance. The marine industry is placing greater emphasis on sustainability and long-term planning due to the rising significance of decreasing environmental impact and adopting cleaner and more efficient operations. Within this particular context, two significant elements warrant attention: sustainability goals and the need to ensure that engine comp). ility decisions align with these overarching aims (Soudagar et al., 2020a). Table 1 represents the heat content for various fuels.

Table 1 Fuel energy density (Ramalingam et al., 2023)

Fuel	Amount	Heat content (BTUs)
Oil	1 gallon	138 095
Gasoline	1 gallon	124 000
Electricity	1 kWh	3 412
Coal	1 Ib	9 241
Diesel or heating oil	1 gallon	139 000
Natural gas	1 cubic foot	1 026
White oak (20% moisture content)	1 cord	27 000 000

2.2 Targets for sustainable development

The maritime sector is establishing ambitious sustainability objectives to mitigate its environmental impact. These objectives frequently encompass reducing emissions, enhancing fuel efficiency, and adopting more ecologically sustainable approaches (Watanabe et al., 2022). When making decisions regarding engine compatibility, it is imperative to ensure alignment with the prevalent sustainability objectives across the sector. The achievement of this alignment may necessitate allocating resources toward developing novel engine technologies, exploring alternative fuels, and implementing emission control systems that provide cleaner and more efficient operations (Soudagar et al., 2019).

Through the implementation of sustainability objectives, marine operators are able to make a significant and meaningful contribution towards the development of a more ecologically conscious and socially responsible business (Prokopenko O and Miśkiewicz, 2020). Additionally, this strategic approach allows them to position themselves favorably for long-term profitability. There is a rising recognition of the significance of sustainable practices among customers, regulators, and the general public. The implementation of such procedures has the potential to enhance a company's reputation, hence allowing the acquisition of new business opportunities and collaborations (Oliva et al., 2022).

The significance of long-term planning arises from the ongoing shift towards sustainable practices within the maritime sector and the recognition that choices made in the present can exert a substantial influence on future operations (Soudagar et al., 2020b). Implementing strategic investments in technology and infrastructure to support sustainability is crucial for marine firms. Such expenditures guarantee adherence to growing legislation and enable these businesses to flourish in a market that is increasingly focused on environmental concerns (Yeo et al., 2023).

2.3 Engagement with engine manufacturers and suppliers

Establishing partnerships with engine manufacturers and suppliers is crucial in effectively managing engine compatibility for sustainable marine diesel engines (Laskar and Giang, 2023). This collaboration guarantees that the chosen machine and fuel technologies are in harmony and backed by the requisite technical competence and assistance required for effective and ecologically conscious maritime operations (Tadros et al., 2023).

Collaborating closely with engine manufacturers, it is evident that they play a pivotal role in spearheading the advancement of state-of-the-art technology for the purpose of creating sustainable marine diesel engines (Hoang and Pham, 2018). Shipowners and operators can acquire vital insights into the newest breakthroughs in engine technology by cultivating a robust working relationship with them. This collaboration facilitates the process of making well-informed decisions regarding the selection of engines for vessels (Fenton, 2020). It enables the consideration of various options, such as low-emission engines, dual-fuel engines, and other sophisticated solutions. Furthermore, engine manufacturers have the capability to offer recommendations on enhancing engine performance, conducting maintenance procedures, and resolving issues, thereby guaranteeing the engines function optimally while adhering to regulatory requirements (Dyatlov et al., 2020).

2.4 Collaboration with Fuel Suppliers

The involvement of fuel suppliers is of utmost importance in facilitating the provision, quality assurance, and accessibility of alternative fuels (Veza et al., 2022). Establishing partnerships with fuel suppliers is necessary to ensure a dependable and uniform supply of alternative fuels, which frequently serve as a crucial element in the operation of environmentally efficient marine diesel engines. This collaboration encompasses the acquisition of suitable powers and the validation of their adherence to regulatory mandates and industry benchmarks (Alamoush et al., 2021).

Through establishing partnerships with engine manufacturers and fuel suppliers, shipowners and operators can foster a harmonized and comprehensive strategy toward developing environmentally friendly marine diesel engines (Christodoulou et al., 2021). This method involves carefully selecting appropriate engine technology and fuel types, the optimization of their operation, the adherence to regulatory requirements, and establishing a sustained commitment to sustainability. The invaluable nature of the guidance and technical support offered by these partners is instrumental in attaining the dual objectives of mitigating environmental impact and upholding operational efficiency within maritime transport (Acciaro et al., 2020).

In essence, establishing productive partnerships with engine manufacturers and fuel suppliers is a crucial strategic measure in guaranteeing engine compatibility for developing environmentally efficient marine diesel engines (Kouzelis et al., 2022)This collaboration not only enables the identification of the most appropriate technology but also empowers marine operators to negotiate the complex realm of sustainability and regulatory adherence, thus making a valuable contribution to enhancing the cleanliness and efficiency of the maritime sector (Wategave et al., 2021).

3 Blending biodiesel: exploring the landscape of sustainable maritime fuel options

Biodiesel blends encompassing a combination of biodiesel and conventional diesel fuel have garnered considerable interest as a feasible and ecologically sound substitute for solely petroleum-derived diesel. These blends are classified by utilizing the “BXX” notation, wherein XX represents the proportion of biodiesel present in the combination. The selection of blend ratio is a critical factor in determining both the environmental implications and engine compatibility (Bach et al., 2021). Figure 1 represents the diverse alternative fuels for reducing carbon emission from marine transport.

One of the key benefits associated with the utilization of biodiesel blends is their capacity to mitigate the environmental impact of diesel engines. Combinations such as B5 (consisting of 5% biodiesel) and B10 (comprising 10% biodiesel) facilitate a progressive shift from traditional diesel to biodiesel, enabling machinery to function with diminished particulate matter emissions and greenhouse gases (Tan et al., 2022). As the biodiesel percentage increases, so do the environmental benefits, contributing to cleaner air quality and reduced carbon emissions (Verma and Goel, 2023). However, it’s essential to balance environmental objectives and engine performance, as very high biodiesel concentrations can have distinct properties, like increased viscosity and lower energy content, which might affect engine efficiency and fuel economy (Harahap et al., 2023) Engine compatibility is a crucial consideration when using biodiesel blends. While most modern diesel engines can run on B5 or B10 blends without significant modifications,

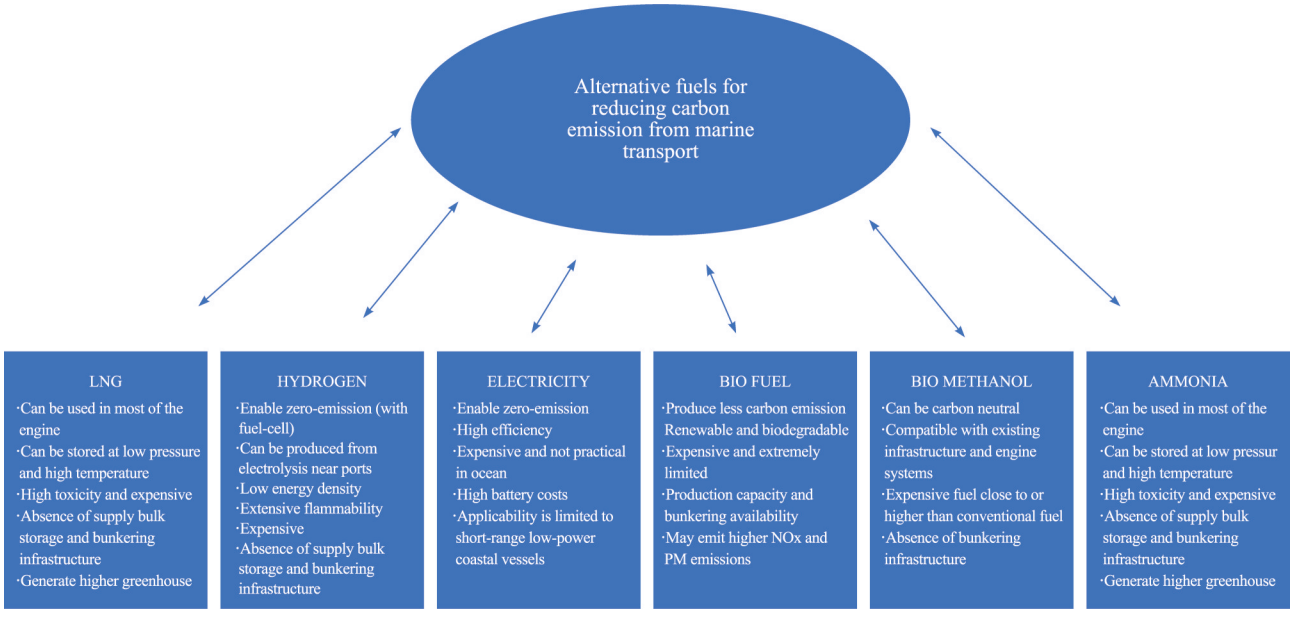

Figure 1 Alternative fuels for reducing carbon emission from marine transport

higher blend ratios may require engine adjustments. Manufacturers often provide guidelines and recommendations for specific engine models, ensuring users can choose the blend ratio that best suits their engine's design and performance requirements (Langerak, 2023). In addition to environmental and engine compatibility considerations, the availability and regulatory landscape of biodiesel blends should be taken into account. Fuel availability can vary depending on location and market demand, so assessing the local supply chain is essential to ensure a consistent source of the desired blend. Furthermore, regulatory compliance is critical, as different regions may have specific standards and requirements for biodiesel blends, ensuring they meet quality and performance criteria (Razzaq et al., 2021). Proper storage and handling of biodiesel blends are also essential. Like pure biodiesel, these blends can be susceptible to microbial growth and oxidation if not managed correctly. Adequate filtration, storage tanks, and maintenance procedures are vital to keep the fuel system clean and maintain engine performance over time (Sahu et al, 2022).

In summary, biodiesel blends present a versatile and environmentally viable strategy for mitigating the ecological consequences associated with diesel engines. The selection of the mix ratio should be guided by factors such as engine compatibility, ecological aims, local legislation, and practical considerations (Fragkos, P. 2022). Through meticulous selection of the optimal blend ratio and adherence to recommended protocols for storage and handling, the utilization of biodiesel blends can effectively contribute to the advancement of cleaner and more sustainable transportation alternatives while upholding engine performance and dependability (Sayyed et al., 2022).

4 Quality assurance in biodiesel: from production to marine engine performance

Biodiesel blends comprising a combination of biodiesel and conventional diesel fuel have garnered considerable interest as a feasible and ecologically sustainable substitute for solely petroleum-derived diesel (Akkoli et al., 2021). These blends are categorized using the "BXX" notation, in which XX represents the proportion of biodiesel in the mixture. The selection of blend ratio is a critical factor in determining both the environmental implications and engine compatibility (Bakır, et al, 2022).

One of the key benefits of using biodiesel blends is their capacity to mitigate the environmental impact of diesel engines. Mixtures such as B5 (consisting of 5% biodiesel) and B10 (composed of 10% biodiesel) provide a progressive shift from traditional diesel fuel to biodiesel, enabling engines to function with less emissions of particulate matter and greenhouse gases (Kaniapan et al., 2021). The augmentation of biodiesel concentration is accompanied by a corresponding increase in environmental advantages, positively contributing to improving air quality and mitigating carbon emissions. Nevertheless, achieving a harmonious equilibrium between ecological goals and engine functionality is imperative. This is because excessively high levels of biodiesel might exhibit unique characteristics such as heightened viscosity and reduced energy content, potentially impacting engine efficiency and fuel economy (Devarajan et al., 2021).

The topic of engine compatibility holds significant importance in using biodiesel blends. Although most contemporary diesel engines can operate with B5 or B10 blends without substantial alterations, the utilization of higher

blend ratios may necessitate specific improvements to the engine (Masera el at., 2023). Manufacturers frequently offer Guidelines and recommendations to users of particular engine types to enable educated decision-making regarding the optimal blend ratio that aligns with the engine's design and performance prerequisites (Noor et al., 2021).

In conjunction with assessing environmental and engine compatibility factors, it is imperative to evaluate the accessibility and regulatory framework of biodiesel mixes. The availability of fuel might be subject to geographical variations and fluctuations in market demand (Tadros, et al., 2021). Therefore, assessing the local supply chain to secure a reliable and uninterrupted source of the necessary fuel blend is crucial. In addition, it is imperative to emphasize the significance of regulatory compliance in the context of biodiesel blends. This is because various geographical areas may impose distinct rules and prerequisites, necessitating adherence to quality and performance benchmarks (Madey, V. 2022).

The adequate storage and appropriate treatment of biodiesel blends are crucial factors. Like pure biodiesel, these mixtures may be prone to microbial development and oxidation if not effectively controlled (Chountalas et al., 2023). Ensuring proper filtration, employing suitable storage tanks, and implementing regular maintenance methods are essential for preserving the cleanliness of the fuel system and sustaining optimal engine performance throughout its lifespan (Okubo and Kuwahara, 2019).

In summary, biodiesel blends present a versatile and environmentally conscious strategy for mitigating the ecological consequences associated with diesel engines. The selection of the mix ratio should be determined by factors such as engine compatibility, environmental goals, regional restrictions, and practical constraints (Torres-Garcia et al., 2020). Through meticulous selection of the optimal blend ratio and adherence to recommended protocols for storage and handling, the utilization of biodiesel blends has the potential to enhance the cleanliness and sustainability of transportation systems while ensuring the preservation of engine performance and dependability (Yaliwal et al., 2022).

5 Lubricity and maintenance considerations in biodiesel-powered marine engines

Compared to regular diesel fuel, biodiesel's distinctive lubricity qualities have significant ramifications for the operation and maintenance of diesel engines. Biodiesel is recognized for its exceptional lubricating properties, principally attributed to its elevated oxygen content and the inclusion of inherent lubricity ingredients (Tadros et al., 2022). The intrinsic lubricating properties of this substance can be advantageous for various engine parts by mitigating friction and minimizing wear, potentially prolonging the engine's operational longevity. Nevertheless, this distinctive attribute also requires meticulous deliberation and adaptations in the machine's upkeep (Wojcieszyk et al., 2019).

An essential factor to consider is the compatibility of the fuel system with biodiesel, especially in older engine models or those constructed with materials that may need to be optimally suited for the qualities of biodiesel. The lack of compatibility between engine components can give birth to various problems, including corrosion and other related issues. It is imperative to adhere attentively to the instructions and guidelines provided by manufacturers to prevent such issues (Awad et al., 2020).

The careful consideration of fuel filters is also necessary in biodiesel utilization. The solvent qualities of biodiesel can remove deposits or pollutants in the fuel system, which may obstruct filters. Regular inspection and replacement of gasoline filters are vital to uphold unimpeded fuel flow and guarantee optimal engine performance. The selection of suitable engine oil is an additional crucial factor to consider. The lubricating properties of biodiesel may impact the choice of motor oil. Seeking advice from the engine manufacturer or a lubrication specialist can assist in identifying the most suitable engine oil to enhance the lubricating characteristics of biodiesel and guarantee the highest engine efficiency (Vellaiyan, S. 2023).

Over a prolonged duration, the utilization of biodiesel has the potential to lead to the formation of deposits within fuel injectors. Regular maintenance or cleaning of injectors may be necessary to mitigate fuel system complications and uphold regular fuel atomization, a critical factor in promoting effective combustion. Ensuring the compatibility of seal materials employed in the engine is crucial to mitigate the risk of leaks or deterioration of seals upon exposure to biodiesel (Venu et al., 2021). The gel point of the biodiesel blend should be considered in cold areas, as biodiesel has the potential to solidify at greater temperatures than traditional diesel fuel. It is advisable to implement preventive measures to mitigate the occurrence of fuel gelling within the engine or fuel lines. Maintaining biodiesel quality and preventing contamination necessitate adherence to appropriate fuel storage protocols. Storing biodiesel in water-free tanks is imperative to prevent microbial growth and fuel breakdown (Sharma et al., 2022). Ensuring regular engine maintenance is essential while utilizing biodiesel. The implementation of scheduled maintenance, which encompasses comprehensive inspections and the replacement of components as necessary, serves as a proactive measure to mitigate potential concerns before they progress into significant problems (Kumar et al., 2022).

In conclusion, the enhanced lubricity of biodiesel presents several potential benefits in mitigating engine wear. However, it is imperative to acknowledge the unique characteristics of biodiesel and their consequential effects on

engine performance. By adhering to the guidelines provided by manufacturers and implementing best practices in maintenance and fuel handling, diesel engines can effectively utilize biodiesel and mitigate any potential issues associated with lubricating qualities (Wu et al., 2020).

6 Building a sustainable biodiesel supply chain for India's energy future

Establishing a dependable supply chain for biodiesel in India necessitates a comprehensive approach involving careful strategizing and precise implementation throughout each phase. Commencing with the process of feedstock sourcing, the detailed and deliberate choice of suitable and environmentally sustainable feedstock sources is paramount. This entails assessing the accessibility and cost-efficiency of alternatives, such as non-edible oils, waste cooking oil, and microalgae. The establishment of robust collaborations with feedstock suppliers is vital in order to secure a reliable and superior supply for the manufacturing of biodiesel (Gülüm, 2022).

Transitioning to the phase of biodiesel production necessitates the presence of well-planned and highly effective manufacturing facilities. To ensure the production of biodiesel that fulfills the required parameters, these facilities must strictly adhere to rigorous quality standards. Ensuring product uniformity necessitates the implementation of routine quality control tests (Wategave et al., 2021). The distribution network is a crucial element within the broader supply chain framework. The safe and efficient transportation of biodiesel from production facilities to distribution sites is vital. As mentioned earlier, the requirement entails establishing storage facilities and transportation techniques appropriate for biodiesel, emphasizing ensuring safety and adherence to environmental regulations. To enhance consumer accessibility to biodiesel, a comprehensive network of refueling infrastructure is required. This entails the implementation of biodiesel refueling stations at strategically chosen sites, with a preference for integration with pre-existing diesel refueling infrastructure and the assurance of biodiesel blend accessibility at these stations (Masera and Hossain, 2019).

Government policies and incentives are crucial factors in stimulating investment within the biodiesel business. Supportive policies, such as blending mandates and tax incentives, can promote growth and facilitate the widespread acceptance of a particular product or service within the market (Devarajan et al., 2020). Sustainable collaborative research and development endeavors must be sustained to enhance production processes, ensure feedstock availability, and promote engine compatibility. These efforts are crucial for supporting innovation and sustainability (Tabatabaei et al., 2019). Consumer awareness campaigns are of significant importance in disseminating knowledge to the broader public regarding the diverse benefits associated with biodiesel, spanning both environmental and economic dimensions. The stimulation of demand for biodiesel can be achieved by highlighting its positive impact on the reduction of carbon emissions and by advocating for the use of sustainable agriculture methods (Narwane et al., 2021).

Integrating environmental sustainability as a fundamental principle across the whole supply chain is necessary to mitigate the adverse environmental impacts of feedstock production, processing, and transportation. Finally, implementing contingency planning is necessary to manage and mitigate potential disruptions effectively, guaranteeing the seamless continuity of biodiesel transportation within the supply chain. By employing careful strategic planning, strict adherence to established quality standards, and a steadfast dedication to sustainability, India has the potential to cultivate a resilient biodiesel supply chain that effectively contributes to energy security, diminished greenhouse gas emissions, and the promotion of sustainable agricultural practices (Gupta et al., 2022).

7 Detailed overview and government policies for the and evaluating the economic viability adoption of biodiesel in Indian maritime operations

The Indian government has strategically devised various policies and programs to promote biodiesel uptake in the maritime industry. One of the prominent initiatives in this regard is the National Biodiesel Mission, which prioritizes the promotion and development of biodiesel production and consumption. The objective of this mission is to decrease the dependence on conventional fossil fuels by advocating for the utilization of non-edible oilseeds as the principal resource for the production of biodiesel. The prioritization of non-edible oilseeds aims to reduce the potential consequences of edible oils, thereby ensuring the protection of food security (Saravanan et al., 2020).

Aligned with its overarching objective, the Biofuel Policy of India assumes a prominent position, emphasizing the advancement of biofuel sources that do not compete with food production. This study emphasizes the utilization of non-edible oils and agricultural waste as primary sources for creating biodiesel. The primary objective of this strategic approach is to mitigate any adverse consequences on the food supply chain, guaranteeing that the production of biofuels does not impinge upon the accessibility or cost-effectiveness of food supplies (Rao et al., 2024).

Furthermore, the government is now pursuing strategies aimed at promoting and incentivizing the production

and consumption of biodiesel through the provision of tax incentives and subsidies. Incentives, such as exemptions or lower taxes on biodiesel production, sale, or consumption, are crucial in stimulating the adoption of biodiesel by both industry and consumers. Financial support contributes to the improved economic sustainability of biodiesel, rendering it a more appealing and viable alternative (Tuli & Kasture, 2022).

The proper implementation of these programs, together with the development of necessary infrastructure, technical breakthroughs, and ongoing support and collaboration between the government and commercial sectors, is crucial for their successful fulfillment. It is advisable to stay informed about the newest government publications and official statements to keep abreast of the evolving nature of policies and activities (Singhal et al., 2020).

Evaluating the cost-effectiveness of biodiesel for marine operations in India is a complex undertaking that necessitates a thorough examination of multiple elements. The availability and affordability of biodiesel feedstock are significant factors that influence the biodiesel industry. Various choices, such as non-edible oils, waste cooking oil, and microalgae, are being examined as potential feedstock sources. Compared to traditional diesel, the cost-effectiveness of these feedstocks is contingent upon their accessibility and cost competitiveness (Vidović et al., 2023).

Additionally, biodiesel providers or producers' utilization of production methods holds significant importance. Typically, the use of more efficient and cost-effective production techniques results in reduced overall costs for biodiesel. Hence, assessing the efficacy and costs linked to the selected mode of production is imperative. The careful selection of the optimal biodiesel mixes for marine engines is an essential factor to be considered. The advice of engine manufacturers and local restrictions should guide the decision. The blend selection can impact multiple factors, including the financial implications and the performance and adherence to regulatory standards of the engine. The compatibility of the engine is a crucial determinant. Modifying marine engines to operate optimally on biodiesel may entail early financial investments. Thoroughly evaluate the expenses and prospective economic benefits that may accrue in the long run (Sagin et al., 2023).

The consideration of price stability holds significant importance. Although biodiesel prices may experience fluctuations, they generally exhibit lower volatility than regular diesel fuel. The strength mentioned above can yield significant cost-saving advantages over an extended period. It is advisable to investigate governmental incentives, subsidies, or grants specifically designed to encourage the utilization of biodiesel. The financial advantages could impact the equation of cost-effectiveness significantly (Perin and Jones, 2019). Monitoring maintenance expenses is of utmost importance due to the distinct lubricating qualities of biodiesel in contrast to conventional diesel fuel. When evaluating cost-effectiveness, it is essential to include any modifications in maintenance expenditures, explicitly of engine lubrication and the impact on wear and tear (Khan et al., 2020). The ecological advantages stemming from the decreased emissions from using biodiesel should be considered. This analysis aims to quantify the possible financial benefits that can be derived from reducing emissions and assess whether there are any regulatory or incentive-driven advantages associated with lower emissions (Khan et al., 2021).

It is imperative to take into account appropriate storage and handling protocols (Rao et al., 2024; Sevim and Zincir, 2022; Singh et al., 2022; Soudagar et al., 2021; Vickram et al., 2023). Preserving biodiesel quality may necessitate using specialized storage tanks and implementing safety protocols, potentially increasing operational expenses. The critical aspect of your biodiesel supply chain lies in its reliability, encompassing the entire process from feedstock procurement to delivery. Disruptions have the potential to lead to higher expenses or operational disruptions (Kothari et al., 2020). To arrive at a well-informed decision, it is crucial to thoroughly evaluate costs and benefits, considering immediate and enduring consequences. Evaluate the return on investment (ROI) of integrating biodiesel into marine activities (Boopathy et al., 2020). Furthermore, it is imperative to perform comparative analyses, including other fuels, such as liquefied natural gas (LNG) or hydrogen, to assess their viability. Additionally, examining the continued utilization of traditional diesel fuel is crucial. The comprehensive assessment would enable well-informed decision-making on the cost-effectiveness of biodiesel for a particular maritime fleet (Awogbemi, et al., 2021).

8 Potential drawbacks and International regulation of using biodiesel in Marine engine

The utilization of biodiesel in marine engines presents a range of obstacles to the resilience of the supply chain, the economic viability of the technology, and the level of acceptance from the general population (Prasad et al., 2020; Christodoulou et al., 2023; Dwivedi et al., 2021; Lubchenco and Haugan, 2023). The landscape of supply chain resilience is intricate, primarily because of the availability of feedstock. The dependence on agricultural or waste sources presents vulnerabilities that are susceptible to market changes, probable crop failures, or fluctuations in trash availability. In addition, the complex logistical aspects associated with the acquisition of feedstock, the manufacturing process, and the distribution of biodiesel may give rise to vulnerabilities that could impact the reliable provision of biodiesel for marine operations (Awogbemi et al., 2021).

The issue of economic viability is another aspect of con-

cern. The expenses associated with the manufacturing of biodiesel, primarily when obtained from non-traditional sources, may exceed those of conventional fossil fuels. The economic viability of biodiesel production, storage, and transportation may be affected by the financial considerations involved, as well as the significant expenditure required to retrofit or construct infrastructure. This could particularly pose challenges for smaller maritime operators (Wojcieszyk et al., 2019). The public perception and awareness of biodiesel in maritime applications provide significant barriers to its widespread acceptance. Concerns surrounding the efficiency of the technology, issues about engine compatibility, and apprehensions regarding performance may pose obstacles to its widespread implementation. Furthermore, the implementation of biodiesel on a large scale has considerable challenges in terms of modifying existing industry procedures and promoting a shift in behavior towards its use (Ravikumar et al., 2022).

The resolution of these complex difficulties necessitates a collective endeavor. Ongoing research and development play a vital role in improving the accessibility of feedstock, refining production processes, and ensuring compatibility with engines. The economic viability and accessibility of biodiesel for maritime operations could be enhanced by government assistance through subsidies and policy incentives. Educational outreach programs are crucial in debunking misunderstandings, enhancing knowledge, and fostering acceptance within the industry and the public (Akram et al., 2022). The collaboration and synchronized endeavors of governmental bodies, industrial sectors, researchers, and the public are crucial in overcoming these challenges and facilitating a smoother incorporation of biodiesel in maritime propulsion systems (Boopathy et al., 2020; Bošnjaković and Sinaga, 2020; Bouman et al., 2017).

The regulation of biodiesel utilization in marine engines worldwide is encompassed by a range of maritime treaties and rules that oversee environmental preservation and operational criteria. Nevertheless, there needs to be clearer laws or standards explicitly addressing the utilization of biodiesel in marine engines. Instead, it falls under the purview of more comprehensive regulations that govern fuel usage and emissions within the maritime sector (Tadros et al., 2021). The International Maritime Organization (IMO) establishes comprehensive standards that have a significant influence on the utilization of various fuels in marine engines, primarily aimed at mitigating emissions and fostering environmental sustainability (Ravikumar Jayabal, 2020). The International Maritime Organization's (IMO) regulations about fuel quality and emissions management exert a substantial influence on the application of biodiesel in marine engines. Implementing rules such as the global sulfur cap and the establishment of Emission Control Areas (ECAs) exemplify measures aimed at enforcing the reduction of sulfur content in marine fuels, with the primary objective of mitigating air pollution. Biodiesel, renowned for its little sulfur content and diminished emissions, exhibits compatibility with these rules, rendering it an appropriate selection for adherence (Ravikumar Jayabal, 2020). Although there is no explicit international rule exclusively addressing the utilization of biodiesel in marine engines, extant regulations of emissions, fuel quality, and environmental preservation implicitly exert influence and promote the adoption of cleaner and more sustainable fuel alternatives like biodiesel. The adherence of biodiesel to these norms and standards establishes it as a feasible and more appealing alternative for the maritime sector, aiming to mitigate its ecological footprint (Tadros et al., 2023).

9 Developing trends

The development trends in non-consumable biodiesel as a sustainable alternative fuel for marine diesel engines involve multiple aspects (Mallouppas and Yfantis 2021; Manikandan et al., 2022; Moshiul et al., 2022; Nouni et al., 2021). The objective of technological breakthroughs is to enhance production processes and investigate the development of enhanced biofuel generations. Research is now being conducted to optimize biodiesel blends by investigating blending methodologies, with the aim of achieving compatibility and maximizing environmental advantages. The emphasis lies on comprehending and measuring the reduction of emissions, as well as cooperating with regulatory entities to establish standards. Efforts are underway to create favorable legislation, incentives, and subsidies, as well as invest in infrastructure and install biodiesel fuelling stations. The integration of worldwide cooperation and life cycle assessments are crucial in adopting a complete strategy, while ongoing initiatives aim to enhance public knowledge and approval. These trends indicate a changing landscape with continuous efforts to improve the practicality and acceptance of non-edible biodiesel in the maritime industry (Aguilar-Rivera et al., 2021; Akram et al., 2022; Bajpai R , 2023).

10 Conclusion

Biodiesel integration in Indian marine diesel engines holds significant promise for sustainability. Derived from renewable sources, biodiesel aligns with India's emissions reduction goals. However, complexities exist, emphasizing the need for careful consideration. Engine compatibility, adherence to guidelines, and strategic biodiesel blend choices are pivotal for optimal performance. While biodiesel brings environmental benefits, its unique lubricity requires meticulous engine maintenance. A resilient supply chain, regulatory compliance, and cost-effectiveness evaluations

are crucial for successful integration. Ongoing research enhances biodiesel production and marine engine efficiency. Adoption of biodiesel in India's maritime sector could reduce carbon emissions, enhance energy security, and align with global environmental goals. A comprehensive approach is key to steering India's marine activities toward a sustainable and environmentally conscious future.

Abbreviations

CNG	Compressed Natural Gas
BTL	Biomass−to−Liquid
CC	Combustion Chamber
EPA	Environmental Protection Agency
CO	Carbon monoxide
DPF	Diesel Particulate Filter
EGR	Exhaust Gas Recirculation
LHV	Lower Heating Value
HVO	Hydrotreated Vegetable Oil
LNG	Liquefied Natural Gas
GTL	Gas−to−Liquid
LPG	Liquified Petroleum Gas
HC	Hydrocarbon
API	American Petroleum Institute
FAME	Fatty Acid Methyl Ester

Competing interest The authors have no competing interests to declare that are relevant to the content of this article.

References

Acciaro M, Renken K, El Khadiri N (2020) Technological change and logistics development in European ports. European Port Cities in Transition: Moving Towards More Sustainable Sea Transport Hubs, 73-88. http://dx.doi.org/10.1007/978-3-030-36464-9_5

Aguilar-Rivera N, Michel-Cuello C, Cervantes-Niño JJ, Gómez-Merino FC, Olvera-Vargas LA (2021) Effects of public policies on the sustainability of the biofuels value chain. In Sustainable Biofuels (pp. 345-379). Academic Press. http://dx.doi.org/10.1016/B978-0-12-820297-5.00004-9

Akkoli KM, Banapurmath NR, Shivashimpi MM, Soudagar MEM, Badruddin IA, Alazwari MA, Yaliwal VS, Mujtaba MA, Akram N, Goodarzi M, Safaei MR, Venu H (2021) Effect of injection parameters and producer gas derived from redgram stalk on the performance and emission characteristics of a diesel engine. Alexandria Engineering Journal, 60(3): 3133-3142. https://doi.org/10.1016/j.aej.2021.01.047

Akram F, ul Haq I, Raja SI, Mir AS, Qureshi SS, Aqeel A, Shah FI (2022) Current trends in biodiesel production technologies and future progressions: A possible displacement of the petro-diesel. Journal of Cleaner Production, 133479. https://doi.org/10.1016/j.jclepro.2022.133479

Alamoush AS, Ballini F, Dalaklis D (2021) Port sustainable supply chain management framework: Contributing to the United Nations' sustainable development goals. Maritime Technology and Research, 3(2): 137-161. http://dx.doi.org/10.33175/mtr.2021.247076

Ampah JD, Yusuf AA, Afrane S, Jin C, Liu H (2021) Reviewing two decades of cleaner alternative marine fuels: Towards IMO's decarbonization of the maritime transport sector. Journal of Cleanerproduction, 320, 128871. https://doi.org/10.1016/j.jclepro.2021.128871

Awad OI, Ma X, Kamil M, Ali OM, Ma Y, Shuai S (2020) Overview of polyoxymethylene dimethyl ether additive as an eco-friendly fuel for an internal combustion engine: Current application and environmental impacts. Science of the Total Environment, 715, 136849. https://doi.org/10.1016/j.scitotenv.2020.137302

Awogbemi O, Kallon DVV, Onuh EI, Aigbodion VS (2021) An overview of the classification, production and utilization of biofuels for internal combustion engine applications. Energies, 14 (18): 5687. https://doi.org/10.3390/en14185687

Bach H, Mäkitie T, Hansen T, Steen M (2021) Blending new and old in sustainability transitions: Technological alignment between fossil fuels and biofuels in Norwegian coastal shipping. Energy Research & Social Science, 74, 101957. https://doi.org/10.1016/j.erss.2021.101957

Bakır H, Ağbulut Ü, Gürel AE, Yıldız G, Güvenç U, Soudagar MEM, Hoang AT, Deepanraj B, Saini G, Afzal A (2022) Forecasting of future greenhouse gas emission trajectory for India using energy and economic indexes with various metaheuristic algorithms. Journal of Cleaner Production, 360, 131946. https://doi.org/10.1016/j.jclepro.2022.131946

Boopathy AB, Jayakumar T, Chinnasamy S, Rajaram MG, Mohan N, Nagaraj S, Chang CC (2020) Biomass and lipid production potential of an Indian marine algal isolate Tetraselmis striata BBRR1.Energies,13(2):341. https://doi.org/10.3390/en13020341

Bouman EA, Lindstad E, Rialland AI, Strømman AH (2017) State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping–A review. Transportation Research Part D: Transport and Environment, 52: 408 – 421. https://doi.org/10.1016/j.trd.2017.03.022

Chountalas TD, Founti M, Tsalavoutas I (2023) Evaluation of biofuel effect on performance & emissions of a 2-stroke marine diesel engine using on-board measurements. Energy, 278, 127845. https://doi.org/10.1016/j.energy.2023.127845

Christodoulou A, Dalaklis D, Ölcer A, Ballini F (2021) Can market-based measures stimulate investments in green technologies for the abatement of GHG emissions from shipping? A review of proposed market-based measures. Transactions on Maritime Science, 10(01): 208-215. http://dx.doi.org/10.7225/toms.v10.n01.017

Devarajan Y, Munuswamy D, Nagappan B. Choubey G (2020) Study on the effect on combining long-chain additive with neat biodiesel fueled engine to examine its ignition characteristics. Fuel, 279, 118400. doi:10.1016/j.fuel.2020.118400

Devarajan Y, Nagappan B, Choubey G, Vellaiyan S, Mehar K (2021) Renewable pathway and twin fueling approach on ignition analysis of a dual-fuelled compression ignition engine. Energy & Fuels, 35 (12): 9930-9936. https://doi.org/10.1021/acs.energyfuels.0c04237

Dyatlov SA, Didenko NI, Ivanova EA, Soshneva EB, Kulik SV (2020) Prospects for alternative energy sources in global energy sector. In IOP Conference Series: Earth and Environmental Science, 434(1): 012014. IOP Publishing. http://dx.doi.org/10.1088/1755-1315/434/1/012014

Fenton P (2020) Port-city redevelopment and sustainable development. European Port Cities in Transition: Moving Towards More Sustainable Sea Transport Hubs, 19-36. http://dx.doi.org/10.1007/

978-3-030-36464-9_2

Fragkos P (2022) Decarbonizing the international shipping and aviation sectors. Energies, 15(24): 9650. http://dx.doi.org/10.3390/en15249650

Gössling S, Meyer-Habighorst C, Humpe A (2021) A global review of marine air pollution policies, their scope and effectiveness. Ocean & Coastal Management, 212, 105824. https://doi.org/10.1016/j.ocecoaman.2021.105824

Gray N, McDonagh S, O'Shea R, Smyth B, Murphy JD (2021) Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. Advances in Applied Energy, 1, 100008. http://dx.doi.org/10.3390/en15249650

Gülüm M (2022) Effects of compression ratio, blending ratio and engine speed on fuel cost, performance and exhaust emissions of a diesel engine fueled with bio-derived alternative fuels. Sustainable Energy Technologies and Assessments, 53, 102464. https://doi.org/10.1016/j.seta.2022.102464

Gupta S, Kar SK, Harichandan S (2022) India's emerging fuel mix for 2050: actions and strategies to decarbonize the transport sector. International Journal of Energy Sector Management, 16 (5): 924-945. https://doi.org/10.1108/IJESM-02-2021-0005

Harahap F, Nurdiawati A, Conti D, Leduc S, Urban F (2023) Renewable marine fuel production for decarbonised maritime shipping: Pathways, policy measures and transition dynamics. Journal of Cleaner Production, 137906. http://dx.doi.org/10.1016/j.jclepro.2023.137906

Hoang AT, Foley AM, Nižetić S, Huang Z, Ong HC, Ölçer AI, Nguyen XP (2022) Energy-related approach for reduction of CO2 emissions: A critical strategy on the port-to-ship pathway. Journal of Cleaner Production, 355, 131772. https://doi.org/10.1016/j.jclepro.2022.131772

Hoang AT, Pham VV (2018) A Review on Fuels Used for Marine Diesel Engines. Journal of Mechanical Engineering Research and Developments, 41(4): 22 – 32. https://doi.org/10.26480/jmerd. 04. 2018.22.32

Kaniapan S, Hassan S, Ya H, Patma Nesan K, Azeem M (2021) The utilisation of palm oil and oil palm residues and the related challenges as a sustainable alternative in biofuel, bioenergy, and transportation sector: A review. Sustainability, 13(6): 3110. http://dx.doi.org/10.3390/su13063110

Khan N, Sudhakar K, Mamat R (2021) Role of biofuels in energy transition, green economy and carbon neutrality. Sustainability, 13(22): 12374. http://dx.doi.org/10.3390/su132212374

Khan H, Soudagar MEM, Kumar RH, Safaei MR, Farooq M, Khidmatgar A, Banapurmath NR, Farade RA, Abbas MM, Afzal A, Ahmed W, Goodarzi M, Taqui SN (2020) Effect of nano-graphene oxide and n-butanol fuel additives blended with diesel—nigella sativa biodiesel fuel emulsion on diesel engine characteristics. Symmetry, 12(6): 961. https://doi.org/10.3390/sym12060961

Kothari R, Vashishtha A, Singh HM, Pathak VV, Tyagi VV, Yadav BC, Singh DP (2020) Assessment of Indian bioenergy policy for sustainable environment and its impact for rural India: Strategic implementation and challenges. Environmental technology & innovation, 20, 101078. https://doi.org/10.1016/j.eti.2020.101078

Kouzelis K, Frouws K, van Hassel E (2022) Maritime fuels of the future: what is the impact of alternative fuels on the optimal economic speed of large container vessels. Journal of Shipping and Trade, 7(1): 1-29. http://dx.doi.org/10.1186/s41072-022-00124-7

Kumar S, Sharma P, Pal K (2022) Application of machine learning approach in internal combustion engine: A comprehensive review. In International Conference on Recent Advances in Materials, Manufacturing and Thermal Engineering (pp. 165-178).Singapore: Springer Nature Singapore. http://dx.doi.org/10.1007/978-981-19-8517-1_12

Langerak L (2023) Fuel Transition for Gas Turbines In a Changing European Energy Landscape. https://urn.kb.se/resolve?urn=urn:nbn:se:umu:diva-213749

Laskar II, Giang A (2023) Policy approaches to mitigate in-use methane emissions from natural gas use as a marine fuel. Environmental Research: Infrastructure and Sustainability, 3(2): 025005. http://dx.doi.org/10.1088/2634-4505/accf33

Madey V (2022) Assessment of the efficiency of biofuel use in the operation of marine diesel engines. Technology audit and production reserves, 2(1/64): 34-41. http://dx.doi.org/10.15587/2706-5448.2022.255959

Masera K, Hossain AK (2019) Biofuels and thermal barrier: A review on compression ignition engine performance, combustion and exhaust gas emission. Journal of the Energy Institute, 92(3): 783–801. https://doi.org/10.1016/j.joei.2018.02.005

Masera K, Hossain AK (2023) Advancement of biodiesel fuel quality and NOx emission control techniques. Renewable and Sustainable Energy https://doi.org/10.1016/j.rser.2023.113235

Mujtaba MA, Kalam MA, Masjuki HH, Gul M, Soudagar MEM, Ong HC, Ahmed W, Atabani AE, Razzaq L, Yusoff M (2020) Comparative study of nanoparticles and alcoholic fuel additives-biodiesel-diesel blend for performance and emission improvements. Fuel, 279: 118434. https://doi.org/10.1016/j.fuel. 2020.118434

Narwane VS, Yadav VS, Raut RD, Narkhede BE, Gardas BB (2021) Sustainable development challenges of the biofuel industry in India based on integrated MCDM approach. Renewable Energy, 164: 298-309. https://doi.org/10.1016/j.renene.2020.09.077

Noor CWM, Mamat R, Ismail MY, Nurdiyana W, Alif S (2021) Performance and Emission Control of Using Steam Injection on Medium-Speed Marine Diesel Engine Running with Biodiesel Fuel. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 84(2): 10-23. http://dx.doi.org/10.1016/j.rser.2018.05.031

Nunes LJ (2023) Exploring the present and future of biomass recovery units: technological innovation, policy incentives and economic challenges. Biofuels, 1-13. http://dx.doi.org/10.1080/17597269.2023.2250973

Ogunkunle O, Ahmed NA (2019) A review of global current scenario of biodiesel adoption and combustion in vehicular diesel engines. Energy Reports, 5, 1560-1579. https://doi.org/10.1016/j.egyr.2019.10.028

Okubo M, Kuwahara T (2019) New technologies for emission control in marine diesel engines. Butterworth-Heinemann. https://doi.org/10.1016/j.egyr.2019.10.028

Oliva FL, Teberga PMF, Testi LIO, Kotabe M, Del Giudice M, Kelle P, Cunha MP (2022) Risks and critical success factors in the internationalization of born global startups of industry 4.0: A social, environmental, economic, and institutional analysis. Technological Forecasting and Social Change, 175, 121346. https://doi.org/10.1016/j.techfore.2021.121346

Oloruntobi O, Mokhtar K, Gohari A, Asif S, Chuah LF (2023) Sustainable transition towards greener and cleaner seaborne shipping industry: challenges and opportunities. Cleaner Engineering and Technology, 100628. http://dx.doi.org/10.1016/j.clet.2023.100628

Panoutsou C, Germer S, Karka P, Papadokostantakis S, Kroyan Y, Wojcieszyk M, Landalv I (2021) Advanced biofuels to decarbonise European transport by 2030: Markets, challenges, and policies that impact their successful market uptake. Energy Strategy Reviews, 34, 100633.

Perin G, Jones PR (2019) Economic feasibility and long-term sustainability criteria on the path to enable a transition from fossil fuels to biofuels. Current opinion in biotechnology, 57, 175-182. https://doi.org/10.1016/j.copbio.2019.04.004

Prokopenko O, Miśkiewicz R (2020) Perception of Green Shipping in the contemporary conditions. Entrepreneurship and Sustainability Issues, 8(2): 269. http://dx.doi.org/10.9770/jesi.2020.8.2(16)

Ramalingam S, Naresh Babu M, Devarajan Y, Dinesh Babu M, Varuvel EG (2023) Environmental and energy valuation of waste-derived Cymbopogon Martinii Methyl Ester combined with multi-walled carbon (MWCNTs) additives in hydrogen-enriched dual fuel engine. International Journal of Hydrogen Energy, 48(99): 39641–39657. https://doi.org/10.1016/j.ijhydene.2023.08.006

Rao R, Sahu C, Bauddh K (2024) Structural tenets of efficient bioeconomy and role of biofuels. In Biodiversity and Bioeconomy (pp. 503-536). Elsevier. https://doi.org/10.1016/B978-0-323-95482-2.00026-2

Ravikumar Jayabal (2020) Combined effect of oxygenated additives, injection timing and EGR on combustion, performance and emission characteristics of a CRDi diesel engine powered by sapota biodiesel/diesel blends. Fuel, 268, 117254. https://doi.org/10.1016/j.fuel.2020.118121

Ravikumar S et al (2022) Multi-objective optimization of performance and emission characteristics of a CRDI diesel engine fueled with sapota methyl ester/diesel blends. Energy, 123709. doi: 10.1016/j.energy.2022.123709

Razzaq L, Mujtaba MA, Soudagar MEM, Ahmed W, Fayaz H, Bashir S, Fattah IMR, Ong HC, Shahapurkar K, Afzal A, Wageh S, Al-Ghamdi A, Ali MS, EL-Seesy AI (2021) Engine performance and emission characteristics of palm biodiesel blends with graphene oxide nanoplatelets and dimethyl carbonate additives. Journal of Environmental Management, 282, 111917. https://doi.org/10.1016/j.jenvman.2020.111917

Sagin S, Karianskyi S, Madey V, Sagin A, Stoliaryk T, Tkachenko I (2023) Impact of biofuel on the environmental and economic performance of marine diesel engines. Journal of Marine Science and Engineering, 11(1): 120. http://dx.doi.org/10.3390/jmse11010120

Sahu TK, Shukla PC, Belgiorno G, Maurya RK (2022) Alcohols as alternative fuels in compression ignition engines for sustainable transportation: A review. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 44(4): 8736-8759. http://dx.doi.org/10.1080/15567036.2022.2124326

Saravanan A, Jayasree R, Kumar PS, Varjani S, Hemavathy RV, Jeevanantham S, Yaashikaa PR (2020) Production of pigment using Aspergillus tamarii: New potentials for synthesizing natural metabolites. Environmental Technology & Innovation, 19, 100967. https://doi.org/10.1016/j.eti.2020.100967

Sayyed S, Das RK, Kulkarni K (2022) Experimental investigation for evaluating the performance and emission characteristics of DICI engine fueled with dual biodiesel-diesel blends of Jatropha, Karanja, Mahua, and Neem. Energy, 238, 121787. http://dx.doi.org/10.1016/j.energy.2021.121787

Sharma P, Chhillar A, Said Z, Huang Z, Nguyen VN, Nguyen PQP, Nguyen XP (2022) Experimental investigations on efficiency and instability of combustion process in a diesel engine fueled with ternary blends of hydrogen peroxide additive/biodiesel/diesel. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 44(3), 5929-5950. http://dx.doi.org/10.1080/15567036.2022.2091692

Singhal A, Prashant (2020) Biofuels: Perspective for Sustainable Development and Climate Change Mitigation. Biotechnology for Biofuels: A Sustainable Green Energy Solution, 1–22. https://doi.org/10.1007/978-981-15-3761-5_1

Soudagar M, Elahi M, Nik-Ghazali N-N, Kalam MA, Badruddin IA, Banapurmath NR, Yunus Khan TM, Bashir MN, Akram N, Farade R, Afzal A (2019) The effects of graphene oxide nanoparticle additive stably dispersed in dairy scum oil biodiesel-diesel fuel blend on CI engine: performance, emission and combustion characteristics. Fuel, 257, 116015. https://doi.org/10.1016/j.fuel.2019.116015

Soudagar MEM, Nik-Ghazali N-N, Kalam MA, Badruddin IA, Banapurmath NR, Bin Ali MA, Kamangar S, Cho HM, Akram N (2020a) An investigation on the influence of aluminium oxide nano-additive and honge oil methyl ester on engine performance, combustion and emission characteristics. Renewable Energy, 146: 2291-2307. https://doi.org/10.1016/j.renene.2019.08.025

Soudagar MEM, Afzal A, Safaei MR, Manokar AM, EL-Seesy AI, Mujtaba MA, Samuel OD, Badruddin IA, Ahmed W, Shahapurkar K, Goodarzi M (2020b) Investigation on the effect of cottonseed oil blended with different percentages of octanol and suspended MWCNT nanoparticles on diesel engine characteristics. Journal of Thermal Analysis and Calorimetry, 147(1): 525-542. https://doi.org/10.1007/s10973-020-10293-x

Tabatabaei M, Aghbashlo M, Najafi B, Hosseinzadeh-Bandbafha H, Faizollahzadeh Ardabili S, Akbarian E, Khalife E, Mohammadi P, Rastegari H, Ghaziaskar HS (2019) Environmental impact assessment of the mechanical shaft work produced in a diesel engine running on diesel/biodiesel blends containing glycerol-derived triacetin. Journal of Cleaner Production, 223, 466–486. https://doi.org/10.1016/j.jclepro.2019.03.106

Tadros M, Ventura M, Guedes Soares C (2022) Assessment of marine Genset performance with biodiesel fuel using the double-Wiebe function. Trends in Maritime Technology and Engineering; Guedes Soares, C., Santos, TA, Eds, 545-551. http://dx.doi.org/10.1201/9781003320272-61

Tadros M, Ventura M, Soares CG (2021) A review of the use of Biodiesel as a green fuel for diesel engines. Maritime Technology and Engineering, 2(5): 481-489. http://dx.doi.org/10.1201/9781003216599-51

Tadros M, Ventura M, Soares CG (2023) Review of current regulations, available technologies, and future trends in the green shipping industry. Ocean Engineering, 280, 114670. https://doi.org/10.1016/j.oceaneng.2023.114670

Tan EC, Harris K, Tifft SM, Steward D, Kinchin C, Thompson TN (2022) Adoption of biofuels for marine shipping decarbonization: A long-term price and scalability assessment. Biofuels, Bioproducts and Biorefining, 16(4): 942-961. https://doi.org/10.1002/bbb.2350, https://doi.org/10.1002/bbb.2350

Tan EC, Hawkins TR, Lee U, Tao L, Meyer PA, Wang M, Thompson T (2021) Biofuel options for marine applications: technoeconomic and life-cycle analyses. Environmental Science & Technology, 55 (11): 7561-7570. https://doi.org/10.1021/acs.est.0c06141

Torres-Garcia M, Garcia-Martin JF, Aguilar FJJE, Barbin DF, Alvarez-Mateos P (2020) Vegetable oils as renewable fuels for power plants based on low and medium speed diesel engines. Journal of the Energy Institute, 93(3): 953-961. https://doi.org/10.1016/j.joei.2019.08.006

Tuli D, Kasture S (2022) Biodiesel and green diesel. Advanced Biofuel Technologies, 119–133. https://doi.org/10.1016/b978-0-323-88427-3.00010-6

Venu H, Raju VD, Lingesan S, Elahi M, Soudagar M (2021) Influence of Al2O3nano additives in ternary fuel (diesel-biodiesel-ethanol) blends operated in a single cylinder diesel engine: Performance,

combustion and emission characteristics. Energy, 215, 119091. https://doi.org/10.1016/j.energy.2020.119091

Vellaiyan S (2023) Optimization of pyrolysis process parameters for a higher yield of plastic oil with enhanced physicochemical properties derived from medical plastic wastes. Sustainable Chemistry and Pharmacy, 36, 101310. https://doi. org/10.1016/j.scp.2023.101310

Verma J, Goel S (2023) State-of-the-art in bioresources for sustainable transportation. International Journal of Hydrogen Energy, 48(10): 3768-3790. https://doi.org/10.1016/j.ijhydene.2022.10.206

Veza I, Afzal A, Mujtaba MA, Tuan Hoang A, Balasubramanian D, Sekar M, Fattah IMR, Soudagar MEM, EL-Seesy AI, Djamari DW, Hananto AL, Putra NR, Tamaldin N (2022) Review of artificial neural networks for gasoline, diesel and homogeneous charge compression ignition engine. Alexandria Engineering Journal, 61 (11): 8363-8391. https://doi.org/10.1016/j.aej.2022.01.072

Vidović T, Šimunović J, Radica G, Penga Ž (2023) Systematic Overview of Newly Available Technologies in the Green Maritime Sector. Energies, 16(2): 641. https://doi.org/10.3390/en16020641

Wang L, Li Y (2023) Estimation methods and reduction strategies of port carbon emissions-what literatures say? Marine Pollution Bulletin, 195, 115451. https://doi.org/10.1016/j.marpolbul. 2023.115451

Watanabe MDB, Cherubini F, Cavalett O (2022) Climate change mitigation of drop-in biofuels for deep-sea shipping under a prospective life-cycle assessment. Journal of Cleaner Production, 364, 132662. http://dx.doi.org/10.1016/j.jclepro.2022.132662

Wategave SP, Banapurmath NR, Sawant MS, Soudagar MEM, Mujtaba MA, Afzal A, Basha JS, Alazwari MA, Safaei MR, Elfasakhany A, Sajjan AM (2021) Clean combustion and emissions strategy using reactivity-controlled compression ignition (RCCI) mode engine powered with CNG-Karanja biodiesel. Journal of the Taiwan Institute of Chemical Engineers, 124, 116-131. https://doi.org/10.1016/j.jtice.2021.04.055

Wojcieszyk M, Kroyan Y, Larmi M, Kaario O, Zenger K (2019) Effect of Alternative Fuels on Marine Engine Performance. SAE Technical Paper Series. https://doi.org/10.4271/2019-01-2230

Wu G, Ge JC, Choi NJ (2020) A Comprehensive Review of the Application Characteristics of Biodiesel Blends in Diesel Engines. Applied Sciences, 10(22): 8015. https://doi.org/10.3390/app10228015

Yaliwal VS, Banapurmath NR, Soudagar MEM, Afzal A, Ahmadi P (2022) Effect of manifold and port injection of hydrogen and exhaust gas recirculation (EGR) in dairy scum biodiesel-low energy content gas-fueled CI engine operated on dual fuel mode. International Journal of Hydrogen Energy, 47(10): 6873-6897. https://doi.org/10.1016/j.ijhydene.2021.12.023

Yeo S, Jeong B, Lee WJ (2023) Improved formal safety assessment methodology using fuzzy TOPSIS for LPG-fueled marine engine system. Ocean Engineering, 269, 113536. https://doi.org/10.1016/j.oceaneng.2022.113536